Annals of Operations Research 67(1996)211–233

Patient risk in anesthesia: Probabilistic risk analysis and management improvements

Elisabeth Paté-Cornell[a], Dean Murphy[a], Linda Lakats[a] and David Gaba[b]
[a]*Department of Industrial Engineering and* [b]*Department of Anesthesia,*
Stanford University, Stanford, CA 94305, USA

In this paper, we present a pilot study in which we use probabilistic risk analysis (PRA) to assess patient risk in anesthesia and its human factor component. We then identify and evaluate the benefits of several risk reduction policies. We focus on healthy patients, in modern hospitals, and on cases where the anesthetist is a trained medical doctor. When an accident occurs for such patients, it is often because an error was made by the anesthesiologist, either triggering the event that initiated the accident sequence, or failing to take timely corrective measures. We present first a dynamic PRA model of anesthesia accidents. Our data include published results of the Australian Incident Monitoring Study as well as expert opinions. We link the probabilities of the different types of accidents to the "state of the anesthesiologist" characterized both in terms of alertness and competence. We consider different management factors that affect the state of the anesthesiologist, we identify several risk reduction policies, and we compute the corresponding risk reduction benefits based on the PRA model. We conclude that periodic recertification of all anesthesiologists, the use of anesthesia simulators in training, and closer supervision of residents could reduce substantially the patient risk.

1 Introduction

Statistical analyses of anesthesia risk typically show that the frequency of severe anesthesia accidents is about one in 10,000 surgical operations (Buck et al., 1987; Keenan and Boyan, 1985; Davies and Strunin, 1984), though this figure varies because it depends in part on subjective assesments of the relative contributions of anesthesia compared to other potential causes of patient death. Based on this, if there are millions of surgeries involving general anesthesia annually in the U.S. (many of which occur outside major hospitals, in surgical clinics and dentists' offices), then anesthesia may account for hundreds or even thousands of deaths per year. In addition to the human costs, these accidents impose significant financial costs through malpractice insurance and litigation. They are unacceptable to patients and anesthesiologists alike, particularly when the victim is a healthy patient undergoing routine surgery. Although some accidents are due to gross incompetence, alcohol or drug abuse by physicians (Inlander et al., 1988), others are caused by generally competent, capable practitioners as the result of a combination of technical and human factors. Some accidents are caused by equipment failures; most mishaps involve human errors (Cooper et al., 1978, 1984;

Gaba, 1989, 1991; Runciman et al., 1993a; Williamson et al., 1993). As in other fields, many of these errors are rooted in organizational and management problems (Paté-Cornell and Bea, 1992) and solutions must therefore come from the management level. Yet, the cost of remedial measures may be high. It is thus important to set priorities in order to identify and implement first the most cost-effective options. This study focuses on the analysis and quantification of anesthesia patient risk (including the primary sources of the risk), and on the evaluation of risk reduction benefits of management changes. It does not attempt to quantify the costs of the different risk management options.

In this paper, we present a model designed to quantify the risk of anesthesia accidents (death or brain damage) for healthy patients in modern, Western hospitals when anesthesia is delivered by an anesthesiologist who is a licensed physician (as opposed to a nurse anesthetist)[1]. We extend this model to characterize the effects of human and organizational factors on anesthesia risk, and we use it to evaluate the potential risk reduction benefits of several proposed policy changes (Paté-Cornell et al., 1994). These results can serve as a guide to focus management attention on risk mitigation measures that promise significant effect.

This study consists of three parts: (1) the development of a system-level risk analysis model for the anesthesia environment; (2) an analysis of the effect of the state of the anesthesiologist on patient risk; and (3) an assessment of the effects of organizational factors on the state of the anesthesiologist, and therefore on patient risk. This extension of the risk analysis methodology to include human and organizational factors follows previous analyses of other technical systems such as offshore drilling platforms (Paté-Cornell, 1990) and the thermal protection tiles of the space shuttle (Paté-Cornell and Fischbeck, 1993).

In the first part of the study (the risk analysis), we divide the set of possible accidents according to the nature of the initiating event that starts the accident sequence (e.g., a breathing circuit disconnect, i.e., an accidental disconnect of the tube that delivers oxygen and anesthetic gases from the anesthesia machine to the patient). We use the probabilistic risk analysis (PRA) framework used in engineering (Henley and Kumamoto, 1981) to quantify the overall risk, combining the probability of accident initiators and the probability of anesthesia accident conditional on the initiator. To compute this conditional probability, we model the progress of anesthesia accident sequences using two embedded (and dependent) stochastic processes: one for the evolution of the anesthesia system, and another one for the evolution of the patient.

In the second part of the study, we analyze the effect of the "state of the anesthesiologist" by separating the anesthesiologists into different categories characterized by various degrees of competence and alertness (e.g., fatigue, or insufficient supervision for residents). We assess a probability distribution for the state of the

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[1] For the purpose of this study, a "healthy patient" is one rated Class 1 or 2 of the American Society of Anesthesiologists (ASA) physical status classification.

anesthesiologist in any given operation, and we estimate the effect of these different states both on the probabilities of initiating events and on the anesthesiologist's performance in the detection, diagnosis and correction of the event. We then compute the increase in accident probability for each anesthesiologist types involving specified problems.

In the third part, we study how management and organizational factors affect the patient risk through their effect on the state of the anesthesiologist. We identify a number of potential policy improvements (for example, restricting the work schedule of anesthesia residents to reduce fatigue) and we quantify the risk-reduction benefits of such improvements. To do this, we assess the effect of each proposed policy change on the probability distribution of anesthesiologist states, and we compute the corresponding change in patient risk. This model can thus be used to quantify the risk implications of management strategies that are usually evaluated only qualitatively.

2 The anesthesia risk analysis model

2.1 *Structure of the model*

Our probabilistic risk model of anesthesia permits the analytical linkage of organizational factors and patient risk through the state of the anesthesiologist (see figure 1). The notation used in this model is as follows:

IE_i : initiating events (e.g., breathing circuit disconnect); index i,

AA : anesthesia accident (death or severe brain damage),

SA_j : state of the anesthesiologist (e.g., fatigued); index j,

O_k : organizational policy (e.g., limit time on duty to twelve consecutive hours); index k.

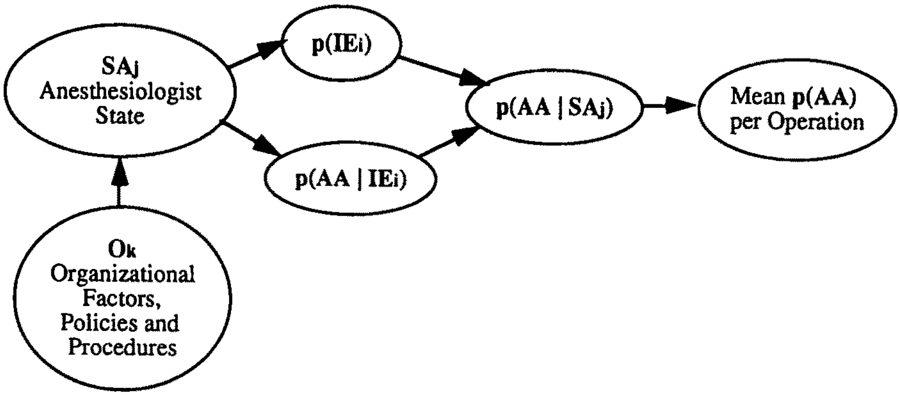

Figure 1. Structure of the generalized risk analysis model for anesthesia.

The structure of our overall risk analysis model is illustrated by the following equations. The total probability of an anesthesia accident is the sum of the patient risk over the different types of initiating events:

$$p(\mathrm{AA}) = \sum_i p(\mathrm{IE}_i)p(\mathrm{AA} \mid \mathrm{IE}_i). \tag{1}$$

The state of the anesthesiologist affects both the probabilities of the initiating events and the probabilities of accidents conditional on the initiating events. Thus, equation (1) can be rewritten as

$$p(\mathrm{AA}) = \sum_i \sum_j p(\mathrm{SA}_j)p(\mathrm{IE}_i \mid \mathrm{SA}_j)p(\mathrm{AA} \mid \mathrm{IE}_i, \mathrm{SA}_j). \tag{2}$$

Organizational policies (O_k) affect the state of the anesthesiologist. Therefore, they can reduce patient risk to the extent that they improve the state of the anesthesiologist, decreasing the probabilities of problem states:

$$p(\mathrm{AA} \mid \mathrm{O}_k) = \sum_i \sum_j p(\mathrm{SA}_j \mid \mathrm{O}_k)p(\mathrm{IE}_i \mid \mathrm{SA}_j)p(\mathrm{AA} \mid \mathrm{IE}_i, \mathrm{SA}_j). \tag{3}$$

This last equation implies that the effects of all organizational policies on the anesthesia risk are captured through their effects on the state of the anesthesiologist (the measures considered address only anesthesiologist problems as opposed to technical ones). Note that the risk associated with "problem-free" anesthesiologists is not zero: they may also make poor decisions, for example, because of production pressures exerted by the organization (Gaba et al., 1994). They may also experience "pure" equipment failures that can increase the probabilities of the initiating events and/or of anesthesia accidents given an initiating event. However, these effects are considered implicitly rather than explicitly in this model, and we do not analyze organizational policies that address them.

2.2 *The Markov model of anesthesia accident sequences*

As indicated in equation (1), the risk of anesthesia accident is modeled in two steps: the probabilities of the different initiating events, which are obtained from statistical data (after de-biasing), and the probabilities of anesthesia accident conditional on initiating event. We model the latter using two embedded Markov models and check the results against available accident statistics.

Following an initiating event, several events that are critical to the recovery of the patient occur in sequence:

- signals of the problem appear either from monitors or from the patient,
- the anesthesiologist observes the signals,
- the anesthesiologist diagnoses the problems,
- the anesthesiologist takes corrective action.

Meanwhile, the patient's state deteriorates until proper corrective measures are taken, at which point recovery begins. However, if too much time passes before the anesthesiologist corrects the problem, the patient will suffer irreversible harm. For some initiating events, the anesthesiologist may misdiagnose the problem and take an inappropriate action which does not halt the patient's deterioration. In other cases, the anesthesiologist may take actions that "buy time", slowing patient deterioration to allow more time to diagnose and correct the underlying problem. Figure 2 illustrates on a time axis the parallel evolution of the patient and the anesthesia system for a generalized initiating event.

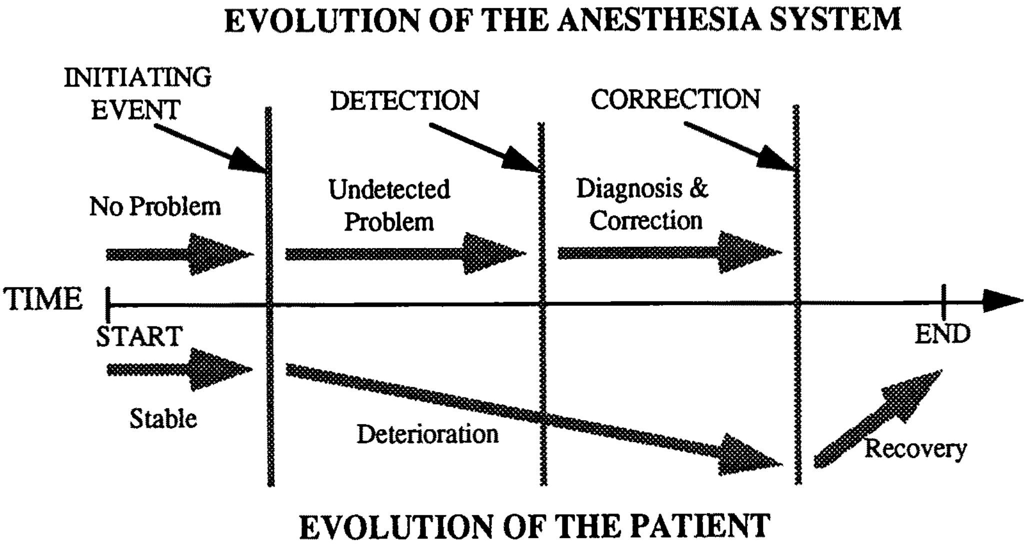

Figure 2. Dynamic modeling of evolution of an anesthesia incident.

The evolution of the patient and the anesthesia system are represented by two embedded Markov models, in which the patient progresses through a series of deteriorating *states* at the same time the anesthesia system progresses through a series of *phases* (the relevant states and phases depend on which of the initiating events is being modeled). The anesthesiologist may detect any combination of several signals: direct signals of an equipment problem, or as time passes, signals of the patient's deteriorating state. For instance, following a breathing circuit disconnect, the patient's state begins to deteriorate because the lungs are not ventilated, reducing the supply of oxygen. If the problem remains uncorrected, the patient will become hypoxemic (low blood oxygen), experience arrhythmia, and eventually go into cardiac arrest, which can lead to death or severe brain damage. In this case, the relevant patient states are:

- Healthy
- Hypoxemia

- Arrhythmia/Arrest
- Brain Damage/Death
- Recovery

These states are obviously a simplification of reality, in which there are degrees of hypoxemia, for example, and arrhythmia is distinct from full-blown cardiac arrest. The first four of these states are sequential (the patient passes through each to get to the next); from any of the first three, the patient can transition into Recovery if the anesthesiologist corrects the problem in time. Once the patient reaches either the Brain Damage/Death or the Recovery state, no further transitions occur. In parallel with the evolution of the patient's state, the phases of the anesthesia system are defined by the following events:

- Disconnect occurs
- Observe equipment signal: No PIP (pressure in airway)
- Detect Hypoxemia
- Detect Arrest
- Detect no PIP *and* Hypoxemia
- Detect no PIP *and* Arrest
- Detect Hypoxemia *and* Arrest
- Detect no PIP, Hypoxemia *and* Arrest
- Ventilate patient
- Treat Arrest; Ventilate patient

The transition probabilities for the evolution of patient state depend on the phase of the anesthesia system (e.g., which, if any, treatment is administered). At the same time, the transition probabilities among the phases of the anesthesia system depend on the state of the patient (e.g., hypoxemia must occur before it can be detected). The models that describe these parallel evolutions can be described as follows. There are m possible patient states and n possible anesthesia system phases (the actual values of m and n depend on the initiating event). All possible combinations of patient states $i = 1$ to $(m - 2)$ and system phases $j = 1$ to n are modeled (though some state/phase combinations may have zero probability of occurrence). The last two patient states, death (patient state $(m - 1)$, shorthand for brain damage/death) and recovery (patient state m) are defined independently. Combinations of these two patient states with each of the possible system phases are not considered separately because the ultimate outcome of interest is the patient's state (not the anesthesia system phases); once the patient reaches death or recovery, there are no further transitions and the anesthesia system phase is no longer relevant. (We do not consider sequences of several initiating events that occur during the same operation; the probability of initiating events is low enough that this is a reasonable assumption.)

The overall state space is thus divided into $[(m-2)n]+2$ states corresponding to the relevant combinations of patient states and anesthesia system phases, plus the final two patient states, defined as follows:

$S_{(i-1)n+j}$: Patient state $= i$,
Anesthesia System phase $= j$,
$i = 1, 2, \ldots, (m-2)$; $j = 1, 2, \ldots, n$.

$S_{(m-2)n+1}$: Patient state $= (m-1)$, Death (or brain damage).
Anesthesia System phase irrelevant.

$S_{(m-2)n+2}$: Patient state $= m$, Recovery.
Anesthesia System phase irrelevant.

The state of the overall system (patient and anesthesia system) can be represented by the state vector S, where the element S_k is the probability that the system is in state k. The model begins with the system in state 1: patient state "healthy" and system phase "initiating event occurred" (but no detections of signals or corrective actions yet), represented by the initial state vector $S = [1, 0, \ldots, 0]$. Transitions among overall system states occur with the probabilities given by the transition matrix T, in which element T_{ij} is the probability of transition from state i to state j in one time period of five seconds. (A time period of 5 seconds was chosen to capture the rapid changes in patient state and system phase that can occur under some conditions; the fastest state transitions modeled have mean times of about 30 seconds.) Therefore, the probabilities that the patient ends in each of the final trapping states, death or recovery (P_D and P_R, respectively) are found by multiplying the initial state vector by the transition matrix raised to a sufficiently large power to simulate the evolution of the system for long enough to reach the limiting probabilities:

$$[1, 0, \ldots, 0] \lim_{k \to \infty} T^k = [0, \ldots, P_D, P_R]. \tag{4}$$

In practice, raising the transition matrix to the power 1,000 is more than sufficient to reach the limiting probabilities. Since each power of the transition matrix corresponds to a time unit of 5 seconds, this corresponds to modeling the system's evolution for about 85 minutes after the initiating event. In fact, the events are virtually always resolved in much less time (typically 5 to 15 minutes) because, if a problem is not corrected promptly, patient state tends to deteriorate quickly to irreversible brain damage or death.

The assumptions of a Markov model, with its exponential transition times and memoryless property, implies that transition probabilities depend only on the current patient state and anesthesia system phase. This does not reflect the possibility that a patient whose condition deteriorates quickly at first may be more likely to deteriorate quickly later in the accident sequence. However, given that the analysis is restricted to healthy patients, a memoryless deterioration process seems reasonable. In any case, this assumption would not have a significant effect on the results of this study, since the range of variation in the rate of patient deterioration is much smaller than the differences in anesthesiologist performance that drive the results.

The evolution of anesthesia accident sequences following an initiating event is analyzed based on expert judgments of the mean transition times between the relevant key events (e.g., the time elapsed between a breathing circuit disconnect and the appearance of signals). From these transition times, we derive transition probabilities for the Markov models of accident sequences as the reciprocal of the mean transition time (in minutes) times the number of time periods per minute. The results of these models are the probabilities of an accident given an initiating incident. The overall results (probabilities of accidents for each type of initiator) are checked against available data, and the expert estimates are revisited so that the overall accident rate is consistent with the available accident statistics. The sources of the data and validation against existing statistics are illustrated in figure 3.

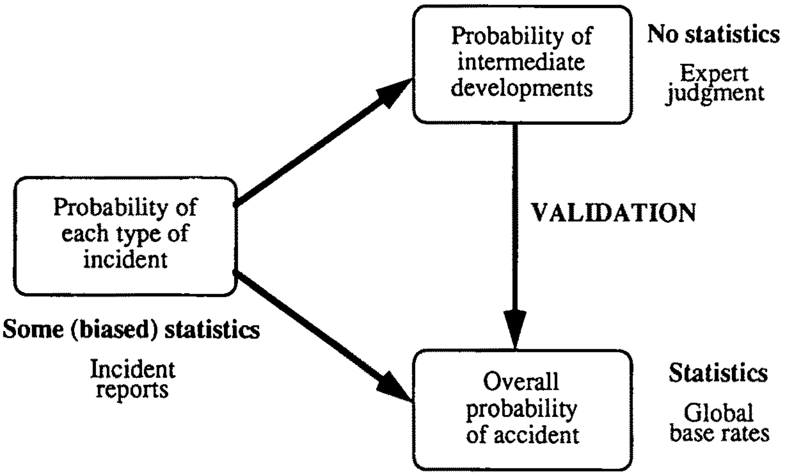

Figure 3. Three levels of analytic detail and statistical information in the analysis of anesthesia risks.

2.3 *Initiating events*

We initially identified both equipment failures and human errors as initiating events. Equipment failures generally involve either the monitors or the breathing apparatus, including ventilator, tubes and connections (Weinger and Englund, 1990). One of the most frequent initiating events is a breathing circuit disconnect, which is made more likely by the simple friction connection of the breathing tube (Cooper et al., 1978) and is, in part, an equipment design issue. However, this and many other "equipment" problems are more appropriately viewed as problems of human error in failing to use the equipment properly (many "equipment failures" consist of failure to check equipment settings or function). The contribution of "pure" equipment failures to the overall patient risk was found to be negligible relative to the contribution of human errors.

Subsequently, we classified initiating events into seven categories which are primarily attributable to human errors:

- Breathing circuit disconnect
- Esophageal intubation
- Nonventilation
- Malignant hyperthermia
- Inhaled anesthetic overdose
- Anaphylactic (allergic) reaction
- Severe hemorrhage

For each of these initiating events, we developed a Markov model of the ensuing accident sequence, and assessed transition times between patients states and anesthesia system phases.

2.4 *Data sources for the model*

One difficulty of probabilistic modeling is the scarcity of statistical data. In this study, the data come primarily from four sources: the Australian Incident Monitoring Study (AIMS) data base (Webb et al., 1993); existing general statistics on perioperative deaths (Campling et al., 1992); case studies (Cook et al., 1991); and expert opinions. The AIMS study provided data on the probability of initiating events, and AIMS and the other statistical data sources were used to validate the results of the model. Expert judgment was used to assess the transition times for the Markov models (it was also used later in the study to assess the effects of human and organizational factors).

The AIMS data base provides a rich and recent source of statistical information about the rates of occurrence of these initiating events. The AIMS data, however, are voluntary self-reports by anesthesiologists, and thus incidents are under-reported, some types relatively more than others. For example, drug errors were judged less likely to be reported than mechanical failures. We therefore corrected the statistical data for initiating events using expert opinions about report rates, in order to compensate for these biases (Paté-Cornell, 1993). Our experts estimated that the reporting rates were quite low, generally in the range of ten percent. The exception is anaphylactic reaction, which is twice as likely to be reported, perhaps because it is a frightful experience for the anesthesiologist, who is not the direct cause of the incident and therefore not implicated by it. Table 1 depicts the incidence rate of the initiating events and their relative frequencies. Nonventilation (38%) and breathing circuit disconnect (34%) are the main contributors to the overall incident rate.

Table 1

Incidence rates of initiating events.

Initiating event	# AIMS reports*	Report rate (%)	Init. event prob.	Relative fraction (%)
1. Breathing Circuit Disconnect	80	10	7.2×10^{-4}	34
2. Esophageal Intubation	29	10	2.6×10^{-4}	12
3. Nonventilation	90	10	8.1×10^{-4}	38
4. Malignant Hyperthermia	n/a	–	1.3×10^{-5}	1
5. Anesthetic Overdose	20	10	1.8×10^{-4}	8
6. Anaphylactic Reaction	27	20	1.2×10^{-4}	6
7. Severe Hemorrhage	n/a	–	2.5×10^{-5}	1

*Out of 1000 total reports in initial AIMS data.

For the Markov models, statistical data were unavailable at the level of detail required, and we used expert judgment to determine the transition rates. For each of the initiating events, we gathered data on average transition times for both patient states and anesthesia system phases. Transition time data can be found in the original project report (Paté-Cornell et al., 1994). Drs. David Gaba and Steven Howard were our primary experts; we encoded their judgments through group interviews. Initial disagreements were discussed until consensus was achieved; the experts occasionally consulted reference materials or colleagues for supporting information. Our experts, however, were not accustomed to thinking of anesthesia accidents in terms of transition times between states, and they sometimes found it difficult to come up with "averages" over different types of patients, facilities, anesthesiologists, and operations. On the other hand, our results do match the statistical data that are available at a more aggregate level quite well, so we expect that the models are reasonably accurate. It may be possible to design future studies to validate some of these estimates, e.g., by using anesthesiologists' performance on simulators to verify times required for detection and diagnosis.

With this data, we used the Markov models to compute the probabilities of anesthesia accident conditional on the occurrence of each type of initiating event. These values, along with the fraction of total risk of death or brain damage that is due to each initiating event type, and the overall probability of anesthesia accident are presented in table 2. These results are in agreement with other studies of anesthesia risk (Webb et al., 1993; Keenan and Boyan, 1985). Note that breathing system problems (the first three initiating events) together account for about 50% of accidents in healthy patients. They are important contributors to risk, not so much because they are particularly likely to cause death when they occur (only about 2% lead to an accident), but because they are relatively frequent incidents. These accident initiators are caused primarily by human error, so it should be possible to reduce patient risk

Table 2

Markov model results – base case.

Initiating event	p(Accident | IE)	p(IE)	Fraction of total risk (%)
1. Breathing Circuit Disconnect	0.018	7.2×10^{-4}	18
2. Esophageal Intubation	0.024	2.6×10^{-4}	9
3. Nonventilation	0.021	8.1×10^{-4}	24
4. Malignant Hyperthermia	0.160	1.3×10^{-5}	3
5. Anesthetic Overdose	0.037	1.8×10^{-4}	9
6. Anaphylactic Reaction	0.216	1.2×10^{-4}	37
7. Severe Hemorrhage	0.014	2.5×10^{-5}	$\ll 1$
Overall probability of Anesthesia Accident = 7.12×10^{-5}			

by decreasing the incidence of these errors. The other major contributor to risk is anaphylaxis (a severe allergic reaction, typically to anesthetic drugs), which is relatively infrequent and often unforeseeable, so attempting to reduce its incidence rate may have little effect on risk. Anaphylaxis, however, is extremely dangerous when it occurs, and sensitivity analysis showed that faster detection and diagnosis may yield significant results. Anesthetic overdose poses a moderate risk, but malignant hyperthermia and severe hemorrhage are so rare that they are small contributors.

3 Human and management effects on anesthesia risk

When we began this study, one of the issues that we perceived as a primary concern was substance abuse and its effects on the ability of the anesthesiologist to perform. For instance, we were told in several of our initial interviews that a significant number of residents used medical or non-medical drugs for recreational purposes. We found in this study that several more common problems encountered by anesthesiologists may have a greater effect on patient risk.

3.1 *Effect of anesthesiologist state on patient risk*

We identified, through accident records and interviews, a number of anesthesiologist problems that appear to affect either the probability of an initiating event or the conditional probability of an accident. When residents and hospital personnel have been on duty for long stretches of time, they experience fatigue due to sleep deprivation (Krueger, 1989; Dement, 1991), with possible detrimental effects on performance. If they must face an emergency at that point, the effect of stress and fatigue may significantly increase the probability of an accident. Also, some individuals may be unfit to practice anesthesia for different reasons: they may be prone to panic and have difficulty reacting to crisis situations (Gaba et al., 1994; Runciman et al., 1993b); or they may simply not have the knowledge and the capabilities to fully comprehend and react to unusual situations. Lack of adequate training in an experienced anesthesiologist may be a problem (Cooper et al., 1984), and lack of supervision for anesthesia residents may be even more hazardous. While an experienced supervisor should always be available, in practice, it may take some time to reach the operating room and discover the problem.

The age of the anesthesiologist may also be a risk factor, since aging ultimately results in some deterioration of both cognitive and physical abilities. In extreme cases, some anesthesiologists may be affected by the beginning of neurological disease and still continue to practice; there is no mandatory retirement age and no periodic health screening to detect such problems. Finally, substance abuse can affect a practitioner's abilities (Gaba, 1991). The concern here is not the occasional recreational use of drugs or alcohol, but the abuse of these substances to the degree that performance on the job is seriously affected. The rate of drug abuse among anesthesiologists is thought to be approximately the same as for the general population (the figure of 10% is often suggested) although it is difficult to obtain more than anecdotal evidence. Stress and easy access to anesthetic drugs may contribute to the problem. Alcohol abuse is also an issue. Some experts believe that it is more prevalent among older practitioners, whereas abuse of other drugs is thought to be more common among residents.

Of course, some of these anesthesiologist "problems" occur and may even be desirable for reasons unrelated to risk. Long work schedules, for example, may allow for greater continuity in patient care, and in some cases a resident's supervisor may be unavailable because they are attending to a more pressing problem. This study does not analyze these other dimensions, though they may be important considerations in policy decisions.

From this, we define ten different anesthesiologist states (nine "problem" states and one "problem-free") (see table 3). We structure these states so that they can be considered as an exhaustive and mutually exclusive set, and therefore, we assume that an anesthesiologist faces only one of these problems at a time. In fact, an anesthesiologist may face more than one of these problems, in which case we assume that his performance is characterized by the most severe problem. For a given operation, we then construct a vector of the probabilities that the anesthesiologist is in each of these states, based on the frequency of each type of problems. Although there is a fair amount of anecdotal evidence about these problems, there is little data on their actual frequency. Therefore, lacking further information, expert judgment was used as the basis of the probability distribution for anesthesiologist states in a given operation. The frequencies given in table 3 reflect the "base case", the current situation before implementing any risk management policy. Where possible, these values have been checked against data on the anesthesiologist population, such as for the number of residents or aged anesthesiologists. In other cases, expert judgments were

Table 3

Distribution for the state of the anesthesiologist for a given operation (base case).

Anesthesiologist state		Frequency (%)
SA_1	Problem-free	53
SA_2	Fatigued	10
SA_3	Cognitive problems	4
SA_4	Personality problems	4
SA_5	Severe distraction	3
SA_6	Drug abuse	3
SA_7	Alcohol abuse	4
SA_8	Aging/neurological problems	3
SA_9	Lack of training (experienced anesthesiologists)	12
SA_{10}	Lack of supervision (residents)	4

also required, for example, in the computation of the rate of fatigued anesthesiologists given the number of anesthesiologists on long shifts, and a judgment of how much sleep they get when they are on duty.

The state of the anesthesiologist can affect the risk to patients in two ways (see equation (3)); it can influence the probabilities of the initiating events, and/or the conditional probabilities of anesthesia accident given an initiating event. For example, a fatigued anesthesiologist is more likely to administer an overdose of inhaled anesthetic drug. He will also tend to take more time to detect signals that something is wrong, and to diagnose and correct the problem. For other initiating events, the state of the anesthesiologist will not affect the occurrence of the event (e.g., a breathing circuit disconnect), but may slow down the process of detection, diagnosis, and correction.

We used expert opinions to encode the multiplicative factors for the probabilities of initiating events for each anesthesiologist state (e.g., how much more likely is esophageal intubation by an unsupervised resident compared to the average of all anesthesiologists?). These multiplicative factors are normalized so that the overall probabilities of each type of initiating event match the base rates shown in table 1. We then encoded, for each anesthesiologist state, multiplicative factors for the average time required to detect signals of the different types of events, and to diagnose and correct the problem (relative to the time for the average anesthesiologist). These multiplicative factors are also normalized so that the probabilities of accident conditional on each type of initiating event match the results of table 2.

The risks of anesthesia accident are then recomputed using the Markov models of accident sequences and the extended risk analysis model described in section 2. The results are the probabilities of different types of accidents for each of the different

Table 4

Effect of anesthesiologist state on patient risk.

State of anesthesiologist (SA_j)	Probability of anesthesiologist state $p(SA_j \mid \text{Operation})$	Probability of anesthesia accident given anesthesiologist state $p(AA \mid SA_j)$
1. Problem-free	0.53	6.70×10^{-6}
2. Fatigue	0.10	8.58×10^{-5}
3. Cognitive problems	0.04	8.63×10^{-5}
4. Personality problems	0.04	8.63×10^{-5}
5. Severe distraction	0.03	2.04×10^{-4}
6. Drug abuse	0.03	1.04×10^{-4}
7. Alcohol abuse	0.04	1.04×10^{-4}
8. Aging/neurological problems	0.03	1.04×10^{-4}
9. Lack of training	0.12	1.34×10^{-4}
10. Lack of supervision	0.04	4.90×10^{-4}
Overall probability of Anesthesia Accident = 7.12×10^{-5}		

anesthesiologist states; the overall accident probabilities for each state (summed over initiating events) are given in table 4.

Anesthesiologists experiencing any of the problems identified here are responsible for a disproportionate share of accidents. Nonventilation and anesthetic overdose, in particular, are more common for almost all the problem states. Unsupervised residents are a particular problem because their performance is worse in many dimensions. They are slower to detect problems, and much slower to diagnose them. The largest effect, though, is due to the increase in the probability of initiating events – in particular, nonventilation and esophageal intubation (accidentally inserting the breathing tube into the patient's esophagus, rather than the trachea, preventing ventilation of the lungs). This is partly a result of the fact that our primary experts judged the likelihood of an unsupervised resident causing esophageal intubation to be ten times the average. However, several experts associated with the AIMS study, who we also consulted, did not fully agree with such a high value. This issue may warrant further investigation, because the result is rather sensitive to the probabilities of these initiating events.

Anesthesiologists with inadequate training are also a significant problem, in part because they are relatively common, and also because poor training can be responsible for significantly poorer performance. The increased risk associated with a lack of training comes because such anesthesiologists are somewhat slower to detect problems, and are much slower to diagnose them. Because inadequate training and a lack of supervision for residents account for such a large portion of the risk, management strategies that address them may be the most promising.

3.2 *Organizational risk management measures*

Anesthesiologists view their job as similar to that of airline pilots: an intense, risky "take-off" period (induction of anesthesia), is followed by a long, usually uneventful, and at times boring period of "level flight" (anesthesia maintenance), followed in turn by another short period of intense activity, higher risk, and heightened attention at "landing" (waking the patient) (Lee, 1987, 1991; Chappelow, 1991). Serious problems are relatively infrequent, but when they occur, there is little time to react: keeping calm and acting fast are critical. Not only is this analogy useful in understanding how anesthesiologists conceive their tasks, but we also found that many of the policies that have been adopted by the airlines could be applied to anesthesia. In fact, like flight simulators used to train pilots, anesthesia simulators have been developed recently, and are becoming available to anesthesiologists who are willing to pay for their own training (Gaba, 1992b, 1994). Opportunities now exist to use the simulator to train experienced anesthesiologists, in particular in the management of crises that they seldom experience. Simulators can also be used for resident training, and perhaps, as a screening device to eliminate individuals who are not suited to the practice of anesthesia in the first place. Simulator tests, along with other tests of fundamental knowledge, could be used to recertify practicing anesthesiologists on a regular basis.

The press has also brought to national attention the problems of substance abuse among physicians (Verhovek, 1994). Detection and treatment of substance abuse problems involve extremely complex issues from practical, human, and legal viewpoints. We considered several options, including random drug testing, and a routine annual medical checkup that may reveal symptoms of substance abuse. Another benefit of a routine checkup is the possibility of detecting performance decline and potential neurological disorders in aging practitioners, which may be particularly useful because there is no mandatory retirement age for anesthesiologists.

We also explored the issue of fatigue among anesthesiologists. Shifts of 24 consecutive hours are not uncommon, and while there is usually some opportunity for sleep, it may not always be possible. In an emergency after 22 hours on duty, the effects of fatigue and the stress of urgency may combine to impair the anesthesiologist's performance and increase the risk to the patient. We thus considered the option of restricting work schedules to at most 12 consecutive hours (similar to current restrictions for residents in the state of New York), which should reduce, though not eliminate, fatigue. In some instances, this policy could create new problems: shift work may disturb the circadian rhythms of workers, and more frequent shift changes could cause communication failures between shifts, although experience also suggests that undetected problems may be noticed by a new shift (Cooper et al., 1978, 1982). While the net effects of a policy that limits time on duty are not certain, it is likely to reduce the number of seriously fatigued anesthesiologists.

Finally, we considered the issue of the supervision of residents. Some of them take a long time to grasp an understanding of the fundamental mechanisms of

Table 5

Descriptions of policy changes evaluated.

Proposed policy	Description
Work schedule restriction	Limiting the consecutive time spent on-duty or on-call to a maximum of 24 hours per shift, a maximum of 80 hours per week, and a minimum of 24 consecutive hours off-duty at least once every 2 weeks.
Simulator test – residents	Testing of clinical competency using an anesthesia simulator (Gaba, 1992a, 1994). Tests would be administered periodically during residency as well as at the end of the third year of residency as part of the process of certifying graduating residents as competent to enter anesthesia practice.
Simulator training – practitioners	One day of mandatory simulator training every year to familiarize the practicing anesthesiologists with infrequent problems, difficult cases, and new equipment, and to provide comprehensive training in crisis management, including leadership, communication, and the use of checklists and mnemonics.
Recertification of practicing anesthesiologists	Formal recertification of all experienced anesthesiologists every 3 years or 5 years, based on tests (perhaps simulator-based tests) designed to demonstrate ability to perform anesthesia. Those not meeting the standard would be required to obtain appropriate remedial training and would not be allowed to resume practice until recertified.
Mandatory retirement	Mandatory retirement from practicing and supervising anesthesia at age 60 (non-OR teaching, research, and administrative duties would be allowed).
Drug testing	Monthly random testing for drug abuse. Anyone identified and confirmed to have a problem (through appropriate follow-up testing) would not be allowed to return to practice until he/she had undergone treatment, demonstrated that the problem had been satisfactorily resolved, and met appropriate re-entry and follow-up criteria.
Alcolhol testing	Monthly random testing for alcohol abuse, similar to drug testing described above.
Annual medical examination	Mandatory annual medical examination; may identify problems such as substance abuse, age-related performance deterioration, chronic fatigue, etc.
Supervision of residents	Strict supervision rules for residents through all 3 years of residency: a supervisor is required to be available in the OR in less than two minutes at all times during an operation. The supervisor is expected to intervene personally if there is any question of patient safety, and residents are instructed to contact the supervisor sooner rather than later.

anesthesiology and to be able to face a crisis situation without panic (Chappelow, 1988), and a supervisor's help may be several minutes away. The supervisor may be at a distant location, or be unable or unwilling to return to the operating room quickly when summoned. Furthermore, residents may be reluctant to call for a supervisor's help because of an unwillingness to admit their own fallibility or for fear of being reprimanded. We thus considered the option of requiring close supervision of all residents at all times. Table 5 describes the organizational policy changes that we evaluated.

For each of these management changes, we encoded expert assessments of their effects on the distribution of the anesthesiologist state. For example, if the work schedule restrictions were enforced, to what extent would it decrease the probability that the anesthesiologist in a given operation is fatigued? Second, how should the anesthesiologists who are no longer "fatigued" be reallocated among the other states? (In this case, they are assumed to be problem-free.)

We thus obtained a new distribution for the state of the anesthesiologist reflecting the effect of each of the proposed policy changes. We then re-computed the patient risk using this new distribution on anesthesiologist state, and calculated the risk reduction benefit as a percentage reduction from the base case risk. The benefits computed for the ten proposed policies are displayed in table 6.

Table 6

Effects of proposed policy changes on the anesthesia patient risk.

Policy	Effects of policy	Replacement	Risk with policy ($\times 10^{-5}$)	Risk reduction (%)
Base case (current policies)		–	7.12	–
Work schedule restriction	Fatigue cut 50%	Problem-free	6.72	6
Simulator test – residents	Cognitive problems cut 90% Personality problems cut 50%	New distribution	7.02	2
Simulator training – Practitioners	Lack of training cut 75%	Problem-free	5.98	16
Recertification – 3 years	Decreases lack of training, aging, cognitive, personality problems For 10 recerts: 84% reduction	Problem-free	5.06	29
Recertification – 5 years	Decreases lack of training, aging, cognitive, personality problems For 6 recerts: 67% reduction	Problem-free	5.48	23
Mandatory retirement	Affects 10% of operations: Aging, lack of training, alcohol abuse more heavily weighted	New distribution	6.89	3
Drug testing	Drug abuse cut 95%	New distribution	7.03	1
Alcohol testing	Alcohol abuse cut 90%	New distribution	6.97	2
Annual medical examination	Aging/neurol. problems cut 75% Drug, alcohol abuse cut 25% Fatigue cut 10%	New distribution*	6.92	3
Supervision of residents	Lack of supervision cut 50%	Problem-free	6.16	14

*Except Fatigued replaced by Problem-free.

Of the policy changes examined, the one that seems to offer the greatest risk reduction benefits is recertification. Sensitivity analysis showed that this is a robust result, because it does not depend heavily on a small set of data elements. Recertification can detect a wide range of problems that impair the anesthesiologist's performance (most significantly, a lack of training), and remedial training can improve the performance of anesthesiologists who do not pass the test initially. This policy may decrease overall risk by about one-fourth. While recertifying every 3 years shows a greater benefit, a 5-year recertification period has nearly as large an effect, and may be more attractive because it would be easier and less costly to implement.

The use of simulators for regular training of practicing anesthesiologists also appears to offer significant risk reduction. Its effect comes from reducing the number of anesthesiologists whose training is inadequate; by familiarizing them with rare but dangerous situations, it can improve their ability to detect and especially to diagnose such problems quickly. Of course, in order to show the benefit we calculate, a simulator training program would have to be designed to effectively improve the skills of anesthesiologists enough to reduce the fraction of inadequately trained anesthesiologists by the 75% that our experts estimated – this would require that the program be a rigorous training procedure, and be required of virtually all anesthesiologists. The costs of such a strategy may be substantial.

Close supervision of residents also shows large benefits; even though it may be inconvenient and require additional supervisors, it may improve both patient safety and the quality of residents' training. The sensitivity analysis results discussed above show that the risk due to unsupervised residents depends heavily on several assumptions about residents' performance (in particular, the increased likelihood of some initiating events), so the benefit of reducing the number of unsupervised residents also depends on these assumptions, and may not be as great as it appears. The costs of closer supervision may be significant, because of the increased need for supervisors' time, and the need to have more supervisors available could also make it more difficult to schedule operations.

While a regular medical exam shows a much smaller risk reduction, it may also be an attractive option because the costs would probably be low in a medical environment. On the other hand, there might be strong resistance to such a move in the profession, and it will be necessary to consider the rights of the anesthesiologist in such a program.

Harsh measures designed to detect substance abuse did not show the kinds of risk reduction benefits that we and our experts initially expected. Subsequent interviews with our experts and sensitivity analysis showed that, in part, this is because serious drug abuse (to the point that it interferes with performance, not just recreational use) is relatively rare. Serious drug abuse causes such severe problems for the abuser that they quickly leave the system in any case, and random testing would not accelerate the process much. Also, the performance deterioration caused by drug abuse is not so severe that it is overwhelming. Medical examinations of anesthesiologists might occasionally detect some of the symptoms of substance abuse, and may be more acceptable than random drug testing in the medical profession, though it would probably not have a major effect because drug abusers are often adept at avoiding detection in this way. In any case, our results show that it is not a particularly large contributor to patient risk. On the other hand, since accidents related to drugs and alcohol abuse are particularly reprehensible, and are incompatible with the image and the ethics of the medical profession, close attention to substance abuse is still warranted. Careful inventories of anesthetic drugs and the informal monitoring that are common now may be better ways to handle this problem than random testing programs.

Work schedule restrictions did not seem to have a large effect on risk, and as they are likely to be quite difficult and expensive, do not seem particularly promising. Some of our experts felt that they may have somewhat underestimated the effects of fatigue on performance, implying that work schedule restrictions might have a greater effect than they appear to. Sensitivity analysis, however, showed that unless their estimates were to change by a very large amount, the results would not change significantly. This is because fatigue is a less severe problem than many of the others examined; its primary effect is to increase the time it takes the anesthesiologist to detect a problem, but it does not have a large effect on other actions, and does not significantly increase the likelihoods of initiating events. Although we feel that our conclusion is unlikely to change, further study to confirm this result may be warranted because of the concern in the anesthesia community over this issue.

3.3 *Limitations of the study*

This study covers a wide spectrum of issues, from the technical causes of accidents, to human errors and the state of the anesthesiologist, to organizational factors that are at the root of the human problems. The global risk analysis model allowed us to compute the benefits of some potential risk reduction options, but required a number of assumptions. Some are meant to restrict the scope of the study and make it tractable. Others are mathematical assumptions that facilitate the computation but may limit the implications of the results. These limitations must be kept in mind when interpreting the results of this study.

Our estimates of the rates of problems among anesthesiologists are based largely on expert opinions, as are the associated effects on anesthesiologist performance. These probabilities have been checked against statistical data where it is available, but such objective confirmations are limited. The anticipated effects of the considered risk reduction measures on the rates of anesthesia problems are also estimated using expert opinions based on their experience. Again, available global statistics allow checking the overall consistency of expert opinions (a "reality check") but do not permit a true validation of each piece of data. While there are problems with expert judgment – it may be biased, experts may disagree, etc. – it is often the only source of data, and at the least, it can offer valuable insight into the parts of the problem that are most important. While we used a relatively small group of experts in this work, the information obtained independently from several of them was consistent overall, which increases our confidence in the data.

Another limitation of this study is that it assumed that anesthesiologists experience at most one problem at a time. Yet, it could be that some anesthesiologists suffer from several problems together, such as severe distraction and fatigue. If anything, the possibility of cumulative problems should increase the benefits of the proposed measures, since the effects of several problems together are probably greater than their individual effects. Similarly, we assumed that the probability of several incidents in a single operation was negligible, particularly for healthy patients. This seems to be a good approximation, but even if it is not, we would expect the benefits of the proposed measures to increase. In addition, the effects of technical equipment failures are considered only implicitly. We did not examine purely technical risk reduction measures, such as daily inspection and maintenance of equipment, though they may offer some benefits.

Finally, the structure of our model implied that all organizational effects on patient risk could be captured through the state of the anesthesiologist. Even though the risk due to "problem-free" anesthesiologists is not inconsequential, we did not examine the management roots of the difficulties that they may encounter in practice (for example, production pressures and communication problems may be important). While this should not affect our results in terms of the relative values of the management policies we considered, there could be other policy changes we did not examine that might also offer significant risk reduction.

The scope of this study is limited to healthy patients. Patients with existing health problems (such as heart disease or reduced lung capacity) may be at greater risk because they are less able to withstand the stresses of anesthesia problems, and may benefit from correspondingly greater risk reductions under the risk mitigation policies evaluated. However, it may be difficult to demonstrate this unambiguously; the analysis of anesthesia risk for unhealthy patients is complicated by the difficulty of separating the effects of anesthesia from those of disease. We also restrict the study to modern Western hospitals, as opposed to outpatient surgery centers and dental offices, and to trained anesthesiologists (licensed physicians) as opposed to nurse anesthetists. It is unclear whether the risks are higher in these other cases, but this may be an important topic for further research.

We have not addressed the costs of the risk reduction measures that were identified as promising, and of course, it is necessary to consider all the costs, benefits, and trade-offs of a strategy before deciding to implement it. There are several ways of looking at cost and benefit. One is from the overall, or social, perspective: does the total benefit of a given policy exceed its total cost, including all non-monetary effects? This can be a difficult question to answer, because of uncertainty in outcomes, and disagreements about the relative values of various dimensions (e.g., monetary value of a life saved). Complicating the question further is the fact that costs and benefits may not be allocated equally to the parties involved. Even if the overall benefits of a given risk reduction measure exceed its cost, it may be ignored if the benefits do not accrue to the specific individual or organization responsible for implementing it. In addition to all this, perceived costs and benefits may differ from their actual values. These factors make the choice of risk reduction measures, like any other management decision, complex and difficult. But a realistic measure of the risk implications is a crucial element of this equation, and is the goal of this study.

4 Conclusions

Again, this study examined only anesthesia risk, and not the costs of implementing risk mitigation measures, which could be significant because these strategies place demands on the limited and valuable time of both anesthesiologists and equipment. While without estimates of costs, we cannot say which strategies would be preferred, we do make three major recommendations for risk management strategies that should be studied in greater detail, because the results of our model show that they have the potential for significant risk reduction, and because they are supported by common sense. These risk management strategies are:

(1) all anesthesiologists receive annual training on an anesthesia simulator,

(2) all anesthesiologists be recertified regularly (every three to five years),

(3) all residents be closely supervised in the operating room, to provide help and crisis management skills within two minutes.

Of these, we have less confidence in the third, supervision of residents, because this result is sensitive to several parameters that are rather uncertain. In addition to these three strategies, we and our experts feel that a regular annual medical checkup for practicing anesthesiologists may also be worth investigating. Though our analysis found that its impact would probably not be large, it may be attractive because it is likely to be a relatively low-cost way to detect some common problems. In contrast with our expectations at the start of this study, aggressive measures to combat drug and alcohol abuse, such as random drug tests, do not appear to be justified on the basis of risk reduction for patients. Of course, the current, mostly informal, mechanisms for monitoring for drug and alcohol abuse should be continued.

It may be valuable to extend this study to look at anesthesia providers who are not licensed physicians, and to patients who are not healthy. In addition, a similar study for surgeons may be useful, because they may experience many of the same types of problems. These risk analysis methods can also be useful for studying medical care outside the operating room, and for problems beyond the health care domain.

Acknowledgements

This study was funded by the Anesthesia Patient Safety Foundation, whose support is gratefully acknowledged. The authors thank Dr. J. Cooper from the Harvard Medical School for his help in this work. They also would like to thank the experts who helped to structure the models and provided probability judgments: Drs. Steven Howard and Richard Botney from the Palo Alto Veteran Administration Hospital and the Stanford Department of Anesthesia; Dr. William Runciman (Department of Anesthesia and Intensive Care, Adelaide, Australia); and Dr. Frederick Doherty (Anesthesiologist, Portola Valley, California). We also benefited from conversations with Drs. Frank Sarnquist and John Brock-Utne (Department of Anesthesia, Stanford University), Dr. Frances Conley (Department of Neurosurgery, Stanford University), Mrs. Kay Rose (Palo Alto, VA Hospital), Mr. Daniel McLennon, and Mr. Robert Linch (Attorneys, San Francisco, CA).

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