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Anesthetic Mishaps: Breaking the Chain of Accident Evolution

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RISKS OF ANESTHETIC ADMINISTRATION were recognized soon after the advent of surgical anesthesia,[1] and much subsequent attention has focused on the role of anesthesia on surgical mortality.[2] The interpretation of the magnitude and source of anesthetic risks has been controversial. A common view[3,4] is that anesthesia risk should be zero because anesthesia is not itself therapeutic, and "anesthetic agents themselves are not lethal except when they are misused."[4] This view was challenged[5] by Keats on the grounds that anesthetic and adjuvant drugs are potent and have complications both known and idiosyncratic. However, Hamilton[6] responded that management of these drug responses "is the essence of the practice of anesthesia and is an important area in which anesthesia differs from other specialities." Studies[4–10] of anesthetic-related mortality have not conclusively shown the exact contribution of anesthesia to perioperative deaths. No comprehensive prospective study of anesthetic mortality will probably ever be undertaken in the United States, because medical-legal considerations stifle confidential inquiry.[10] More recently, empirical investigations of "near misses"[11–16] have attempted to determine the causes of anesthetic mishaps independent of the occurrence of actual patient injury. These investigations have suggested that many mishaps are due to human error rather than equipment failure, and are therefore "discoverable"[17] and "preventable."[11–13] Extrapolation from these studies suggests that, of the 2,000–10,000 deaths annually attributable to anesthesia in the United States, approximately half are preventable.§

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The Normal Accidents Model

WHAT IS PREVENTABLE IN PRINCIPLE IS NOT NECESSARILY PREVENTABLE IN PRACTICE

The accident at Three Mile Island (TMI), and more recently the Challenger explosion, Bhopal disaster, and Chernobyl incident have brought greater public attention to the areas of human factors and accident prevention. A new view of accidents and risks, which grew out of an analysis of the events at TMI, has been introduced by the organizational theorist Charles Perrow.[18] He notes that accidents continue to occur, despite both powerful incentives to prevent them, and the existence of multiple technological and operational fail-safe systems. Perrow terms this phenomenon "normal accidents" or "system accidents," suggesting that "in certain systems multiple and unexpected interactions of failures are inevitable."[18] System accidents are different than simple component failure accidents, in that they involve unanticipated interactions of multiple failures. Thus, a system designed to correct routine single equipment failures or human errors may be incapable of handling more complex mishaps. The analysis which Perrow applies to nuclear power, spaceflight, aviation, chemical manufacturing, and shipping applies equally to anesthesiology.

Characteristics of Systems Predisposing to System Accidents

The two key elements which make a system vulnerable to system accidents are *complexity of interactions* and *tightness of coupling* between components. Systems combining these elements will likely have accidents despite the efforts to avoid them.

COMPLEXITY OF INTERACTIONS

Routine interactions are those which are expected in familiar sequence, and those that are quite visible even if unplanned. "Complex interactions are those of unfamiliar sequences or unplanned and unexpected sequences, and are either not visible or not immediately comprehensible."[18] We extend Perrow's analysis by identifying three types of complexity.

Intrinsic complexity. The physical process in question can only be achieved with a high-technology production system, using precision components acting in a closely coordinated fashion. Spaceflight and nuclear power are good examples, since making either happen at all requires enormous effort. In these settings, failure of the coordination between systems can unleash catastrophic forces.

Proliferation complexity. The physical process may be more simple, but the operation of the process requires a large number of simple components (for example, wires, pipes, switches, valves) which are interconnected in a very complex fashion. Electrical grids or chemical plants are good examples.

Uncertainty complexity. The physical processes, while simply achieved, are poorly understood. Cause-effect relationships are not clear-cut, and have a high degree of unpredictability. The means of describing and monitoring the process are limited, and of uncertain predictive value.

An anesthetic state can be achieved easily, but the mechanism of anesthesia and other pharmacologic and physiologic actions are poorly understood, leading to a large amount of uncertainty (uncertainty complexity, above). To reduce these uncertainties, extensive monitoring is used to help manage the anesthetic state, thereby generating substantial proliferation complexity (proliferation complexity, above). The increased number of components leads to a high probability of single component failures, and the complexity of the interaction between equipment, the anesthesiologist, and the patient may be hidden until unmasked by a crisis.

Coupling

"Tight coupling describes systems in which there is no slack, buffer, or give between two items. What happens in one part of the system directly affects other portions of it."[18] Loose coupling then describes systems in which the causal network is more flexibly linked, or linked in a much slower temporal fashion. The Chernobyl reactor was more tightly coupled than many reactors, and, when operated inappropriately, it easily got out of control.[19,20]

The human body presents examples of both tight and loose coupling. The body is physically compartmentalized, and there is redundancy in many systems (spare neuromuscular receptors, collateralization of blood flow, two lungs, two kidneys, etc.). The cardiovascular, respiratory, and nervous systems are intrinsically tightly coupled, but highly integrated homeostatic reflexes control these organ systems. These mechanisms loosen coupling and provide the buffers necessary to prevent variations in one system from propagating further, or affecting other organ systems. For example, in response to hemorrhage, the heart rate increases, blood vessels constrict, stress hormones are released, and so on. Yet anesthesia ablates or eliminates many homeostatic mechanisms, and thereby tightens the coupling between systems. The anesthetic state itself eliminates conscious aversion to noxious stimuli. Anesthetics and muscle relaxants attenuate ventilatory responses to hypoxia or hypercarbia, coupling ventilation to outside support. Anesthetics may abolish pulmonary or systemic vasoconstriction and baroreceptor reflexes. Conversely, some common preventive measures are aimed at loosening coupling, such as pre-oxygenation before induction, or cricoid pressure to decouple gastric events from the lungs.

Though there are differences between the complexity and coupling in anesthesia compared to that encountered in other high-risk industries, the end result is similar. Anesthesia-related accidents, while often triggered by single component failures, have all the elements of system accidents. As Orkin states:[21] "It is the unfortunate confluence of several of these events and factors that often leads to catastrophe."

Incidents *Versus* Accidents

Given unpredictable physiology and pharmacology, the addition of surgical trespass, and a multitude of electromechanical devices in use, it is no wonder that problems, failures, and errors occur commonly during anesthetic care. They may arise *de novo* from the patient's diseases (hypertension before surgery), they may be due to an interaction between these diseases and the anesthetic or surgical intervention (hypertension after laryngoscopy or surgical incision), or they may be due to equipment failure or error by the anesthesiologist or surgeon. When such a deviation is of minimal immediate significance, it constitutes a "simple incident." Such incidents are extremely commonplace and, in some cases, planned (disconnect to allow suctioning); the critical issue is whether the incident then disappears, remains the same, or propagates and interacts. Propagation and interaction of an incident occurs when it becomes more severe, spreads within the system, or adversely affects other systems. It requires tight coupling between system components and the possibility of complex interactions.

Through propagation and interaction, a simple incident may become a "critical incident," defined by Cooper *et al.*[13] as: "A human error or equipment failure which could have led (if not discovered or corrected in time) or did lead to an undesirable outcome ranging from increased length of hospital stay to death."[13] A critical incident is said to have a "substantive negative outcome" (SNO) if it results in "mortality, cardiac arrest, cancelled operative procedure, extended stay in recovery room, intensive care

unit, or hospital." A critical incident which is associated with a SNO may thus be considered an accident.

Breaking the Chain of Accident Evolution: Recovery from Simple Incidents

Regardless of the cause of the original simple incident, most incidents are detected and accidents averted. Recovery from incidents has proved life-saving in spaceflight (Apollo 13),[18] nuclear power (TMI,[18,22,23] Brown's Ferry[18]), and chemical manufacturing (Union Carbide's Institute plant leak¶). The disaster at Chernobyl occurred in part because recovery pathways were purposefully disabled,[20] a far worse catastrophe was later prevented only by heroic Soviet recovery efforts.[24] Recovery processes are extremely important in anesthesia. Ninety-three percent of over 1000 critical incidents reported by Cooper[13] were recovered from without a negative outcome. Although successful recovery from some incidents will extend the patient's stay in the post-anesthesia or intensive care unit, or the hospital, it is recognized that such minor negative outcomes are acceptable if a more severe one has been prevented.

The normal accidents model predicts the evolution of some incidents to accidents because the presence of tight coupling and complex interactions makes recovery from a propagating and interacting incident difficult. Experience with other high-risk industries suggests that successful intervention in the chain of an accident cannot be guaranteed.[18] To recover from anesthesia incidents, the anesthesiologist must: 1) detect one or more of the manifestations of the incident in progress; 2) verify the manifestations and reject false alarms; 3) recognize that the manifestations represent an actual or potential threat; 4) assure continued maintenance of life-sustaining functions; 5) implement "generic" diagnostic or corrective strategies to provide failure compensation and allow continuation of surgery if possible; 6) achieve specific diagnosis and therapy of the underlying causes; and 7) provide follow-up of recovery to ensure adequate correction or compensation.

Factors that are associated with unsuccessful recovery are: 1) lack of recognition of the most serious problems; 2) failure to initiate life-sustaining therapies first; 3) lack of adequate back-up or safety equipment; 4) ignorance of appropriate recovery procedures; 5) improper implementation of known recovery procedures; 6) inadequate follow-up of recovery status; and 7) lack of patient response to properly applied appropriate recovery procedures.

¶ Perrow C: Text of an address to the American Sociological Association, August, 1986.

Since recovery procedures are often unfamiliar and carried out in haste, they may generate new failures or errors; even error-free but inappropriate recovery efforts waste valuable time.

The majority of potential problems are effectively dealt with by a combination of prevention and recovery. For example, hypotension from spinal anesthesia may be prevented by fluid loading. If significant hypotension does occur, recovery is achieved with positioning, fluid, and vasopressor administration. Recovery pathways need to be considered in advance, and reviewed in detail when difficulties can be anticipated. Such planning can make the difference between an incident and an accident. When recovery would be very difficult or impossible, prevention is of the utmost importance, and substantial efforts may be necessary to insure that these problems are avoided. For example, unlabeled syringes are routinely discarded, even when the contents are probably known. Extensive cross-checks of the identity of blood units are made, since infusion of even a small amount of unmatched blood could be devastating.

Successful recovery requires previously identified equipment, including alternate oxygen supplies, backup breathing circuit bags, endotracheal tubes, laryngoscopes, etc. Certain recovery equipment or drugs are routinely made immediately available (suction; ephedrine for spinal anesthetics), while other items are provided as a common emergency resource (backup anesthesia machine, crash cart, defibrillator). Routine backup equipment should be checked before each case, and common equipment should be checked on a regular basis. An additional factor in successful recovery from severe incidents is the availability of backup personnel for assistance during crises.

Vigilance, Monitoring, and Mental Maps

If recovery from inevitable failures is the key to patient safety, the first step is to recognize that something is wrong. This has been equated with vigilance—the ability to sustain attention. Data indicating that many mishaps occur during the middle of the case[11] have been interpreted to signify that vigilance is reduced at this time of reduced mental and physical workload.[25] However, similar data[13] suggest that at least 33% of critical incidents are due to errors in judgement, not vigilance. Perhaps uncertainty is higher during the middle of the case, making greater mental demands on the anesthesiologist than estimated from observations of actions alone.

Vigilance is thus a necessary, but not sufficient condition for averting accidents. Anesthesia vigilance is different from laboratory tests of attention or the vigilance of a ship's lookout, because the anesthesiologist must carry out many diverse tasks which often require both visual

attention and manual dexterity.[25,26] A variety of simple and complex monitors are used to track both the status of the patient and the correct operation of anesthetic equipment. Each monitor is prone to artifact (false readings), due in part to motion and electrical interference; and transients (true readings of no significance), due to rapidly changing physiologic conditions. Identifying real problems in this environment is difficult. The presence of frequent false positives can vitiate the benefits of alarms or other vigilance aids. Inactivating an alarm may be a rational decision if the likelihood of danger is low, the false alarm rate is high, and the alarm is sufficiently distracting. Such behavior has been observed in shipping[18] where collision avoidance radars are frequently turned off because of too much screen clutter. In nuclear power[18,23] and chemical manufacturing,[18] gauges and alarms have been left inoperative for similar reasons.

Scanning many monitors and responding to alarms can paralyze personnel, and both novices and veterans have become locked into finding the cause of a meaningless alarm, to the exclusion of more important tasks. It may be hard to know which monitor "really tells the story." As Perrow states[18] about the Apollo 13 explosion: "There is no gauge that reads 'Oxygen tank explosion,' only gauges of pressure and temperature and levels." Similarly, there is no monitor that reads "hypovolemia," none that reads "pneumothorax," etc. In fact, Calkins[27] suggests that anesthesiologists need a "sixth sense . . . a general sensation of something gone wrong but without delineation of the actual problem."

This is an era of high technology, and there is an unstated assumption that detection of incidents by new monitoring equipment will necessarily lead to successful recovery. Yet, the contribution of monitors depends on the abilities of the anesthesiologist to use the data in a setting likely to be full of artifact or contradictory information. Both invasive and non-invasive monitoring is thus a two-edged sword, and few data exist** on how monitored information and clinical observations are used.[28] Increased integration of monitors and alarms†† has come about as a response to the confusion generated by a proliferation of components,[29] but this approach has not been validated. Perhaps, as Ream[30] notes, we do not need *more* integrated monitors, but fewer, *better* monitors that are more directly connected to patient physiology and outcome. Our understanding of which variables to monitor is still rudimentary.[31]

** Gravenstein JS, Weinger MB: Why investigate vigilance? J Clin Monitoring 2:145–147, 1986

†† Waterson CK, Calkins JM: Development directions for monitoring in anesthesia. Seminars in Anesthesia 5:225–236, 1986

Mental Maps

Data is useless without a context in which to place it. Operators of complex systems have a "mental map"[18,32,33] of the system and how it behaves in certain states. Judgements made in the course of operations are based on this underlying map. One of the lessons learned from TMI, ship collisions, and other system accidents is that, in the face of uncertainty, even highly skilled professionals may act incorrectly because they have constructed an erroneous map of the situation. While the operators of TMI were criticized[18] for failing to deal properly with the problem (originally triggered by a valve failure), Perrow quotes the testimony of a supervisor at TMI:

> "I think we knew we were experiencing something different, but I think each time we made a decision it was based on something we knew about. For instance: pressure was low, but they had opened the feed valves quickly in the steam generator, and they thought that might have been "shrink." There was a logic at that time for most of the actions, even though today you can look back and say, well, that wasn't the cause of that, or, that shouldn't have been that long."[18]

Accidents involving faulty mental maps may be the most insidious. Frequently, many of the indications of a problem are readily available; they are just never put together in the proper context. It is not a question of lack of vigilance or equipment failure. As Perrow states concerning the oxygen tank explosion on the Apollo 13 mission:

> "The accident allows us to review some typical behavior associated with system accidents: (1) initial incomprehension about what was indeed failing; (2) failures are hidden and even masked; (3) a search for a *de minimus* [minimal] explanation since a *de maximus* [maximal] one is inconceivable; (4) an attempt to maintain production if at all possible; (5) mistrust of instruments since they are known to fail; (6) overconfidence in engineered safety devices and redundancies, based on normal experience of smooth operation in the past; (7) ambiguous information is interpreted in a manner to confirm initial (*de minimus*) hypotheses; (8) tremendous time constraints, in this case involving not only the propagation of failures, but the expending of vital consumables; and, (9) invariant sequences, such as the decision to turn off a subsystem that could not be restarted".[18]

These descriptions are hauntingly familiar. For example, a tachycardia may be ascribed to light anesthesia, a common occurrence (*de minimus* explanation). Contradictory data may be rejected if they do not support the initial hypothesis, and because judgements must be made frequently using incomplete data. Making the switch from handling routine perturbations to coping with a catastrophe is difficult, especially when true catastrophes are rare and the indications of catastrophe are not clear-cut.

Faulty mental maps might explain Cooper's[12] finding that problems were discovered or correctly diagnosed by new personnel in 30% of critical incidents which were coexistant with a personnel exchange. The "discovering"

personnel were usually more experienced, consistent with the hypothesis that experience improves mental maps as much as it does vigilance. The investigation of how anesthesiologists make decisions in the setting of dynamically changing information has barely begun.‡‡ This research should be a major priority, since it can help determine the actual utility of various monitors, as well as new approaches to training, certification, and continuing education.

Time and Production Pressures

A final key factor in industrial catastrophes is the pressure to produce. The temptation in anesthesia to "cut corners" is great, and the perceived risk is small, since, as Cooper writes:[13] "Perhaps the most insidious hazard of anesthesia is its relative safety." Production pressures may prevent the cancellation of surgery for patients who are inadequately prepared; or they may cause anesthesia to be started before all the necessary equipment has been checked. Production pressures may also prevent the termination of surgery after a mishap, even when this is the safest thing to do. These pressures are real and not trivial. However, retrospective analysis of accidents, including litigation, may show where production pressures have apparently affected decision making.

Vulnerability to such pressures is an inevitable part of human activity, which other industries have tackled with formal procedures governing risky decisions. NASA established a set of explicit Flight Readiness Reviews and Launch Commit Criteria[34] governing the exact conditions to be met before proceeding with launch. Furthermore, specific launch constraints are imposed which preclude launch when serious unsolved problems exist. These policies place on each contractor or division the burden of proving readiness to launch. The disregard of established procedures by shifting the burden to prove that launch should not take place, and the repeated waiver of launch constraints without hard supporting data, played primary roles in the Challenger explosion.[34] Also, in planning spacecraft operations, specific failure modes are analyzed and recovery procedures explicitly defined. Criteria for abort of missions are pre-established, removing some pressure from decision-makers in crisis situations. We suggest that, in each institution, anesthesiologists, in consultation with their colleagues in surgery, internal medicine, and pediatrics, could clarify "commit criteria," "constraints," and "readiness reviews" for preoperative evaluation of patients, and criteria for termination of surgery in various circumstances. Such approaches are already used in an informal manner, but there is frequently great pressure to bend the rules. Explicitly clarifying the guidelines could provide a firmer basis on which to base difficult, and sometimes costly, decisions.

New safety technology has sometimes led primarily to growth of production rather than to safety. Adding radar to merchant ships increased pressures to bring in cargoes "on time," regardless of stormy weather. Advances in air traffic control led to reduced aircraft separation and increased traveling speed.[18] The shuttle was launched in unprecedently cold weather because of a false sense of technological security. Advanced monitoring, such as oximetry and capnography, could create similar pressures to perform anesthetics or utilize techniques that previously were considered hazardous.

The Larger System

Maintaining patient safety is a complex issue for which there is no simple resolution. There is no easy technological fix. Commercial aviation, often suggested as a model for anesthesia,[10,35] was made acceptably safe only by a relatively complete understanding of aerodynamics and aircraft design, centralized airway control, and large bureaucracies devoted to airline safety and regulation. Despite all that, accidents still infrequently occur. Enormous expenditures, public scrutiny, and complex regulation of nuclear power have not prevented serious reactor mishaps.

Other high risk industries live within a framework established by the larger social system. Interactions between the elements of the larger system have sometimes created an "error inducing system,"[18] which provides negative incentives for safety and positive incentives for unsafe actions. Anesthesia practice has evolved within a larger system of medical staffing, financial incentives, cost constraints, legal precedents, and regulations that do not promote patient safety in a coordinated manner. Our profession and the public have begun to recognize the importance of actively promoting safety during anesthesia. The incentives and constraints of the larger system will determine to what extent we can or must go to enhance our safety record. The professional societies, standards and review agencies, medical payment authorities, health and liability insurance carriers, and courts are major players in determining the way that patient safety will be addressed.

Summary

Anesthesia and surgery are a risk for all, the healthy as well as the sick. While the prevention of adverse outcomes in healthy patients is paramount, enhancement of safety for critically ill patients is also essential, since they are more likely to suffer a SNO after a critical incident.[13] Dangers originate from a variety of sources, not solely

‡‡ Waterson CK, Calkins JM: Development directions for monitoring in anesthesia. Seminars in Anesthesia 5:225–236, 1986

from errors by the anesthesiologist. Simple incidents of all description are inevitable, and we should focus on promoting recovery as well as avoiding error.

Processes that lead to negative outcomes after critical incidents should be investigated to reduce the uncertainty complexity associated with managing the human body during anesthesia, and to establish the most effective detection and recovery techniques. Outcome studies are lacking, and clinical and animal research is highly dependent on the chosen model or population, making the results hard to apply to variable clinical conditions. Wherever possible, a consensus should be sought on therapeutic and adverse effects of drugs and techniques in common, specific patient populations. These can serve as a basis for developing therapeutic plans, recognizing that customizing to individuals is always necessary.

A mainstay of anesthetic practice already involves attempts to loosen couplings, by keeping homeostatic mechanisms intact when possible (awake intubation, regional anesthesia); providing temporal buffers (titration of drugs, and use of drugs with short onset times and rapid termination of effect); and providing safety margins using appropriate pre-treatments (pre-oxygenation, atropine in children, etc.). Further means of loosening coupling should be identified and promoted.

Specific attention to recovery from simple incidents should attack several facets of the problem.

Improve detection of simple incidents. New monitors may help, especially those that measure parameters more closely related to life-sustaining functions (oxygenation, end-tidal CO_2), but the actual contribution of such monitoring needs to be more clearly established. Alarms should be improved so that their benefits clearly outweigh their annoyance and potential confusion. The hypothesis that integrated monitor displays will reduce mental workload and enhance decision-making must be validated. And, even if proven successful, integrated monitors will only be as good as their components. It might be equally advantageous to standardize interfaces between separate instruments, rather than promote single source integrated devices.

Improve the anesthesiologist's abilities to construct and utilize useful mental maps of anesthetics in progress. We believe that anesthesia simulators[36] should be developed to assist in training and education. Anesthesia simulations should emphasize differentiating critical from non-critical events, and making the switch from routine management to recovery from catastrophe. Eventually, such techniques might become a part of routine training and certification, much as advanced simulators can be the sole training and examination modality for commercial pilots,[37] and are a component of examinations of nuclear power plant operators.[37] Simulators can be used as rehearsal aids, to develop skills, to build confidence, and to control stress.[38]

Enhance recovery by detailing backup equipment appropriate for various types of surgery. Guidelines for inspection and checks of anesthesia apparatus§§ should extend to routine and common resource recovery aids. Backup personnel should be available whenever possible, and non-professionals (*i.e.*, technicians, orderlies) might be trained to assist the professional staff during crises.

Catalog and disseminate effective protocols for handling of rapidly propagating incidents, as has already been done for malignant hyperthermia[39] *and for Basic and Advanced Cardiac Life Support.*[40] These emergency protocols could be formally taught, and recovery pathways practiced using simulators. Continual re-evaluation of diagnoses and therapies should be emphasized, since the initial approach is not always the optimal one, and patients do not always respond to even appropriate therapies.

Production pressures should be lessened to allow time for proper equipment checkout and adequate preoperative evaluation of patients. A basis for decisions concerning suitability for induction or termination of anesthesia and surgery should be established cooperatively by anesthesiologists and their colleagues in each institution. Advanced monitoring cannot guarantee safety, and should not substitute for appropriate perioperative management.

As anesthesiologists, we are the most important link in the chain of safe anesthetic care. We have two responsibilities. The first is to scrutinize our own abilities and limitations as carefully as we investigate those of our drugs and tools, and implement the procedures and training that can be shown to optimize patient safety. This process is underway, but substantial research lies ahead. The second responsibility is to reexamine the entire structure of our industry, attempting to steer the interacting sources of incentive and constraint towards a system that promotes patient safety. The path to this goal has yet to be defined; but the public expects no less, and our profession must take the initiative to see that it is so.

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