

Ergonomic and Human Factors Affecting Anesthetic Vigilance and Monitoring Performance in the Operating Room Environment

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Although difficult to determine precisely, it has previously been estimated that at least 2,000 preventable occurrences of anesthesia-related death or permanent brain damage occur in the United States each year.^{1,2} Recent studies suggest that anesthesia-related mortality may be decreasing,^{3,4} and yet preventable anesthetic mishaps will always be an important concern of the anesthesiologist.^a Human error appears to be a major contributor to these preventable anesthetic mishaps.⁴⁻⁷ In a 1985 survey of nearly 300 private practitioners across the western United States, 24% admitted to committing an error in anesthetic practice that had lethal consequences.^b Analysis of data provided by one of the largest medical liability insurance carriers suggests that one or two malpractice claims are filed for every 10,000 anesthetics administered.^c Research has only recently begun on factors contributing to anesthetic errors and mishaps. Studies thus far indicate that a large portion of the anesthesiologist's job involves complex vigilance and monitoring tasks. The act of vigilance has been described as requiring a state of maximal physiologic and psychological readiness to react.⁸ What is poorly understood is what factors influence this state of readiness and thereby affect the anesthesiologist's ability to sustain vigilance.

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This paper reviews some of the factors that may influence monitoring performance and anesthetic vigilance and emphasizes their practical relevance to the anesthesiologist. The term "human factors" (or "ergonomics," in Europe) refers to the designing of equipment, machines, or systems to accommodate the characteristics, expectations, and behaviors of the humans who use them in their everyday working and living environments.^{9,10} There is a large body of knowledge on the factors affecting performance in other, nonmedical monitoring tasks, particularly in aviation.^{11,12} This work has been based largely on research performed by experimental psychologists studying signal detection (for a recent review, see reference 13). This paper attempts to apply these concepts to anesthesiology.

Why Study the Factors Influencing Anesthetic Mishaps?

There is a long history of interest in the incidence and causes of perioperative deaths.¹⁴ Early studies emphasized the association between increased anesthetic morbidity and specific patient or surgical factors.^{2,15,16} Whereas many perioperative deaths may be unavoidable because of intrinsic patient disease, advanced age, or surgical trespass,¹⁶ it has become increasingly clear that most *anesthesia-related* morbidity is preventable.⁴⁻⁷ It even has been suggested that a significant number of "idiosyncratic" drug reactions are, in fact, due to inappropriate dosage, and therefore also are avoidable.¹⁷

Several studies have demonstrated that human errors, such as "inadvertent gas flow change" or "syringe swap," could account for up to 70% of anesthetic mishaps.^{7,18} In the study by Keenan and Boyan,⁴ 75% of the intraoperative cardiac arrests observed appeared to be preventable. Holland¹⁵ examined all deaths occurring during anesthesia in one part of Australia over a 9-yr period; he found that the anesthetic was, to some extent, responsible for the fatality in approximately one fifth of the studied cases. In one third of the deaths, "inadequate patient observation" could be cited as a contributing factor. In the initial study by Cooper and co-workers, many factors associated with critical events constituted "human failure" (*e.g.*, "inattentiveness," "carelessness," and "failure to perform a normal check").¹⁸ Subsequently, Cooper *et al.*⁵ reported 70 critical incidents that had resulted in substantive negative outcome. Of these, 28 were due to "technical errors"; 23 were due to "judgmental errors"; and 16 (23%) were due to "monitoring or vigilance errors."

A review of studies of anesthetic mortality over the last 40 yr suggests a trend toward decreased mortality associated with the operative experience. Over this same period of time, surgical and anesthetic techniques have improved significantly even as more ill and debilitated pa-

tients are being operated upon. Recent studies^{4,16,19} have suggested a decrease in the risk of perioperative mortality, especially among healthy patients. Some have speculated that this decreased risk could be due to the widespread implementation of new technology, such as pulse oximetry and end-tidal carbon dioxide monitoring.²⁰ These devices may provide earlier and more accurate indications of anesthetic mishaps or unusual adverse responses to therapy than can previous monitoring techniques.^{21,22} Nevertheless, preventable anesthetic mishaps will continue to be a significant cause of perioperative morbidity and mortality until the factors influencing the occurrence of anesthesiologist error are more completely understood and the design of the operating room environment has improved substantially.

What Is the Job of the Anesthesiologist?

The anesthesiologist and the operating room environment can be viewed as a complex "human-machine" system. The factors influencing performance within this system (*i.e.*, the safe administration of an anesthetic) fall into three general categories: the environmental component, the human component, and the equipment component. In order to relate research from laboratory and field studies to factors that may influence the anesthesiologist's performance in the operating room environment, it is important to describe the job.

In the course of caring for the patient intraoperatively, the anesthesiologist usually performs a sequence of tasks to acquire information about the progress of the anesthetic. Data are obtained by querying many sources, which include the patient, the various electronic and manual devices, and other operating room personnel. The anesthesiologist then verifies the validity of the information and formulates a hierarchy of data in terms of immediate importance. A hypothesis is formed regarding the patient's current status, and this hypothesis is compared to the desired condition of the patient. New plans of action then are executed; the anesthesiologist monitors the outcome of the intervention and thereby returns to the beginning of the task sequence.^{23,24} Throughout the anesthetic, the anesthesiologist also must perform technical procedures that require fine motor skills (*e.g.*, insertion of intravascular catheters or laryngoscopy). The cognitive demands of the job—the demands of rapidly and reliably accessing a large volume of relevant information—are tremendous, perhaps as great as for any job. Thus, administering anesthesia is a complex monitoring task requiring sustained attention.²⁵ Sustained attention, or "vigilance," is comprised of three distinct components: alertness, selection of information, and conscious effort.²⁵ As will be shown in subsequent sections, complex memory, decision-making, vigilance, and attention are all quite

vulnerable to compromise under the work conditions of most anesthesiologists.

Why do highly-trained anesthesiologists make errors? What factors influence the occurrence of these errors? What can be done to decrease their incidence or to mitigate their negative outcome? Thus far, adequate answers to these important questions are not available.

Research in Anesthetic Vigilance and Performance

The first notable modern reference relating to human factors and the ergonomic design of anesthesia equipment can be attributed to Ludwig Blum.²⁶ In a letter in the July 1971 issue of ANESTHESIOLOGY, Blum advocated the redesign of certain gauges and valves on anesthesia machines in order to prevent clinical catastrophes. One of the earliest formal ergonomic studies of anesthesia care was published by Drui and colleagues in 1973.²⁷ "Link analysis" was used in that well-done study to evaluate how anesthesiologists used their time in the operating room. This analytical process consisted of dividing the practice of anesthesia into a number of discrete activities and then determining, based on filmed observations ("time-motion" analysis), the frequency and sequence of each activity. The relationships (or links) among different activities then were analyzed. One principal finding was that anesthesiologists directed their attention away from the patient 42% of the time. The authors also noted that 40% of the time the anesthesiologist was "idle" (not performing any apparent active task). They believed that this time, however, was productive; it was being used to monitor, think, and analyze. A subsequent time-motion study by Kennedy *et al.*²⁸ appeared to support several of the findings of Drui and colleagues.

Although flawed, probably the most in-depth study of anesthesia ergonomics to date was performed by Boquet *et al.*²⁹ Anesthesiologists were filmed while working, and an oculometer measured the direction of the subjects' vision each moment. The authors analyzed 16 h of film, and dividing the anesthetic activities into discrete components, examined the frequency and duration of 24 visual and 31 manual tasks. They found that 60% of the visual activity was directed at either the patient or at the surgical field. Only 10% was spent looking at the reservoir bag, and less than 5% was directed at the monitors. Seventy-two per cent of the time the anesthesiologist was "idle." The authors also analyzed the frequency of common scan patterns (the frequency with which one task immediately led to another, presumably related, task). The most common visual task sequence was from the patient to the surgeon to the reservoir bag (or the reverse). This study had several methodological shortcomings. A

single analysis combined new and old equipment configurations, even though different types of equipment may require different manual or visual activity profiles. The study also mixed experienced and inexperienced personnel as subjects.

In the most recent of these time-motion studies, McDonald and Dzwonczyk analyzed data from 32 surgical procedures and divided the activities of the anesthesiologist into 13 tasks.³⁰ Each task was classified as either "direct patient care" (actually observing or touching the patient), "indirect patient care" (observing the monitors or the anesthesia delivery system), or "nonpatient care" (*e.g.*, record-keeping, nonpatient-related communication, and idle time). The most frequent activities were "observation of the circle system" (25%, concentrated in the latter part of the case), "direct patient-care" (17%), "completion of the anesthesia record" (12%), and "patient-unrelated communication" (9%). Overall, 39% of the anesthesiologist's time was spent on activities unrelated to the immediate care of the patient. The authors also noted that "direct patient-care activities" were most frequent at the beginning and end of the case and only half as frequent in the middle. Overall, only 26% of the intraoperative time was spent on patient observation activities (similar to the data of Kennedy *et al.*²⁸). Based on their results, the authors made three recommendations: paraprofessional personnel should perform many of the nonspecialized tasks; automated record-keeping devices should be used; and integrated monitoring and alarms should be developed. Unfortunately, this study had methodological flaws similar to those described previously.

Despite their shortcomings, these pioneering task-analysis studies provided some new information about the complex task of administering anesthesia. However, time-motion analysis may not be ideal for assessing anesthesia tasks because this technique assumes a single-channel model of human attention.³¹ The technique is, therefore, more applicable to externally paced schedules such as assembly-line work. More recent studies in nonmedical fields strongly suggest that the design of future operating room environments and equipment might benefit from other types of task analysis.³² Nevertheless, more well-controlled studies of this nature are essential to understand the character of anesthesia vigilance and monitoring performance. Studies should be designed to use techniques and procedures that have been validated repeatedly by investigators in other fields. Some aspects of this human-factors literature were introduced to anesthesiologists by the 1981 review article by Paget and colleagues.²⁴ It now is somewhat dated, and it includes a noncritical presentation of some vigilance studies of questionable merit; however, this paper admirably introduced the potential role in intraoperative vigilance and task performance of such fac-

tors as sleep deprivation, fatigue, drug abuse, and task complexity.

Relationship of Research in Other Fields to Anesthesia Ergonomics

Psychologists and engineers have studied vigilance as a theoretical phenomenon for many years. Investigators in fields outside of medicine, most notably in aviation and more recently in other industrial and military environments, have applied this information to the understanding of performance on complex monitoring tasks. Although a task like flying a high-performance fighter jet is different from administering anesthesia, it undoubtedly requires many similar sophisticated cognitive skills. It therefore may be useful to apply information obtained from studies of this environment to the anesthesiologist in the operating room.

Human error contributes to a significant number of mishaps in aviation.^{33,34} Accidents usually are caused by the cumulative effect of a number of events rather than by an isolated incident.³⁴ Human contribution to an accident is almost always a factor in complex systems like the anesthesia workspace.^{23,35} Studies in other fields have shown that a number of environmentally induced factors and human-machine interface variables can have a negative impact on vigilance and monitoring performance in air traffic control,³⁶ train driving,^{37,38} automobile driving,³⁹ or nuclear power plant control.^d Jennings and Chiles⁴⁰ showed that, of all performance skills, complex monitoring tasks (like those in anesthesia or aviation) are the most likely to be influenced by environmental or procedural variables. In recognition of this, the military now requires the consideration of human and ergonomic factors in the design stages of all new equipment.^{41,e}

Perhaps the greatest influence that inadequate design, procedure, and training can exert on performance occurs during a critical event. Because of the infrequency of critical events in the routine administration of anesthesia, it is extremely difficult in most clinical settings to study the anesthesiologist's response to these events. The same problem of infrequency of unusual or potentially dangerous conditions occurs in aviation and other complex tasks. One solution to this problem has been the use of simulated systems, particularly since the advancement in the application of artificial intelligence technology.⁴²

The remainder of the current article focuses on two areas: the effects of the anesthesiologist's work environment and the factors intrinsic to the individual anesthesiologist. A third area, the influence of the equipment the anesthesiologist uses, is discussed only briefly because of space limitations and the existence of several recent excellent reviews.⁴³⁻⁴⁵

The Work Environment

NOISE

The noise level in the operating room can be quite high. Shapiro and Berland measured noise levels associated with specific tasks in the operating room during several typical surgical procedures,⁴⁶ and found that "the noise in the OR frequently exceeds that of a freeway." The effects of noise on performance depend on the type of noise and on the task being performed.^{47,48} In addition, other environmental and human factors can interact with noise to affect task performance.⁴⁹ Noise levels similar to those found in operating rooms detrimentally affect short-term memory⁴⁸ and also may mask task-related cues and cause distractions during critical periods.⁵⁰ Difficult tasks that require high levels of perception processing or information processing are negatively affected by noise.⁵¹ High noise levels (particularly with long-term exposure) produce physiologic changes consistent with stress. Noise activates the sympathetic nervous system, resulting in peripheral vasoconstriction, arterial hypertension, and pupillary dilation.⁵²

There is little doubt that background noise interferes with effective verbal communication. When multiple tasks are required, the presence of background noise may bias attention toward the dominant task.⁵³ There is an interaction between the effects of noise and sleep deprivation: the former is an "activator" (or "arouser") and the latter is a "deactivator." When both factors are present, they often cancel each other's effects.^f Time of day appears to play a differential role in the impact of each of these influences on task performance.⁵⁴

Whereas loud noise clearly is disruptive and can impair auditory vigilance (e.g., monitoring the esophageal stethoscope), several studies have shown a beneficial effect of lower levels of background (white) noise on complex task performance.⁵⁵ In addition, Wolf and Weiner⁵⁶ have suggested that the presence of familiar background music may improve vigilance. Subsequent studies^{57,58} substantiated the potentially beneficial effects of background music on monitoring performance. Background music may even prevent performance decrements over time in complex vigilance tasks.⁵⁹ These studies indicated that vigilance performance was better when music was used on a discontinuous schedule and was more diversified in content. Improvements in productivity at manual tasks with music appear to be greater in the morning than in the afternoon.⁶⁰ However, the effects of music appear to be quite sensitive to subject and task factors. Thus, while a noisy operating room environment should be discouraged, further study will be required before definitive conclusions can be drawn regarding the effects of music on anesthesia vigilance and performance.

TEMPERATURE AND HUMIDITY

An uncomfortable environmental temperature, a common situation in many operating rooms, can influence performance.⁶¹ For example, Epstein *et al.*⁶² exposed five healthy volunteers to 2 h of either 21, 30, or 35° C temperature. They found that increased environmental temperature produced increases in body temperature, heart rate, fluid intake, and degree of dehydration. Although the subjects' response time on a complex task was faster at 30° C (86° F) than at 21° C (70° F), errors increased significantly. Fine and Kobrick⁶³ demonstrated that volunteers wearing chemical protective clothing in a hot environment had marked deterioration in cognitive performance after 4–5 h. Although there appears to be significant variability, depending on the experimental situation, in the effects of temperature on performance, as a general rule, temperatures that promote general fatigue decrease performance.⁶¹ These effects probably are augmented by other factors that enhance fatigue or impair performance. Thus, the evidence suggests that during a prolonged anesthetic on a neonate or a burn patient in an overheated, dry operating room, the anesthesiologist (as well as the surgeon) may experience a performance decrement.

Extremely cold temperatures have a deleterious effect on some cognitive tasks, primarily because of distraction and decreases in manual dexterity.⁶⁴ These effects appear particularly as increases in errors and memory deficits.⁶⁵ Studies in the industrial workplace suggest that when temperatures fall outside a preferred range (17–23° C), workers are more likely to exhibit unsafe behaviors (which could lead to occupational injury).⁶⁶ Additionally, workload and time-on-shift have significant interactive effects with abnormal temperatures.

Prolonged exposure to conditions of low humidity lead to dehydration if access to liquids is limited.⁶⁷ Even moderate dehydration can impair performance.⁶⁸ A temperature range of 17–18° C with moderate humidity (50%) is recommended for work environments similar to the operating room.⁶⁹ These data suggest that the incidence of anesthesiologist errors may be higher in operating rooms in which the temperature is above or below the optimal, particularly when other factors detrimental to performance coexist.

ENVIRONMENTAL TOXICITY (EXPOSURE TO VAPORS)

There is voluminous and controversial literature on whether trace anesthetic vapors influence anesthesiologist performance. For example, Bruce *et al.*⁷⁰ reported that exposure of healthy volunteers to 550 ppm nitrous oxide and 14 ppm halothane resulted in a significant decrease in performance on complex vigilance tasks. However, their results were subsequently disputed by Smith and

Shirley,⁷¹ who found in naive volunteers that acute exposure to trace anesthetic gases in amounts commonly seen in an unscavenged operating room had no effect on performance. Although the data still are somewhat controversial, it appears that impaired vigilance due solely to trace anesthetic gases is probably not a problem in the modern, well-scavenged operating room. This assertion is supported by a recent well-controlled cross-over study in which anesthesiologists showed no differences in either mood or cognitive ability when working in a scavenged operating theater (with average levels of nitrous oxide of 58 ppm and of halothane of 1.4 ppm) compared to working in the intensive care unit (with no trace gases).⁷² The National Institute of Occupational Safety and Hygiene (NIOSH) and the American Conference of Government Industrial Hygienists have set 25 ppm nitrous oxide and 2 ppm halogenated agents as the safe standards for medical worker environments.⁸ These levels were chosen on the basis of experimental and case history data.⁷³ Malodorous conditions in the operating room (*e.g.*, fecal or abscess odors), on the other hand, may have a significant detrimental effect on anesthetic vigilance.⁷⁴ There also is increasing concern among anesthesiologists about the risks of needle stick injuries.

AMBIENT LIGHTING

Surgery and anesthesia usually are performed in an enclosed environment requiring artificial illumination. Clinical information gathering and monitoring are gained primarily visually. The use of illumination to enhance task performance has received much attention from human factors and lighting specialists.⁹ The characteristics of a given task—level of work detail, contrast, size of materials to be manipulated, and others—determine the illumination requirements. The illumination requirements of an operating room are determined both by the background lighting needs and by the special task requirements of the surgeons, nurses, and anesthesiologists. For example, the surgical field generally requires very high levels of light (up to 20,000 lux), whereas monitoring in the anesthesia workspace may require much lower levels (*e.g.*, 750–1,500 lux).^h Of course, unusual tasks or procedures may have increased illumination requirements.^{75,76} However, the optimal illumination level is age-dependent; older individuals require more illumination.^{77,i}

An important consideration when determining lighting sources is the minimization of glare. General (overhead) lighting must be diffused in order to prevent overriding of equipment displays and other critical discrete visual inputs. When formatting display requirements, designers of anesthesia equipment must consider general background lighting and the glare from surgical operating lights as well as display illumination and the interaction

of color. Although anesthesia equipment manufacturers have used color for displays and alarms, coding recommendations have not yet been standardized.⁷⁸ Multiple displays using the same colors may result in some loss of the discriminatory value of color among displays.

Studies have indicated that an increase in illumination is more satisfying and may improve performance,⁹ decrease reaction time,⁷⁹ and increase social interaction among people.⁸⁰ Color can affect mood,^j blood pressure, respiratory rate, reaction time, and perception of spatial size and complexity.⁸¹ Therefore, the choice of color for operating room walls and equipment and the use of color and lighting in equipment systems can be a source of improved performance, mood, and interaction.

WORKPLACE CONSTRAINTS

Several studies have suggested that the arrangement of anesthesia equipment in the operating room is haphazard at best.^{27,28,30} Part of the reason for this disorganized workspace may be lack of appreciation of the importance of team dynamics, human-machine, and human-environment interactions in optimizing monitoring performance, or insufficient study of operating room design requirements.

McIntyre⁸² examined the influence of field of view on clinical vigilance tasks by studying the position in the operating room that the anesthesiologist voluntarily selected relative to the patient and to the monitoring equipment. He found that the angle of view most commonly chosen was between 130 and 170°, consistent with the concept that an operator will take a position that permits the minimal amount of physical work to gather the information necessary to perform the task. The study's results were somewhat limited, however, because the anesthesiologist was not allowed to reposition either the operating room table or the anesthesia machine.

Childs and Halcomb⁸³ defined "response complexity" as the amount of physical effort required to respond to a signal. They showed that up to a point, more complex response situations yield better signal detection rates, whereas situations in which excessive effort is required to perform a task resulted in performance decrement. Both the duration and the intensity of the work influence response complexity. The physical demands of the anesthesiologist's job routinely include standing, moving about, positioning equipment, and performing many rapid, fine-motor manipulations. These physical demands, when combined with the auditory and visual shortcomings of the operating room environment, may interact to decrease the overall effectiveness of the operating room team effort. For more specific recommendations regarding workplace design, the reader is referred to the Eastman Kodak handbook.⁶⁹

The Human Component

HUMAN ERROR

Humans err. Errors are a normal component of human cognitive function and play a major role in learning.³⁵ Most errors, however, do not result in damaging consequences. It has been demonstrated that, even under ideal conditions, performance on most complicated tasks is rarely perfect.^{10,84} An error that results in an unacceptable outcome often is called an accident.⁸⁵ It has been said that accidents occur at "the most inopportune time and place."³⁵ This is because errors are most likely to deteriorate into a damaging situation when conditions prevent the appropriate corrective responses. Errors committed by anesthesiologists can have catastrophic consequences if not corrected. Nevertheless, as Cooper and colleagues showed, most critical events in anesthetic practice were discovered and corrected before a serious mishap occurred.¹⁸ It is crucial to understand the determinants of recovery from anesthetic errors. Human factors such as sleep deprivation, fatigue, or stress not only can increase the potential for error but also may preclude effective recovery.

In one accepted classification of human errors applicable to the operating room context, two of the most common types of errors are slips and mistakes. Each of these types of errors can take the form of errors of omission (omitting a task step or even an entire task) or errors of commission (incorrect performance).⁸⁶ Slips are most likely to occur during activities for which one is highly trained. Slips occur when actions are performed without conscious thought. Drug syringe swaps, a commonly described anesthetic critical event,¹⁸ are a form of slip. Errors of omission can occur when unexpected distractions interrupt a well-established behavioral sequence. Errors of commission occur when automated schemes (or preprogrammed subroutines) are inappropriately called into play by specific stimuli without conscious processing.³⁵ There is a tendency to revert to a high-frequency (well-learned) response in such situations,⁸⁷ particularly when the individual is under stress. Experts, in fact, may be more likely to make slips than are novices. A more extensive form of slip has been called "false hypothesis behavior."³⁵ In this type of slip, an individual inappropriately follows routine patterns of behavior; that is, he or she responds to the usual or expected event, rather than to the actual event demanded by the immediate clinical situation. This is most likely to be seen in the operating room under conditions in which: an expected event is very probable; the anesthesiologist is anxious; the anesthesiologist's attention is distracted; or there is a required reaction after a period of high stress, and a set pattern of interpretation and action has been held for a long time.³³ False hypothesis be-

havior may play a pivotal role in the "inaccurate mental map" theory of accident propagation.²³

In contrast, mistakes are technical or judgmental errors. Administering sodium thiopental to a patient with a history of acute intermittent porphyria (either because an inadequate preoperative history was obtained or because there is inadequate knowledge of the disease's anesthetic implications) is an example of a mistake. Thus, mistakes are due to inadequate information, inappropriate decision-making skills or strategies, inadequate training or experience, or insufficient supervision or support.

The occurrence of a "critical" or nonroutine event generally does not result in a negative patient outcome, because the anesthesiologist responds appropriately. However, if the seriousness of the event is misjudged, a bad outcome is more likely. This conclusion is supported by analyses of aircraft accidents and incident reports.⁸⁸ Even if the nature of the event is correctly identified, misassessment of its seriousness may result in an incorrect course of action. If the potential consequences of the event are not appreciated, then definitive correction may be delayed. On the other hand, overassessment of the consequences of the event creates a stressful situation which, in itself, can lead to a rapid deterioration in judgment and performance.⁸⁹ It is noteworthy that whereas assessment errors occur with great frequency in simulated cognitive performance tasks, the tendency to over- or underassess the consequences of nonroutine situations is relatively consistent within individuals.⁸⁸

It has been stated that "people have great confidence in their fallible judgment."⁹⁰ In many situations, neither the amount of professional training and experience nor the information available necessarily increases predictive ability.⁹⁰ This appears to stem from the tendency of most humans to prefer to seek additional confirmatory evidence for an existing hypothesis rather than to attempt to disprove it.⁹¹ However, when people do obtain explicit falsifying information, they use it to reject a standing hypothesis. In general, in making decisions, even highly trained individuals do not appreciate the importance of the probability over the frequency of event occurrence. Fortunately, some recent data with simulator-based training suggest that sound judgment in complex situations can be learned.⁹²

People are more likely to commit errors when they are mismatched to the task or when the system is not "user-friendly." Specialists in the field commonly refer to factors influencing human performance as "performance-shaping factors" (PSFs).^k In this section, we discuss the internal (human) PSFs that can influence error commission such as skills, attitudes, inexperience, and stress.⁸⁶ In addition, faulty performance also can stem from poor supervision,^l task complexity,⁸⁶ or inadequate system design.

For more information on the subject of human error

in anesthesia, the reader is referred to excellent reviews by Gaba *et al.*^{23,93} and Allnutt.³⁵

INTERPERSONAL AND TEAM FACTORS

The anesthesiologist must function as an integral part of the operating room team. In other highly complex tasks involving teamwork (*e.g.*, commercial aviation), the team generally has been together for a long time and is well-practiced. In contrast, in the operating room, the members of the team may not have worked together frequently, and yet the effectiveness of communication between the anesthesiologist and the other operating room team members can significantly affect the quality of patient care. In an elegant study, Kanki and colleagues⁹⁴ examined the specific speech patterns that characterized the communication between two-person commercial flight crews during simulated missions. They found that the speech patterns of crews with infrequent flight errors were characterized by marked homogeneity consistent with the adoption of a standard form of communication. In contrast, the high-error crews had more heterogeneous speech patterns. The authors concluded that the development of "conventions" for interacting, based on mutual expectation and understanding, leads to a more efficient transfer of information among individuals. Team communication involves unspoken expectations, traditions, general assumptions regarding task distribution, and chain-of-command hierarchies, as well as individual emotional and behavioral components. Alterations in any of these factors can impair effective team function. These findings, extended to the operating room, suggest that the anesthesiologist who is confronted with a new surgeon, operating room nurse, or anesthesia resident should be sensitive to the "new interpersonal environment" and should make a special effort to communicate clearly and unambiguously, particularly in stressful situations. Communication may be more difficult when other stress-inducing factors, such as fatigue or sleep deprivation, affect any of the team members.

Interactions with patients, patients' families, or colleagues that result in emotional stress may impair the anesthesiologist's intraoperative performance. Other external distractions, such as outside personal phone calls or difficulties with previous patients in the recovery room, also may affect performance. It is possible that effective team work among groups of anesthesiologists may reduce the impact of these types of distractions. Emergency surgery is associated with a four- to six-fold increased incidence of anesthetic morbidity and mortality compared to that in elective surgery.^{4,95} Part of the reason for this may be the inadequate preparation time, both mental and medical, for the patient and all members of the operating room team. It remains to be seen if the trend toward

admitting increasingly complex cases the morning of elective surgery will result in increased morbidity.

FATIGUE

The phenomenon of fatigue is difficult to define and to measure. Fatigue can be conceptualized as the inability or unwillingness to continue effective performance of a mental or physical task. Fatigue is considered to result from hours of continuous work and work overload, whereas boredom, described below, is considered by some to be a function more of insufficient work challenge and understimulation.⁹⁶ Extreme fatigue results in objectively measurable symptoms of exhaustion and psychological aversion to further work. Nevertheless, it has been shown that subjects can exhibit significant physical fatigue and yet, with sufficient incentive, continue to perform.⁹⁷ There is, however, marked variability among individuals in their response to factors or situations leading to fatigue or its amelioration. There is a powerful psychological component to the continued ability to perform skilled physical or mental tasks in the face of worsening fatigue. Although some extremely fatigued individuals can be "induced" to perform, the quality and wisdom of continued work under these circumstances is questionable, and certainly so in situations where human lives may be at stake.

Few fatigue studies have used physicians as subjects. Those that have, have typically involved sleep loss, and primarily because of poor methodology, have raised more questions than they have answered. Fatigue and sleep loss often are co-variants in studies examining continuous long work schedules, and in turn, both are modulated by circadian processes. Since the effects of these variables interact,⁹⁸ it is difficult to separate the relative contribution of each factor to performance decrement. Parker⁹⁹ reviewed many of the physician-related studies but did not elucidate their methodological difficulties. Nevertheless,

Parker's conclusions generally are supported by well-performed nonmedical studies of the effects of fatigue, sleep deprivation, and shift work. What is clear is that individuals subjected to excessive work, fatigue, or inappropriate shift schedules show degraded performance, impaired learning and thought processes, irritability, memory deficits, and interpersonal dysfunction.

Careful examination of the literature indicates specific ways in which fatigue impairs the anesthesiologist's performance. Early studies,¹⁰⁰ confirmed recently,¹⁰¹ showed that fatigued subjects paid less attention to peripherally located instruments and showed increases in response variability and timing. Holding⁹⁷ demonstrated that fatigued subjects, when coping with task demands, exhibited less control over their own behavior (were less "inhibited") and tended to select more risky alternatives (took "shortcuts"). The general level of arousal (as indicated by the delay between responses) appears to be decreased in fatigued subjects, independent of their degree of sleep deprivation.^{102,103}

Fatigued subjects, if sufficiently motivated, can attain relatively normal performance on short-duration tasks,¹⁰⁴ even when circadian effects must be overcome.¹⁰⁵ On the other hand, it is more difficult for the fatigued subject to sustain performance on long-duration monitoring tasks^{106,107}: effectiveness decreases by as much as 50% depending upon the type of task and its duration.^{104,108,109,m} Adding sleep loss or shift work as factors accentuates fatigue-induced performance impairment. Sleep deprivation can result in complete inability to perform by the 3rd day of sustained work.¹⁰⁹ Simple tasks are less affected than are complex ones,¹¹⁰ and "interesting" tasks are more resistant to impairment unless fatigue and sleep loss are extreme.¹⁰⁴

The effects of fatigue on physical *versus* mental task performance are distinguishable. In sustained work, particularly in the presence of extreme environmental con-

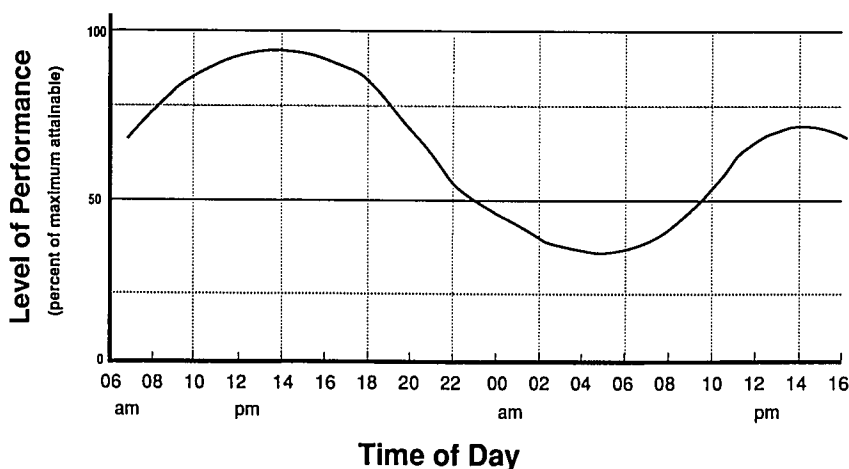


FIG. 1. The theoretical performance on a complex task as a function of circadian and sleep loss influences over a 36-h period. Note that performance is best at certain times of day, generally between 10 AM and 3 PM. Performance decreases markedly during the early morning hours. After a sleepless night, the amplitude of circadian fluctuations is dampened and performance remains depressed below that seen the previous day. This figure is a composite based on multiple studies of sustained cognitive performance using different tasks in nonphysician daytime workers.^m

ditions, cognitive performance deteriorates faster than does physical performance.¹⁰⁹ The addition of moderate physical work to a complex cognitive task can negatively affect performance and mood.^m On the other hand, periodic mild exercise may be "arousing" to those performing cognitive tasks immediately after the exercise.¹⁰⁴ Hockey⁹⁶ and Holding⁹⁷ both mention Bartlett's 1943 study of flight simulator performance in the presence of extreme physical fatigue. Subjects were able to fly the simulator successfully even when they were too exhausted to walk.

It thus appears that the fatigued anesthesiologist may be careless, less likely to detect the occurrence of a perioperative critical event, and unable to respond optimally to evolving clinical situations. One peril afflicting the medical profession is the stereotype traditionally held by physicians—that because of rigorous training, devotion to duty, and intellect, they are somehow immune to the effects of fatigue and sleep loss. This misguided assumption is held also by other professionals, such as ships' officers, pilots,^{111,112} and managers, to the possible misfortune of the recipients of their services as well as their own families.

SLEEP DEPRIVATION

Though similar in some of their performance-shaping effects and though certainly interrelated, sleep deprivation and fatigue are different processes. A large body of research shows that sleep deprivation and circadian rhythm disturbances can dramatically impair performance on monitoring tasks.^{103,104,109,113–116,n} In this review, we discuss only those effects of sleep loss that can be directly relevant to the anesthesiologist. The effects involve cognitive, psychomotor, and mood changes.

Even a single night of sleep loss can produce decrements in performance, especially on skilled cognitive tasks (fig. 1). Impairment can be seen shortly after initiation of the task, and within 20–35 min for many tasks.¹¹⁷ However, in most sustained work activities, major decrements usually occur after 4 h and again after 18 h.¹⁰⁸ Like fatigue, sleep loss affects physical tasks less than it does cognitive tasks. Young, physically fit men usually can maintain performance on physical tasks for which they are well-trained for extended periods without sleep, even under adverse environmental conditions.^o People can tolerate infrequent bouts of sleep loss, particularly if they are young, if the work is interesting (or perhaps critical), or if there are other team members involved who can "help out" or exert psychological pressure to perform.¹¹⁸

Studies involving 1 or more days without sleep show progressive decreases in reaction time and increases in response variability.¹⁰³ Work rate is appreciably slowed, particularly when subjects are required to make choices.¹¹⁹

In vigilance tasks, omission errors increase,¹²⁰ whether the signals presented are visual or auditory.^{121,122} There also is an increase in the frequency of lapses (known as "microsleeps"). Sleep loss impairs active use of working memory,¹⁰³ particularly when the sleep loss precedes learning.^{123,124} Hockey showed that being awake even for 30 h affects one's ability to maintain appropriate strategies for allocating attention and setting task priorities and also reduces the tendency to sample for potentially faulty information.^{125,126} Since many of these skills are essential for optimal anesthesiologist performance, it is clear that sleep loss can be extremely detrimental.

Insufficient sleep has a cumulative effect. Reducing one's sleep time to below 6 h per night increases negative mood and fatigue.¹²⁷ Vigilance, calculation ability, and memory are impaired by the 4th day of reduced sleep.¹²⁸ It is not clear, however, how much sleep is necessary to ensure optimal performance since performance and what affects it are task- and context-specific. Although 3 h per night for 3 nights resulted in impaired performance on one vigilance task,^p in another study using different performance criteria, 5 h per night for 8 weeks produced no changes in either mood or performance.¹²⁹ A sleep debt of greater than 3 h reduced test-taking performance of medical interns, but if the total sleep debt was less than 8 h, many were able to compensate.¹³⁰ Under conditions of sleep deprivation, cognitively exciting tasks appear to be the least affected.¹³¹ It must be noted, however, that there are wide individual differences in the amount of daily sleep required.¹³²

In one of the first studies of the effects of sleep loss on physician performance, Friedman *et al.*¹¹⁴ showed that the cardiac arrhythmia detection skills of medical interns who were sleep-deprived were significantly compromised compared to those of normally rested interns. The sleep-deprived interns felt sad, fatigued, unsure of themselves, and alienated. In a follow-up psychiatric analysis, the sleep-deprived interns also exhibited depersonalization, inappropriate affect, irritability, and memory deficits.¹³³ Hart and colleagues,¹³⁴ in a well-designed study, demonstrated mild but significant disturbances in memory, decision-making, and motor execution in on-call residents deprived of normal sleep (2.7 ± 2.2 h slept) compared to those who had obtained a full night's rest (7.9 ± 1.3 h).

Other studies have assessed the impact of sleep deprivation on the ability of house staff to perform clinical duties. Unfortunately, many of these studies were methodologically flawed. For example, Storer and colleagues¹³⁵ examined the cognitive and skills performance of 45 "sleep-deprived" pediatrics residents with the use of medical-knowledge questionnaires and patient-care tasks. The absence of any significant detrimental effects of acute sleep loss must be questioned because neither an appropriate control group nor a cross-over design was included.

These researchers also did not accurately quantify chronic sleep deprivation or control for circadian or training effects. In addition, knowledge tests are very insensitive measures of sleep-deprivation-induced changes in cognitive performance. Other studies, examining effects of acute sleep loss on mood, memory, and performance in anesthesia residents, have similar design flaws.^{136,q,r}

Recently, Deaconson and colleagues¹³⁷ studied 26 surgical residents and concluded that the usual on-call schedules of these residents did not impair their performance on some psychomotor and cognitive tests. These results, like those discussed above, are questionable because of study design flaws: 1) there were extreme variations between subjects in the amount of sleep deprivation; 2) the diagnostic tests used were relatively insensitive to small performance decrements upon repeated administration; 3) there was no task training, and as a result, there was a significant training effect over time in both groups of subjects; and 4) the subjects were paid well and were given only very brief tests, a situation in which even highly sleep-deprived subjects can rise to baseline levels of performance.^{104,s}

NAPS

Haslam's field work on subjects involved in military exercises indicated that some sleep (2–3 h per 24 h) is better than none at all.^o In studies on sleep-deprived military subjects, the effects of interposing naps of various durations between successive episodes of sustained physical and mental work were carefully examined.^{104,138,m} Although a 2-h nap was insufficient and 3 h permitted a maintenance of previous levels of (already impaired) performance, subjects required a full 4-h nap before acceptable baseline levels of performance were restored. There is some evidence that naps are more effective when taken at certain times of day than at others.^m Taking a short nap (<2 h) at the circadian low-point (see next section) produces greater cognitive impairment than does the same length nap taken at the peak of the circadian cycle.^{139,140} However, the length of the nap is probably more important than the time of day at which it is taken.¹³⁸ One common side-effect of napping is "sleep inertia." If a sleep-deprived subject is permitted to nap, then, after the nap, there will be a period of sleep inertia during which the subject will exhibit a low level of arousal and significantly impaired vigilance. Sleep inertia can last as long as 2 h.¹⁰⁴

When sleep-deprived subjects are allowed to sleep, they immediately fall into slow-wave, nonrapid eye movement (REM) sleep (stages 3 and 4 of sleep).¹⁴⁰ Upon awakening from slow-wave sleep, subjects exhibit greater cognitive performance decrements, longer sleep inertia,¹³⁹ and increased sensory-motor deficits^{141,142} than at other stages in the sleep cycle. Interrupted sleep can result in dimin-

ished grip strength, delayed reaction times, and impaired performance for up to 2 days.¹¹⁸ Unfortunately, these kinds of sleep interruptions are common for on-call physicians. In a recent study, medical house officers (at three different hospitals) slept an average of 2–4.5 h per night when on call. However, their sleep was routinely interrupted every 40–90 min.¹⁴³

From these data it can be concluded that the sleep schedule of the anesthesiologist can affect intraoperative vigilance and monitoring performance. Individuals must recognize that it is neither unprofessional nor weak to admit sleepiness or fatigue when on the job,¹⁴⁴ and in addition must attempt either to make time to recuperate or to seek a clinical replacement. There are significant individual differences in the response to acute or chronic sleep loss; each anesthesiologist must be aware of his or her own limitations. Nevertheless, on the basis of the above data, we make the following general recommendations to the anesthesiologist who has been kept awake most of the night and then faces a full day of work: If at all possible, go home and do not work. If you must work and there is time for a 2-h nap only, do not nap; just stay up. If you can take a 4-h uninterrupted nap, then do so, but expect to awake with some sleep inertia.

CIRCADIAN CHANGES AND SHIFT WORK

Periodic, rhythmic fluctuations in bodily processes, including performance and work efficiency, have been well documented.^{96,f} Over 50 neurophysiologic and psychological rhythms that potentially influence human performance have been identified.¹⁴⁵ Most studies of rhythmic changes in efficiency have focused on cycles of about 1 day, those called circadian processes. Rhythm characteristics, such as amplitude of the effect, show as much individual variability as do fingerprints. An individual's normal rhythm can be affected by environmental conditions, illness, time-zone changes, or alterations in shift schedules. Typically, for the young, healthy traveler or permanent shift worker, adjustment to a new time schedule is accomplished in 2–7 days. However, this adjustment time varies considerably depending on the individual's age, the particular biological rhythm, and biological flexibility. Abrupt, but short, changes in the normal sleep (night) to wake (day) cycle cause temporary biologic and psychological discomfort as well as performance impairment. Field studies indicate that during normal wake time, circadian-related fluctuations in performance range from 14 to 43%.^f In laboratory-based studies, significant performance impairment occurred both during travel across multiple time zones and during single extended days without sleep.^{146,147} Although typically alertness closely follows the body temperature rhythmic pattern, all modalities or capabilities influencing task performance do

not have the same circadian pattern.^{148,149} There is a diurnal rhythmicity to pilot error-induced aviation accidents; the highest incidence occurs in the morning hours (7–8 AM), shortly after the pilot awakens.¹⁵⁰

In rapidly changing shifts, performance varies as much as 50% across shifts.¹⁵¹ The rate and amount of adjustment to shift changes or extended work days is an individual matter.^{152,153} However, in a study of nurses doing shift work, some individuals *never* were able to adjust.¹⁵⁴ Workers on rapidly changing or unstable shifts have greater sleep, social, and health problems.^{155,156,t} Efficiency of permanent night-shift workers is at least 10% less than that of comparable day-shift workers on the same job,¹⁵⁷ and minor accidents¹⁴⁸ and errors in vigilance occur most frequently during night and early morning hours.¹⁵⁸ On the other hand, fully acclimated night-shift workers have a realigned circadian cycle such that *their* best performance occurs during their shift. Swing-shift workers seem to have the most difficulty establishing a normal diurnal rhythm.¹¹³ If shift rotations are required, the rotation should be clockwise and never less than 2 weeks per shift.¹⁵⁵ Since adjustment to shift work takes from a few days to several weeks, rapidly changing shifts should be considered inefficient⁹⁷ at best and dangerous at worst.

Phase shifts are introduced by sleep interruption. Normal circadian rhythms may be disrupted even after multiple brief interruptions in an otherwise full night's sleep.¹¹⁸ The peak and minimal performance times normally expected by the individual are shifted similarly. This situation can lead to a false sense of competence during "normal working hours" after acute sleep loss. For example, an anesthesiologist who has been working most of the previous night may feel remarkably "awake," and perhaps even euphoric, after recovering from sleep inertia in the early part of the next morning. However, studies have documented degraded performance on complex tasks in these situations¹⁴⁰ (see fig. 1). By midafternoon, however, dramatic decreases in arousal and decreases in feelings of well-being accompany parallel decrements in performance. That evening, the anesthesiologist probably has difficulty falling asleep, especially if an afternoon nap had been taken. In fact, sleep-to-wake cycles can be disturbed for up to 36 h, and the anesthesiologist may remain more error-prone during this recovery phase.^{159,u} It also should be noted that when extended shifts are started midday, the extent of subsequent performance impairment the afternoon of the next day is magnified.^{m,v}

SLEEP LOSS AND PERFORMANCE IN ANESTHESIA

The applicability of these issues to anesthesia was first investigated in a 1977 report of the effect of sleep loss on performance in six anesthesiology residents.¹⁶⁰ Although

impaired performance after sleep deprivation was demonstrated in four of the six subjects, the study's results were marred by several methodological flaws. The authors did not account for the confounding effects of training; the testing environment was inconsistent; the sleep-debt phase was poorly defined; and several of the performance tests were applied inappropriately.

In a more recent study, 21 anesthesia residents were randomly tested in the morning after either a normal night's sleep (average duration 6–7 h) or after a night on call (average amount of sleep 2–3 h).¹⁶¹ The residents were shown a 30-min videotape of an anesthetic machine and vital signs monitor simulating a standard general anesthetic, as well as a videotape of a "monotonous" lecture as a distraction. In the course of the experiment, the subjects were expected to detect the occurrence of two abrupt gas-flow changes (resulting in an hypoxic mixture) and eight significant changes in vital signs. Vigilance scores were significantly lower in "fatigued" residents. However, the results could have been more credible if a cross-over design had been employed. Also, the potentially most interesting data were discarded: 8 of the 42 test sessions were discarded because the subjects had not followed directions or because errors had occurred in the testing process. It would have been useful to investigate which subjects were more prone to these problems.

In another study, six anesthesia residents were trained to perform visual and auditory reaction time tests as well as a test of fine-motor coordination.¹⁶² They then were tested in two morning sessions 24 h apart, with the use of a cross-over design. While there were no differences between the on-call and not-on-call groups in baseline performance, at the end of the 24-h period, the on-call residents showed worse performance than the not-on-call residents on the visual reaction time and coordination scanning tests but not on the auditory reaction-time test. Subjective fatigue was also significantly greater in the on-call residents. The authors noted that the performance decrements observed in the on-call residents were of the same order of magnitude as those observed (using the same psychomotor tests) after a moderate oral dose of alcohol.

These studies are consistent with other research on sleep deprivation and performance and lend support to the contention that patient care may be compromised if a fatigued or sleep-deprived clinician is allowed to administer an anesthetic, to operate, or to perform other medical procedures. The issue of decreased clinical performance of house officers and other physicians as a result of overwork and sleep deprivation has recently gained national attention.^w The State of New York has enacted legislation that prohibits physicians from working more than 24 consecutive hours without an intervening 8-h rest period. In addition, physicians may not work more than

80 h/week (averaged over 4 weeks).^x Other states are considering similar legislation.^y Whereas some praise the legislation as a way to attain improved patient care and fairer employment practices, others complain that it will sharply increase the cost of medical care. New York State hospital officials estimate that the additional yearly cost of physician coverage may run as high as \$200 million. Nevertheless, similar laws are already in force for airline pilots (no more than 30 h on duty during any 7 consecutive-day period),^z locomotive drivers (no more than 12 h of continuous duty and at least 10 h of rest before the next work period),^{aa} and commercial maritime captains (no more than 8 h of work during any 24-h period).^{bb} In England, preliminary calculations suggest that the establishment of a 60-h work week for physicians-in-training at a reasonable cost is feasible.¹⁶³ Given the available scientific information on the effects of sleep loss, fatigue, and shift work on vigilance and performance, we believe that reasonable restrictions on anesthesiologists' work schedules are both desirable and necessary.

REST SCHEDULES

Common sense suggests that relief from a prolonged monitoring task should enhance subsequent performance. Both anecdotal reports and laboratory studies have indicated that people prefer self-paced tasks and will take a break when needed.¹⁰⁸ Short breaks have been shown to alleviate fatigue as well as increase employee satisfaction and productivity in machine-paced jobs.¹¹⁷ For worker-controlled sedentary jobs, short breaks or a change in activity increases performance and relieves boredom.^{108,164} However, most of the literature regarding rest breaks deals with the standard 8-h daytime worker. There appears to be little or no information on the effectiveness of breaks for night or extended shift schedules. Thus, there is little experimental evidence to support the widely held belief that during a prolonged complex monitoring task such as administering anesthesia, performance will improve after a break.

Cooper *et al.*,^{165,166} in a study of critical incidents associated with intraoperative exchanges of anesthesia personnel, describe 90 incidents that occurred during a break. Twenty-eight of these were said to be favorable (*i.e.*, the relieving anesthesiologist discovered and corrected a potentially dangerous preexisting situation), and only 10 were cited as being unfavorable (*i.e.*, the relieving anesthesiologist "caused" the critical incident). In the remainder of the incidents, either the problem was perpetuated by the relieving anesthesiologist or the incident could not be classified. Unfortunately, because of the possibility of biased reporting, the relative frequency with which relief results in favorable *versus* unfavorable out-

comes cannot be determined from this type of study. On the other hand, of the 1,089 total critical incidents studied by Cooper and colleagues, none of the incidents due to relief resulted in significant morbidity or mortality. The successful detection of problems during a break probably depends on a systematic and comprehensive review of the anesthetic course by the relieving anesthesiologist.¹⁶⁶

The optimal frequency and duration of breaks is still unknown for most occupations. According to Krueger,¹¹⁷ in his review of factors influencing performance in continuous-work situations, effectiveness on sustained vigilance tasks noticeably decreases within 20–35 min of initiation and then significantly decreases further after 2 or more hours. The performance decrements associated with sustained vigilance generally are characterized by decreases in correct detections and increases in omissions, response time, boredom, and fatigue. Warm¹⁶⁷ has recommended that monitoring tasks be limited to sessions of less than 4 h. Breaks have been required by many union contracts and are supported by legislation in some countries, particularly for occupations in which impaired performance may endanger worker or public safety (*i.e.*, transportation workers). Although attempts have been made to determine objectively the optimal timing and duration of rest breaks,¹⁶⁸ little data currently are available, and much research is needed.¹¹⁷

Even though breaks may be beneficial, anticipation of a break (or the end of an anesthetic) which then is delayed can lead to a significant letdown and thereby result in impaired vigilance and task performance.¹⁶⁹ On the other hand, knowledge of task-ending time or of an upcoming break serves as a motivator. If the relief opportunity is recent news to the worker or subject, then a spontaneous increase in performance is often seen.^{117,170,171}

What one does on a break may be important. Nourishment or distractive activity is known to be refreshing and results in performance enhancement. Taking a nap, however, may not always be beneficial.^{104,138,140} Preliminary data suggest that for those performing a continuous complex monitoring task, a brief nap (<30 min) during the first night of sleep loss may be beneficial. However, the same duration nap during the second 24 h of continuous work results in debilitating sleep inertia.^{cc} In support of the recommendations of many health consultants, workers given a choice during scheduled breaks or at lunch times often select fun and games over other activities. The literature is mixed regarding the value of physical activity or exercise as a performance maintainer. Periodic light aerobics and walking are currently being recommended for those working at continuous sedentary jobs. Performance on cognitive tasks is enhanced when vigorous exercise is performed during rest breaks, but this effect is diminished in sleep-deprived subjects.¹⁷² In fact, in the presence of sleep deprivation, exercise does not improve

cognitive performance during extended continuous-work segments lasting up to 64 h.^{104,173,174}

It is worthy of note that meal breaks may not always improve monitoring performance. In one preliminary study, adult subjects given either a high-carbohydrate or a high-protein meal were assessed 2 h later for mood and performance.¹⁷⁵ Whereas the high-protein meal had no adverse effects, the high-carbohydrate meal produced subjective sleepiness in female, but not male, subjects. Significant objective performance impairment was demonstrated in older subjects (>40 yr old) 2 h after a high-carbohydrate lunch. This impairment was characterized predominantly by increased omission errors on a test of selective attention. Hawkins *et al.*¹⁷⁶ studied 68 medical house officers to assess the effects of sleep, nutritional, and behavioral habits on intellectual and psychomotor performance the morning after being on call. Using multivariate analysis, they claimed that better performance occurred in residents who were younger, who had eaten more full meals in the preceding 24 h, or who had consumed a better quality of food while on call. Unfortunately, this study was marred by a number of methodological problems (*e.g.*, extreme brevity of test tasks, age contamination, and training effects), and practical recommendations based on these findings would be premature. For an extensive review of work schedules and work-to-rest cycles, see Alluisi and Morgan.¹⁰⁸

BOREDOM

Boredom generally occurs when tasks are repetitious, uninteresting (monotonous), and undemanding. Boredom results from the need to maintain attention in the absence of relevant task information¹⁷⁷ and is most likely to occur in semi-automatic tasks that prevent mind-wandering but are not fully mentally absorbing. Boredom is thus a problem of information *underload*.⁹⁶ In an early study of vigilance, Mackworth demonstrated that lower signal rates produced more frequent false alarms.¹⁷⁸

Boredom appears to be a major problem in many complex real-life tasks. Kogi and Ohta³⁷ examined the influence of sleepiness on monotonous task performance by studying 288 Japanese train drivers over a 3-week period. They recorded 198 near-accidents and found that these most commonly occurred during steady driving at a constant speed under ordinary track conditions. Drowsiness caused 17% of the near-accidents, and 79% of the near-accidents occurred between midnight and 6 am. In a more recent study of the cause of train accidents on the Japanese National Railway, human error was responsible for nearly 40%.¹⁷⁹ Based on their data, these latter authors asserted that boredom and automatic behavior were the major contributing factors to human error in train driving. Similarly, during prolonged routine flight tests in high-per-

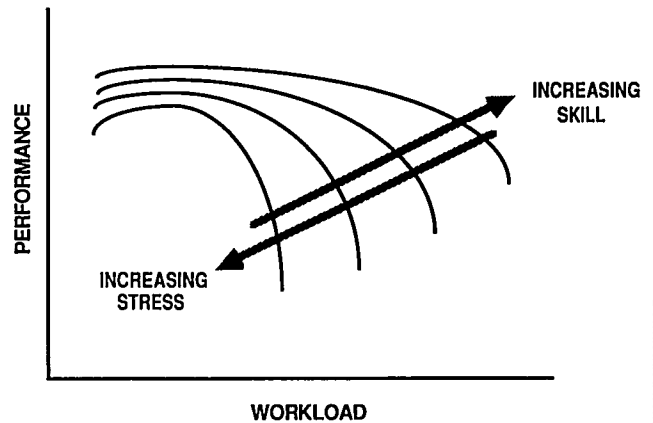


FIG. 2. The theoretical curvilinear relationship among performance, workload, and skill based on the results of a comprehensive examination by Harris and co-workers²⁴² of pilot performance during simulated flight. However, this relationship probably applies equally well to the administration of anesthesia. Performance is optimal at an intermediate workload because low work levels result in boredom and inattention, whereas high workloads are stressful and disruptive. Note that increased experience (or skill) shifts the curve upward and to the right, whereas stress (environmental, personal, or task-related) has the opposite effect.

formance aircraft, experienced pilots exhibiting decreased emotional tone (consistent with low arousal or boredom) had impaired vigilance, missed more signals, had slower reactions, and were sleepier.¹⁸⁰ These results, as well as those from laboratory experiments, suggest that in the presence of boredom, increased effort is necessary to suppress distracting stimuli and to suppress a generalized feeling of fatigue.⁶⁰ Adding tasks to a monotonous job¹⁸¹ may decrease boredom,⁶⁰ and dividing attention among several tasks (time-sharing) may, in some circumstances, improve monitoring performance.^{182,183}

The results of the study by Drui and colleagues²⁷ revealed that 40% of the time during a surgical procedure the anesthesiologist was physically inactive. In Boquet and co-workers' follow-up study,²⁹ the anesthesiologist was inactive 75% of the time. Both investigators implied that this idle time was beneficial to patient care because it allowed the anesthesiologist the opportunity to think, reflect, and analyze. However, an examination of the theoretical relationship between performance and workload reveals an inverse U-shaped distribution whereby both very low- and very high-workload situations result in decreased performance (fig. 2). Since low workload can result in a low arousal state, and as confirmed by previous work, low as well as high arousal states are associated with impaired performance,¹⁸⁴ there is no certainty that this idle time is *a priori* good for patient care. On the other hand, it has been suggested that some anesthesiologist idle time is essential because it acts a reserve to be called into play during critical events when additional cognitive

and physical resources must be rapidly deployed to optimize patient care.^{dd}

WORKLOAD AND TASK CHARACTERISTICS

Many factors, including personal problems, excessive workload, and specific characteristics of the task itself, influence job performance.⁴² An example of how workload or task requirements can influence performance comes from a recent study of 12 relatively inexperienced private pilots asked to perform a series of flight maneuvers on a simulator under increasingly difficult conditions until performance failure occurred.¹⁸³ Under high-workload conditions, subjects omitted portions of the tasks which were not essential to maintain a minimum level of performance (*i.e.*, not essential to the safe flying of the aircraft). Often the omission of a task component is unintentional—such as in a lapse of memory during a routine but important procedure—as dramatically demonstrated in studies of artillery teams during simulated sustained combat.^{ee} This type of behavior, resulting in dire consequences in real life, becomes more noticeable in sleep-deprived or stressed individuals.

Stress and Performance

Sources of stress affecting performance can be found in the work environment (social and physical), in the tasks involved (mental load and pacing), and in the individual (health-related, job-matching, and personality).¹⁸⁵ "Stress" is a broad term, and depending on its type and magnitude, it can result in either degraded or enhanced performance. Many studies have documented the stress associated with being a physician in general and a resident physician in particular.¹⁸⁶

Mental stress associated with problems in the workplace can have a profound effect on performance and job satisfaction. According to a recent insurance industry study, approximately 14% of all occupational disability claims are "stress-related."¹⁸⁷ A striking example of how on-the-job stress can affect psychological well-being was seen in a survey of a group of commercial pilots working for an airline (Eastern) undergoing a hostile takeover *versus* a comparable group employed by another carrier. Almost 70% of the Eastern pilots reported a state of low psychological *well-being*, versus only 20% of pilots in the control group. Twenty times as often, the control pilots expressed feelings of career satisfaction, and cited "a sense of mastery" nearly twice as often as did the Eastern pilots. As a result, 25% of the Eastern pilots reported an increased use of alcohol; sick time doubled; and the rate of pilots leaving Eastern was ten times the airline average. In a related study, 25% of the pilots involved in a labor dispute showed objective signs of significant psychological stress,

including anger–hostility, paranoia, and obsessive–compulsiveness.¹⁸⁸ Like these pilots, resident physicians have been shown to be more depressed and angry than are age-matched peers.^{186,189,190}

There are many personal interactions in the operating room that could affect performance adversely (*e.g.*, the difficult surgeon or the uncooperative nurse). Other, outside factors—for example, financial or personal problems—also can influence an anesthesiologist's performance. These domestic stresses have been shown to increase the likelihood of accidents.¹⁹¹ Other individual factors that may affect performance include overall quality of life, personality, practice style and patient mix, job burnout, and self-image. Applicants for critical positions such as nuclear submarine operator, nuclear power plant worker, policeman, or commercial pilot are required to submit to psychological testing as a condition of employment.^{192,193} The administration of psychological tests to applicants for anesthesiology training would certainly be controversial, but further study seems indicated.

Physiologic Response to Stress

Stressful environmental conditions impair vigilance, especially in situations of conflict.¹⁹⁴ The level of stress can be assessed by measuring either physiologic or psychological parameters. The physiologic correlates of stress generally correspond to sympathetic nervous system activity. Studies have used heart rate,^{194,195} skin conductance,¹⁹⁶ respiratory rate,¹⁹⁷ and catecholamine excretion¹⁹⁸ to assess stress levels during performance on complex tasks. Several investigators have suggested that even more sensitive physiologic indicators of stress include beat-to-beat variability in heart rate,^{180,199} T-wave peak amplitude on ECG,¹⁸⁰ and changes in voice characteristics (tone, timing, and inflection).¹⁸⁰ With increasing workloads during simulated and real flights in high-performance aircraft, cosmonauts who exhibited decreased beat-to-beat variability, higher T-wave peak amplitude, and voice changes had more false alarms and were more disorganized. Hart and Hauser¹⁹⁵ observed that working astronauts' subjective ratings of stress, workload, and mental effort correlated with their heart rate. Corroborative data have been obtained from firefighters aroused from sleep for a simulated drill.²⁰⁰ In another study, continuous ECG recordings from healthy military pilots flying actual surface attack training missions revealed episodes of significant ST elevations, ST depressions, T-wave inversions, and marked sinus arrhythmias.²⁰¹

That increased workload or mental stress produces increased sympathetic nervous system activity and deleterious physiologic responses is supported by the recent work of Rozanski and colleagues.²⁰² Thirty-nine patients with documented coronary artery disease and 12 control

subjects were subjected to a series of mental tasks during radionucleotide ventriculography. Whereas no control subject exhibited myocardial dysfunction during mental stress, 59% of the patients with coronary disease had wall-motion abnormalities indicative of myocardial ischemia, and 36% had significant decreases in ejection fraction. This mental-stress-induced ischemia was silent in 83% of the patients. In addition, the ischemia occurred at lower heart rates than does exercise-induced ischemia. Also, a personally relevant, emotionally arousing speaking task induced more frequent and severe episodes of myocardial ischemia than did less specific stressful cognitive tasks.

The physiologic response of the anesthesiologist to the stress of giving anesthesia therefore may be a crucial variable, and yet it has received little attention. Toung and colleagues^{ff} looked at the change in the heart rate of anesthesiologists during induction and intubation. First-year residents experienced a 60% increase over baseline heart rate during intubation of the patient. In more experienced clinicians, the increase was less. Subsequently, these investigators showed that prior medical training, even if not anesthesia-related, was associated with a diminished stress response during the administration of anesthesia.^{gg} This is consistent with the finding that repeated exposures to a specific situation results in diminished endocrine (stress) responses if the subject has learned to cope with the situation.¹⁹⁸

STATE OF HEALTH

Anxiety is a major stress factor affecting performance. Individuals indicating stress reactions or performance decrements due to anxiety can be classified into either state- (situation-dependent) or trait- (personality-dependent) related anxiety. Anxiety affects working memory capacity²⁰³ and selectivity of attention.²⁰⁴ Anxiety has a greater effect on complex than on simple tasks.²⁰⁴ According to Hockey,⁹⁶ stress-related memory failures probably cause the difficulties in planning and decision-making seen in individuals under stress. The inability to cope with anxiety and stress probably is an important contributing factor in the development of mental illness.^{205,206} Physicians, like the patients they care for, develop both physical and mental illnesses.²⁰⁷

Substance Use and Abuse

Data from the American Medical Association suggest that 1–2% of practicing physicians may be addicted to drugs and that up to 8% may be classified as alcoholics.²⁰⁸ Anesthesiologists may be at even higher risk for drug abuse than are other physicians.²⁰⁹ While the serious abuse of drugs and alcohol is, of course, detrimental to job performance, a variety of other, ostensibly innocuous drugs also can influence vigilance and monitoring skills.

Small doses of caffeine, such as that found in a typical caffeinated soft drink, can have a positive effect on vigilance and performance.²¹⁰ However, the use of caffeine also has its drawbacks. For instance, a recent study suggested that even among regular coffee drinkers, caffeine ingestion can magnify the physiologic consequences of stress.²¹¹ Significant caffeine consumption will produce a noticeable tremor and may also increase subjective anxiety.²¹²

While it may be readily accepted that the acute administration of other central nervous system-active drugs like barbiturates or benzodiazepines may have deleterious effects on performance,²¹³ what may not be appreciated is that antihistamines have also been associated with performance decrements on simulated tasks.^{213,214} However, the new “nonsedating” antihistamines, such as terfenadine (SeldaneTM) or astemizole (HismanalTM) may be without significant performance-degrading effects.²¹⁵ Phenothiazines and perhaps other antiemetics also can impair performance on complex tasks.²¹⁴

There is little doubt that alcohol ingestion markedly impairs vigilance as well as psychomotor performance.^{216–218} In fact, pilot simulator-based training studies have documented significant impairment in performance at blood alcohol concentrations (BACs) as low as 20–35 mg/dl, well below that at which a person legally can be considered drunk.²¹⁹ Perhaps more important from the anesthesiologist’s point of view, the effects of hangover from alcohol can significantly impair performance,²²⁰ even in the absence of the perception of impairment by the individual being tested. For example, Laurell and Tomros^{hh} studied 22 healthy volunteers driving an automobile through a test course. Normal scores (accuracy and braking time) were established, and then the subjects consumed alcohol to attain an average BAC of 147 mg/dl. The next morning, once the subject’s BAC had reached zero, they were tested again. Nineteen of 22 subjects scored worse under the hangover condition; the average performance decrement was approximately 20%. Of particular concern, there appears to be no correlation between how poorly a subject with a hangover feels and his or her actual level of performance.^{220,221} A study of Navy pilots flying a simulator 14 h after acute alcohol intoxication produced similar results.²²² For commercial and private pilots, the Federal Aviation Administration (FAA) states that “no person may act as a crewmember of a civil aircraft within 8 hours after the consumption of any alcoholic beverages; while under the influence of alcohol, or, while using any drug that affects his faculties in any way contrary to safety.”ⁱⁱⁱ However, more recent work on hangover effects suggests that pilots should wait at least 14 h after alcohol consumption before flying. Should anesthesiologists adhere to a similar standard?

It is well known that marijuana intoxication impairs

performance,²²³ and marijuana ingestion has been implicated as a causative factor in recent railroad and airline accidents.^{ii-ll} What may not be appreciated is that, like alcohol, marijuana intoxication can be associated with a hangover condition which may also impair performance. Yesavage and colleagues²²⁴ studied ten experienced pilots trained on a flight simulator. Each pilot then smoked a cigarette containing 19 mg tetrahydrocannabinol, and 24 h later significant impairment in pilot performance was noted. The pilots had no awareness of their impaired performance.

Some studies have suggested that cigarette smokers may be less vigilant than nonsmokers²²⁵ and may also have impaired visual discrimination skills.²²⁶ Others, however, have found conflicting results.²²⁷ Nevertheless, there are valid data to suggest that the stress response of smokers is more prominent than that of nonsmokers.¹⁹⁸ The implications of these findings for the anesthesiologist who smokes have yet to be clarified.

While the data presented in the previous sections are insufficient to draw any definitive conclusions, they suggest that physical condition and personal habits can have a significant influence on vigilance and monitoring performance.

PERSONALITY FACTORS

Subjects of different personality types perform differently on vigilance tasks.¹⁹⁹ In fact, individual psychological or physiologic differences may be the most important factors affecting performance on vigilance tasks.²²⁸ For example, in some tasks, the incidence of error may be better predicted on the basis of individual personality traits (such as emotional stability) than on the nature of the particular task.^{mmm} For years, investigators have attempted to classify people according to one psychological dimension or another.²²⁹⁻²³² The personality dimension of "morningness" or "eveningness," a measure of time-of-day preferences with regard to sleep and wake times, permits a correlation of psychophysiologic rhythms with performance effectiveness²³¹; for example, body temperatures with reaction time^{mm}; level of alertness with the ability to concentrate²³³; and adrenaline excretion,²³⁴ circadian phase,²³⁵ and physical fitness with adaptation to shift changes.^{236,237} Significant differences in performance in a vigilance task was found between groups classified as morning or evening types.²³⁸ Thus, working or sleeping at times diametrically opposed to one's biologically-rooted personality characteristics leads to performance impairment and fatigue. Important factors in predicting adjustment to on-call duties may include one's adaptability to changes in normal sleeping schedule and the ability to overcome drowsiness.²³⁹

Reeve²⁴⁰ tested 231 British anesthetists on a battery of personality tests and then asked their peers and supervi-

sors to assess their anesthesia skills. Personality traits that correlated with a "good" anesthesiologist included "independent," "conscientious," "stable," "reliable," "achievement-oriented," "goal-directed," "intolerant of incompetence," "serious," "calm," and "cooperative." Curiously, there was a 30% incidence of unstable personalities. Although the study was generally well-performed, there was a suggestion in the distribution of personality traits that the sample may have been biased. In another study of anesthesia residents, the personality traits that best correlated with overall clinical competence included "common sense," the ability to "set priorities," and good "performance under stress".^{oo} However, this study was contaminated by a biased assessment technique and the failure to account for differences among subspecialty rotations. Baker and colleagues suggested that individual "learning styles" can influence an anesthesia resident's success, and the importance of this factor depends on the "learning style distribution" of the training program the resident attends.^{pp}

The American Board of Anesthesiologists dictates that for Board certification a trainee must have a "personality suitable for patient care and for serving as the leader of the anesthesia care team."^{qq} Several anesthesia program directors have stated that occasionally trainees leave or are unable successfully to complete residency training primarily because of "unsuitable personality traits." Although personality characteristics may be a crucial factor in the selection of individuals for careers in anesthesiology, currently there are little objective data to guide the specialty.

TRAINING AND EXPERIENCE

Few people would argue that training and experience are important for optimizing individual performance on complex tasks.²⁴¹ Aviation accident rates directly correlate with flight experience.³³ Individual clinical practice may influence anesthetic morbidity.²⁴² Additional training and experience may obviate the negative effects on performance of stress or increased workload.²⁴³ Gaba and DeAnda²⁴⁴ showed that more experienced residents were better able to correct simulated untoward intraoperative events but had no faster detection times than residents with 1 yr less training. However, individual differences, perhaps in experience or education, appeared to be much more important than amount of training. Studies in other fields support a relationship among performance, workload, and skill or level of training (fig. 2).²⁴⁵

PERSONAL PHYSICAL ATTRIBUTES

Anesthesiologists with visual deficiencies may be at increased risk for monitoring errors. The incidence of airplane accidents has been shown to be higher among pilots

with visual deficiencies compared with those with normal vision,²⁴⁶ although a more recent study suggests that the wearing of corrective lenses may obviate this risk.²⁴⁷ Other deviations from the expected physical "norms" may result in an ergonomically undesirable mismatch among equipment, environment, and the anesthesiologist. The slightly hearing-impaired may have difficulty understanding the surgeon's comments; the short anesthesiologist may not be able to see the surgical field; and the obese may find it difficult to maneuver in the anesthesia workspace in critical situations. Obviously, the equipment and environment must be designed to accommodate a range of anesthesiologists' needs. No consistent gender differences have been identified in studies of vigilance or performance.^{248,249}

PRIMARY TASK FACTORS

In most complex monitoring tasks, performance is never perfect over time,²⁵⁰ and increased task complexity or duration generally results in decreased performance.^{251,252} One major factor in the limitations of humans as monitors is that the human senses can be particularly inaccurate, especially in dynamic situations.^{33,253} For instance, one generally can effectively process only one input channel at a time (in what is called "resource allocation"). There also is a built-in time-lag between data input and appropriate response. Finally, the presentation of the required information must be compatible with the sense organ responsible for gathering it. For example, analog displays of information appear to be easier to process than are digital displays of the same information, especially in high-workload situations.²⁵⁴ Similarly, color coding appears to improve search time.²⁵⁵ Novel methods of displaying critical information such as rate-of-change functions²⁵⁶ also may improve performance. The military is also making extensive use of "heads-up" displays, in which the necessary information is projected onto a visor worn by the operator. This eliminates the need to refocus or change eye position and therefore decreases information-gathering times by up to 50%.³³

TIME-SHARING AND SECONDARY TASK FACTORS

In an elegant study of the influence of human factors on complex task performance, Harris and colleagues²⁴³ attempted to measure workload accurately under a variety of conditions for different levels of aviator experience. Using a flight simulator with seven instruments, subjects were instructed to fly straight and level in the face of mild turbulence. A secondary task was used to increase the workload of the subjects ("loading"). The subjects had to repeat aloud sequences of three numbers spaced either 2 or 4 s apart. The investigators then used a modified Honeywell oculometer to determine exactly how often

and for how long the subjects gazed at each instrument in the simulator panel. With increasing secondary task workload (*i.e.*, more frequent repetition of the sequence of numbers), subjects tended to stare longer at the primary instruments (for instance, the attitude indicator). In addition to fixating less frequently on their secondary instruments ("load shedding"), when they did gaze at these instruments, it was for a longer time. The investigators concluded that, with increasing workloads, the subjects required more processing time to perceive the information available from each instrument. They also found that the performance of more experienced pilots was less strongly affected by workload. As task complexity increases in a busy anesthetic case, this same phenomenon may be manifested by poor record-keeping, careless anesthetic routine, or lapses of vigilance.

The absolute level of workload influences the effects of time-sharing. However, a major factor in the effect of an additional task on performance appears to be what personal resources (perceptual, cognitive, output modalities) are required for the new task and whether those resources are taxed already. According to this "structure-specific resource model,"²⁵⁷ if a given resource modality (*e.g.*, vision) is busy, then a new task requiring that modality will impinge on overall performance, while a task requiring a different modality (*e.g.*, hearing) would be better accommodated. It is noteworthy that Tsang showed that highly-trained pilots were no more efficient at handling a novel complex time-sharing task than were college students.²⁵⁸ Thus, while performance in a time-sharing environment can be enhanced with training and experience, appropriate system design may be the most important factor. In the operating room, Lambert and Paget²⁵⁹ examined the influence of intraoperative teaching on the time spent by residents in patient- and equipment-oriented tasks. They found that tutoring during "inappropriate" times markedly detracted from patient monitoring.

Observation of practicing anesthesiologists reveals that during times of low workload, many add an additional (often unrelated) task to their routine, presumably in order to prevent boredom. These secondary tasks can include clinically relevant (though perhaps unnecessary) functions such as rechecking the composition or organization of the anesthesia workspace. Alternatively, it is not uncommon to observe anesthesiologists reading, listening to music, attending to personal hygiene, or conversing with their intraoperative colleagues about matters not directly related to patient care. How these activities affect vigilance is difficult to assess.

During anesthetic cases that are long and impose minimal physical and intellectual demands, the addition of nonpatient care tasks such as reading could potentially improve vigilance by maintaining arousal. However, given the absence of formal training of anesthesiologists in time-

sharing techniques and multi-tasking paradigms, there is likely to be tremendous individual variability in the impact of these nonpatient care activities on anesthetic vigilance and clinical care. Laboratory studies^{40,260} have suggested that there is a discrete time-sharing ability that can be separated from other vigilance skills. It therefore is possible that only for a few anesthesiologists would intraoperative vigilance be enhanced by performing nonpatient care tasks. This problem must be studied further before any definitive recommendations can be made. In any case, the conditions of the intraoperative environment, tasks, and equipment must be redesigned to minimize boredom and yet not be so continuously busy as to be stressful. This will yield the highest consistent levels of vigilance and optimal performance for all anesthesiologists.

The Equipment (and System) Component

Applying human factors principles and data to the design, development, and testing of equipment and anesthesia systems can increase human reliability and reduce the probability of error. Calkins⁴³ provides an extensive review and indictment of current anesthesia systems, citing statistics that support the need for research on and development of new equipment. He strongly emphasizes safety and risk reduction. Because the importance of good anesthesia equipment design has been covered elsewhere,^{43,44,45} in this section we discuss a few areas where equipment design directly affects overall system performance.

Kumar and colleagues randomly examined 169 anesthesia machines of varying ages in use in 45 hospitals for level of function and maintenance.²⁶¹ They found many inadequacies and malfunctions. For instance, 9% of the machines had significant leaks, and 4% of the vaporizers were out of calibration. Thirty-six per cent of the machines did not have functioning oxygen analyzers; 3% lacked a backup oxygen supply; and 15% were without a functioning low-pressure alarm. Regular preventive maintenance and the use of an anesthesia preuse inspection checklist would have assisted in the detection of many of the malfunctioning components.

Although the percentage of anesthesia mishaps that are due to equipment is relatively small,¹⁸ the contribution of poor equipment design, poor maintenance, or poor performance to anesthesiologist error may be significant. The most common equipment-related critical event in anesthesia is the circuit disconnect.¹⁸ Until recently, circuit disconnects were a major contributor to anesthetic-induced morbidity and mortality.^{3,6,262} However, with the increasingly widespread use of disconnect or circuit low-pressure alarms, specific maneuvers by anesthesiologists to prevent its occurrence, and several connector design modifications to decrease its likelihood, the circuit dis-

connect is being relegated to the status of a still frequent but noncritical event.²⁶³

SYSTEM ERRORS AND RISK ASSESSMENT

At least some of what appears on first glance to be human error often can be traced back to poorly designed human-machine interfaces.¹⁷ Poor operational design can significantly increase the risk of system failure due to operator error.^{35,264} This topic has been covered in some detail by Gaba.^{23,93} Human behavior is much more difficult to predict than are inanimate systems. Reliable techniques have been developed to quantify the probability of operator slips, lapses, and misperceptions. However, there always will be some uncertainty in the prediction of individual behavior in the face of crisis situations.⁵⁵ The initial response of system designers to the risk of operator errors in complex human-machine environments was the extensive use of emergency protocols. Although this technique does increase the likelihood of appropriate operator response in anticipated or straightforward emergency situations, in novel or more complex system failures, the use of rote protocols can lead to a worsening of the situation. The shortcomings of protocol-driven operator response was apparent in both the Three Mile Island and the Savannah River nuclear power plant accidents.¹⁷ More recently, increasing emphasis has been placed on educating operators in system function so that they can improvise during an accident and potentially mitigate its consequences.

ALARMS AND VIGILANCE

Although alarms can be useful in terms of improving recognition of critical situations, if improperly designed, they can result in markedly degraded performance.²⁶⁵ Intraoperative alarms can give misleading information as well as be distracting. Porciello's²⁶⁶ survey of critical care unit clinicians revealed that many of them found arrhythmia alarms to be inaccurate, misleading, and disturbing. Many anesthesiologists disconnect or ignore alarms that sound falsely or are annoying.²⁶⁷ In fact, in a recent study, it was found that many common commercially used clinical alarms induced a negative affective response.²⁶⁸

Studies have suggested that for critical information, auditory presentation results in a quicker and more reliable response than does visual presentation.²⁶⁹ Recent data suggest that synthesized-voice warning messages may be even more effective.²⁷⁰ However, in a complex environment with many different alarms, there must be a proper mix of alarm notification modalities to prevent confusion or decreased subject responsiveness. It is clear that human factors principles must be applied to the design of intraoperative alarms. This includes selection of physiologic variables to be monitored, control of alarm limits, reliable

detection of out-of-range events, intelligent decisions regarding nonalarm states, provision of user-friendly output signals to the operator, and standardization across medical systems.²⁶⁵

AUTOMATION

There are several reasons to automate complex systems: to enhance system performance, to increase safety, and to reduce human workload.²⁷¹ However, automation will not necessarily lead to improved system performance in every situation.

A major advance in future anesthesia equipment will be the incorporation of microprocessor-based "intelligent" systems.^{272,tt} In particular, studies have shown that the precise control of ventilators and measurement of many patient parameters can best be performed with microprocessor-based systems.²⁷³ A number of institutions have developed modular computer-based anesthesia delivery systems (*e.g.*, the Boston Anesthesia System,^{tt} the Arizona Program,^{uu} and the Utah Anesthesia Workstation²⁷⁴), and these concepts gradually are being incorporated into new commercial anesthesia workstations, such as the Ohmeda Modulus[®] CD Anesthesia System. An understanding of the ergonomic factors which affect anesthetic performance will enhance the ability to effectively implement automated anesthesia tasks like drug administration and record-keeping, the development of smart alarms, and novel ways of presenting clinical information.

Each year brings a wide variety of new, expensive, and complicated monitoring technologies to "assist" anesthesiologists with their clinical vigilance tasks. The most recent additions of this onslaught include the pulse oximeter, the end-tidal carbon dioxide monitor, the processed EEG, the transesophageal echocardiogram, and others. Setting up, calibrating, attaching to the patient, and monitoring these new devices will require additional time-sharing in the operating room environment, and thereby further decrease the amount of time spent directly observing or interacting with the patient. In addition, as systems become more complicated and automated, they may become more prone to human error. This has been clearly shown with the pilot-aircraft interface.²⁵³

The question must then be answered: does a new device provide sufficient additional information (or early warning of some critical condition) to justify its cost, both in terms of financial economy and in terms of decreased use of the already available monitoring strategies? Currently, it is very difficult, if not impossible, objectively to answer this crucial question. Only by gaining a complete understanding of the factors influencing the specific vigilance tasks involved in anesthesia monitoring can one begin to scientifically study the impact of new devices or procedures on clinical performance.

The ultimate goal of any study of anesthesia vigilance or monitoring performance should be to determine the influence on clinical outcome. In this context, the most important situation may be the anesthesiologist's response to a critical event. Because of the infrequency of critical events in most routine anesthetics, it is extremely difficult to study the anesthesiologist's response to these events in the clinical setting. Some have proposed using simulators to recreate and study anesthesia practice.^{23,275-277,vv} It is hoped that this type of innovative research will lead to an improved understanding of intraoperative monitoring performance and permit changes in anesthesia practice and education and in equipment design and implementation, with the goal of decreasing anesthetic mishaps and ultimately negative outcomes.

Conclusions

Preventable anesthetic mortality remains a serious problem, and human error is a major contributor to this mortality. Scientists and engineers in aviation, nuclear power, transportation, and other fields are now able to design new equipment and work environments based on sound ergonomic principles and hard empiric data. Currently, very few studies have been performed to assess the factors influencing an anesthesiologist's intraoperative vigilance and his or her response to critical events. In this article we have reviewed the major ergonomic and human factors affecting vigilance and monitoring performance on complex monitoring tasks. Most of the data are from nonanesthesia settings, but they appear to be relevant to anesthesiologists interested in optimizing their work environment and their individual performance. A number of specific suggestions have been made based on the available data. However, further research is long overdue and will be crucial to assure optimal performance in the increasingly complex operating room environment of the future.

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Appendix: Footnotes

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