Vigilance, Alarms, and Integrated Monitoring Systems

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INTRODUCTION

This chapter discusses several topics in which the interface between human and machine, or more accurately, between anesthesiologist and anesthesia equipment, plays a crucial role. Given the title of the chapter, some may think at first glance that the topics are unrelated. However, these three topics – vigilance, alarms, and integrated monitoring systems – are, in fact, closely interrelated.

The administration of anesthesia is predominantly a complex monitoring task and, as such, requires sustained vigilance. Unfortunately, humans are not very good at monitoring because they are error-prone and their vigilance is susceptible to degradation by a variety of human, environmental, and equipment factors. Therefore, designers of anesthetic equipment have attempted to “aid” the anesthesiologist by incorporating devices and systems to augment vigilance and clinical performance. Alarms, intended to notify the operator of potentially critical situations, are only effective if properly designed and implemented. While many modern anesthesia delivery devices are physically integrated (generally containing systems for gas delivery, monitoring, alarms, and sometimes record keeping), many of the promised benefits of full-scale integration (e.g., “smart” alarms, decision aids, etc.) are as of yet unfulfilled. The successful implementation of comprehensive integrated anesthesia workstations will require not only further technological advances but a more complete understanding of the task of administering anesthesia and of the factors that affect performance of the anesthesiologist in this complex man-machine environment. Research to elucidate these “performance shaping factors” in anesthesia has been underway for a number of years and is beginning to bear fruit. **Chapter 17** discusses the role that the field of Human Factors should play in modern anesthesia practice.

Anesthesia Mishaps

It was estimated about 10 years ago that many as 3000 preventable occurrences of anesthesia-related death or brain damage occur in the United States each year \(^1\). Although it is believed by some that anesthesia has become progressively safer \(^2\), many more surgical procedures are now being performed and thus the absolute number of adverse events may not have decreased appreciably. Additionally, patients undergoing surgery today may be older and sicker than they were 10 or 20 years ago, as a consequence of population demographics and economically driven changes in the American health care delivery system (which may delay, but not prevent, the use of surgical therapy). Finally, studies suggest that the incidence of “potentially serious” clinical events is actually quite common under anesthesia, although relatively few evolve into adverse patient outcomes \(^3\).

A number of investigators have suggested that human error is a major contributor to the occurrence of anesthetic mishaps \(^1,4-7\). For example, clinician errors, such as “inadvertent gas flow change” or “syringe swap,” accounted for up to 70% of anesthetic mishaps in two early studies \(^4,8\). In a study by
Keenan and Boyan, 75% of intraoperative cardiac arrests were attributed to preventable anesthetic errors. Holland suggested that inadequate patient observation was a contributing factor in one-third of perioperative patient deaths. In the intensive care unit, clinical errors may often be associated with failed communication between care providers. On the other hand, as is discussed in detail later in this chapter, the root cause of a vast majority of adverse anesthesia incidents is probably systemic factors over which the anesthesia provider has little or no control (e.g., device designs which predispose to human error).

Even under ideal conditions, performance on complicated tasks is rarely perfect. In complex systems consisting of humans and machines, human error is almost always a factor in degraded or faulty performance. For example, the percent of accidents due to air crew error was reported as being greater than 50%. Accidents are usually caused by the cumulative effect of a number of events rather than one isolated incident. Why do highly-trained and experienced individuals make errors and what factors influence the occurrence of these errors? What can be done to decrease their incidence or to mitigate their negative outcome? Unfortunately, research thus far has only begun to provide adequate answers to these questions.

**Human Error**

Errors are a normal component of human cognitive function and play a major role in learning. However, most errors do not result in damaging consequences. An error that results in an unacceptable outcome is often called an accident. 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. Yet, Cooper and colleagues showed that most critical events in anesthetic practice were discovered and corrected before a serious mishap occurred. It is crucial to understand the determinants of recovery from anesthetic errors. Factors such as sleep deprivation, miscommunication, or equipment problems not only can increase the potential for error but may preclude effective recovery.

Two types of error are slips and mistakes. Both of these can take the form of errors of omission (omitting a task step or even an entire task) or errors of commission (incorrect performance). Slips are most likely to occur during activities for which one is highly trained and, therefore, are performed outside of active conscious thought. Drug syringe swaps, a commonly described anesthetic critical event, 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 schema (or preprogrammed subroutines) are inappropriately called into play by specific stimuli without conscious processing. There is a tendency to revert to a high-frequency (well learned) response.
in such situations, particularly when the individual is under stress. Experts may, in fact, be more likely than novices to make these kinds of error than are novices.

In a study of anesthesia residents doing cases using a comprehensive anesthesia simulation environment, DeAnda and Gaba documented 132 unplanned incidents (i.e., not part of the simulation script but rather created by the subject) during 19 simulations; a rate of nearly two per case. Human error accounted for 86% of the incidents while equipment failure only accounted for 3% \(^{22}\). Of the incidents due to human error, nearly one quarter were due to fixation errors. Fixation errors occurred when the subject was unable to focus on the most critical problem at hand because of persistent, inappropriate attention or actions directed elsewhere. The overall incidence of human error observed during simulated anesthesia was similar to that suggested by Cooper for anesthesiologists in the operating room \(^{8,23}\). This study is important not only because it substantiates the frequent occurrence of error in anesthesia but also because it validates the use of simulation to study the types and causes of critical incidents in anesthesia. Clinical decision making can also be adversely impacted by a number of other types of cognitive biases such as confirmation bias, inappropriate over-confidence, false attribution, the availability and representativeness heuristics, anchoring and framing, etc. \(^{24,25}\).

In contrast to slips and fixation errors, mistakes are technical or judgmental errors. Thus, mistakes are due to inadequate or incorrect information, inappropriate decision-making skills or strategies, inadequate training, lack of experience, or insufficient supervision or back-up.

People are more likely to commit errors when they are mismatched to the task or the system is not user-friendly. Factors which can influence error commission include skill level, attitude, inexperience, stress \(^{19}\), poor supervision \(^{26}\), task complexity \(^{19}\), and inadequate system design (Box 18-2). The topic of human error in anesthesia has been covered in some detail elsewhere \(^{17,27-29}\).

At least some of what, on first glance, appears to be human error, can often be traced back to poorly designed man-machine interfaces \(^{30,31}\). In fact, Norman \(^{32}\) suggests that “the real culprit in most errors or accidents involving complex systems is, almost always, poor design.” Poor operational design can substantially increase the risk of system failure due to operator error. Factors related to system-induced error include boredom due to over-automation \(^{33}\), over-reliance on automated devices, and poor team coordination. Good operating practice is essential but not sufficient for minimizing system risk: 1) the design of the system must be fundamentally sound; 2) it must be properly constructed and implemented; 3) the operators must be thoroughly familiar with the system; and 4) ongoing quality control must assure that system use is appropriate over the full range of possible conditions. This applies to the anesthesia workspace and must be considered when introducing new anesthesia equipment to this unique environment.
VIGILANCE AND MONITORING PERFORMANCE

Vigilance has been equated to “sustained attention” 34. Attention requires alertness, selection of information, and conscious effort. Alertness indicates the receptivity of the individual to external information. Mackworth 35, the father of vigilance research, defined vigilance as “a state of readiness to detect and respond to certain specified small changes occurring at random intervals in the environment.” Early research was stimulated by the errors of early radar operators who, for extended periods, performed the task of detecting barely perceivable events at infrequent and aperiodic intervals.

The presence of “vigilance” in the official seal of the American Society of Anesthesiologists underscores the perceived importance of careful attention to details and detection of subtle signs out of the ordinary. Thus, in a broader sense, “anesthetic vigilance” might be viewed as a state of clinical awareness whereby dangerous conditions are anticipated or recognized (Box 18-3). Monitoring is, by definition, a vigilance task and the administration of anesthesia is a complex monitoring task. The anesthesiologist must continuously evaluate the patient’s medical status while assessing the effects of anesthesia and surgical intervention. Memory tasks, decision making, and vigilance are the most vulnerable to compromise under the stressful work conditions often experienced in the operating room.

While monitoring during quiescent periods of the maintenance phase of anesthesia appears to closely resemble the classical vigilance tasks studied in the laboratory, anesthesia practice commonly involves more complex situations which require divided attention, prioritization, and “situation awareness” 36, skills which fall outside the classical definition of vigilance.

A large number of laboratory studies have demonstrated a decline in monitoring performance over time, called the “vigilance decrement” 37. The performance decline is typically complete within the first 30 minutes of a monitoring session. The vigilance decrement seems to arise primarily as a function of necessity of attending to a relatively infrequent signal for a prolonged length of time.

Psychologists and engineers have studied vigilance for many years. Investigators in fields outside of medicine, most notably in aviation, have applied this information to understanding performance on complex monitoring tasks. Studies have identified environmentally-induced factors and man-machine interface variables that can impair vigilance and performance in air traffic control 38, train driving 39,40, automobile driving 41, and nuclear power plant control 42. The armed forces consider the potential impact of such factors at the earliest stages of the design of new weapons systems 43.

In most complex monitoring tasks, increased task complexity or task duration generally results in impaired performance 44,45 (Fig. 18-1). A major factor in the effect of additional tasks on performance appears to be what personal resources (perceptual or cognitive) are required for each new task and whether those resources are already taxed. Other factors known to impair vigilance include noise, environmental pollution, fatigue, sleep deprivation, and boredom (see 21). Performance may also be impaired if the individual is under stress, of ill health, or using drugs. Personality factors,
training, and experience also affect performance. Performance on complex monitoring tasks can be strongly affected by environmental or by task variables.  

**RESEARCH ON VIGILANCE IN ANESTHESIA**

In one of the first ergonomic studies of anesthesia, Drui et al. used time-motion analysis to examine how anesthesiologists spent their time in the operating room. The practice of anesthesia was divided into a number of discrete activities and the frequency and sequence of each activity was measured. One principal finding was that anesthesiologists directed their attention away from the patient 42% of the time. Subsequent time-motion studies have corroborated and expanded these early results.

Recent research has examined the effects of level of provider experience and of new technologies such as electronic anesthesia record keeping on the workload and vigilance of residents administering anesthesia. Others have investigated anesthesiologist’s vigilance to auditory and visual alarm cues as well to changes in clinical variables, in both the laboratory and during actual cases. For example, Weinger et al. demonstrated that novice anesthesia residents were slower to detect the illumination of an alarm light placed within their monitoring array (Fig 18-2). Response rate was further impaired during periods of high workload such as the anesthetic induction.

Well-controlled studies are essential to understand the nature of anesthesia vigilance and monitoring performance. Studies should be designed to utilize techniques and procedures which have been repeatedly validated by investigators in other fields. Chapter 17 describes in more detail current research in anesthesia related to clinical performance.
FACTORS AFFECTING VIGILANCE

A wide range of factors can affect anesthetic vigilance and clinical performance (Box 18-4). The following discussion will provide the reader with a perspective on how a variety of everyday occurrences in the operating room have the potential to significantly impair vigilance, potentially leading to increased risk of critical events and, as a result, anesthetic morbidity or mortality. The following sections will address some of the more important anesthesia performance shaping factors organized into environmental, human, and equipment categories.

Environmental Factors

NOISE AND MUSIC

The noise level in the operating room can be quite high. In the early 1970’s, Shapiro and Berland measured noise levels associated with specific tasks in the operating room during several typical surgical procedures, finding that “the noise in the OR frequently exceeds that of a freeway.” These findings appear to still be valid today. Continuous background noise in the modern operating room may range from 75-90 dB (see Box 18-10). High noise events include mechanical ventilation, suction, music, and conversation. Noise levels of up to 118 dB can occur, notably during high-speed gas-turbine drills. Suction tips with trapped tissue yielded up to 96 dB. High noise levels create a positive-feedback situation, where noisy rooms require louder alarms, which contribute to the noise, etc.

The effects of noise on performance depend on the type of noise and the task being performed. In addition, other environmental and human factors can interact with noise to affect task performance. Noise levels similar to those found in operating rooms detrimentally affect short-term memory tasks and may also mask task-related cues and cause distractions during critical periods. Difficult tasks that require high levels of perceptual and/or information processing are negatively affected by noise. Chronic exposure to high noise levels produce physiological changes consistent with stress. Exposure to loud noise activates the sympathetic nervous system, a situation which may augment the effects of other performance shaping factors resulting in impaired decision making during critical incidents.

There is little doubt that background noise interferes with effective verbal communication. It is critical for the anesthesiologist to be able to hear clearly what other members of the operating room team are saying. When multiple tasks are required, the presence of background noise may bias attention towards the dominant task. When both noise and sleep deprivation are present, they may cancel out each other’s effects. Time of day, however, may modulate the impact of these types of performance shaping factors.
While loud noise is clearly disruptive and can impair auditory vigilance (for instance, the ability to monitor the esophageal stethoscope or detect and identify alarms), studies have found a beneficial effect on complex task performance in the presence of lower levels of background (white) noise. Several studies suggested that the presence of familiar background music could improve vigilance. A positive effect of preferred background music on surgeons’ mood and laboratory task performance was recently described. However, the validity of this study’s findings were questioned and the impact of the surgeon’s preferred music on the anesthesiologist’s monitoring performance. What if the surgeon wanted to listen to country music, for example, and the anesthesiologist hated that type of music? Swamidoss et al. studied the effects of background music on the performance of 30 anesthesia providers using a screen-based computerized anesthesia simulator. They found no significant differences in the time to recognition and correction of critical incidents, level of anxiety, or autonomic responses whether the subject listened to their “most enjoyed music,” “least enjoyed music,” or “no music” at all. However, the number of subjects studied was small and the applicability of these results to the actual OR environment remains to be examined.

TEMPERATURE

Uncomfortable environmental temperatures, a common situation in many operating rooms, can impair vigilance. Although there appears to be significant variability in the effects of temperature on performance depending on the experimental situation (i.e., other environmental, task, and subject variables), as a general rule, temperatures that promote general fatigue decrease performance. Extremely cold temperatures have a deleterious effect on some cognitive tasks, primarily due to the distraction of the cold environment and the associated decrease in manual dexterity. These effects often show up as increased errors and memory deficits. Studies in the industrial workplace suggest that when temperatures fall outside a preferred range (17°C-23°C), workers are more likely to exhibit unsafe behaviors that could lead to occupational injury. Temperatures in some adult operating rooms can be as low as 7°C and those in pediatric OR’s may approach 30°C. The negative effects of temperature are probably augmented by other factors which enhance fatigue or impair performance.

ENVIRONMENTAL TOXICITY (EXPOSURE TO VAPORS)

There is a voluminous literature on the effects of trace anesthetic vapors on anesthesiologist performance. The early studies of Bruce, et al. reported that exposure to 550 ppm N20 and 14 ppm halothane led to a significant decrease in performance on complex vigilance tasks. However, their study used as subjects Mormon dental students who may have been uniquely sensitive to the effects of the anesthetic gases. Smith and Shirley subsequently showed that acute exposure to trace anesthetic gases in amounts commonly seen in an unscavenged operating room had no effect on performance in
naive volunteers. It thus appears that impaired vigilance due solely to trace anesthetic gases is probably not a problem in the modern, well-scavenged operating room. This is supported by a subsequent well-controlled cross-over study in which anesthesiologists showed no differences in either mood or cognitive ability when working in a scavenged operating theater compared with working in the intensive care unit (with no trace gases) \(^83\). However, other noxious smells or the need to wear bulky and uncomfortable protective gear could have an adverse impact on clinical performance \(^84\).

**Human Factors**

FATIGUE

Fatigue is caused by hours of continuous work or work overload \(^85\) whereas boredom is thought to be a function of insufficient work challenge or under-stimulation. The two, nonetheless, often co-occur. Extreme fatigue will result in objectively measurable symptoms of exhaustion and psychological aversion to further work. There is marked individual variability in the response to factors or situations which can produce fatigue. The continued ability to perform skilled physical or mental tasks in the face of worsening fatigue is strongly dependent on psychological factors including motivation. Although some extremely fatigued individuals can be induced to perform \(^86\), the quality and wisdom of continued work under these circumstances is questionable, and this is 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 their poor methodology, have raised more questions than they answered. Fatigue and sleep loss are often covariants in studies examining continuous long work schedules and, in turn, both are modulated by circadian processes. Since the effects of these variables interact \(^87\), it is difficult to separate the relative contribution of each factor to the performance decrement observed.

Individuals subjected to excessive work, fatigue or inappropriate shift schedules show degraded performance, impaired learning and thought processes, irritability, memory deficits, and interpersonal dysfunction (see \(^21,88\)). Fatigued subjects pay less attention to peripherally-located instruments and are inconsistent in their response to external stimuli. Fatigued subjects, when coping with task demands, exhibit less control over their own behavior and tend to select more risky alternatives (or short-cuts) \(^86\). If sufficiently motivated, fatigued subjects can attain relatively normal performance on tasks of short duration \(^89\) but they find it difficult to sustain performance on vigilance or monitoring tasks of long duration \(^90,91\). Adding sleep loss or shift work will accentuate fatigue-induced performance decrements \(^92\).
SLEEP DEPRIVATION

There is a large body of research which supports the contention that sleep deprivation and circadian rhythm disturbances can dramatically impair performance on monitoring tasks 89,93-97. Although sleep deprivation and fatigue are similar in some of their performance-shaping effects and are certainly interactive, they are different processes. A single night of sleep loss can produce measurable performance decrements, especially on skilled cognitive tasks. Impairment can be seen shortly after task initiation; within 20-35 minutes in some situations 98. However, in most sustained work activities, major decrements usually occur after 4 hours and again after 18 hours 99. In a recent study, Dawson and Reid showed that the magnitude of cognitive psychomotor impairment after remaining awake for 24 hours was roughly equivalent to that produced by acute inebriation with a blood alcohol level of 0.10% (Fig. 18-3) 100.

While there are wide individual differences in the amount of daily sleep required 101=, studies involving one or more days without sleep consistently reveal progressive decreases in reaction time and increases in response variability 102 (Box 18-5). Work rate is appreciably slowed, particularly when subjects are required to make choices 103. In vigilance tasks, omission errors increase, whether visual or auditory signals are presented 104-106. Sleep loss impairs active use of working memory 102, particularly when the sleep loss precedes learning 107. Sleep-deprived workers fail to appropriately allocate attention, set task priorities, or sample for sources of potential faulty information 108,109. Since many of these skills are essential for optimal anesthesia care, it suggests that sleep loss could be extremely detrimental to clinical performance.

Haslam's field work 110 indicated that some sleep (2-3 hr/24 hr) is better than none at all, at least for soldiers involved in military exercises. For example, in studies on sleep-deprived soldiers, while a 2-hour nap was insufficient and 3 hours permitted a maintenance of previous levels of (already impaired) performance, a full 4-hour nap was required before baseline performance was restored 89,111,112. Taking a short nap (<2 hr) at the circadian low point (see the section on Circadian Changes) produces greater cognitive impairment than the same length nap taken at the peak of the circadian cycle 113,114. Additionally, if a sleep-deprived subject is permitted to nap, then, following the nap, there will be a period of “sleep inertia” during which the subject will exhibit a low level of arousal as well as significantly impaired vigilance and performance. Sleep inertia may persist for up to two hours 89.

In one of the first studies of the effects of sleep loss on physician performance, Friedman et al. 94 showed that the ability of sleep-deprived medical interns to detect cardiac arrhythmias was significantly compromised compared with well-rested interns. Hart and colleagues 115, in a well-designed study of 30 first-year medical residents, demonstrated mild but significant disturbances in memory, decision-making, and motor execution in on-call residents deprived of normal sleep (2.7±2.2 hr slept) compared with those getting a full-night’s rest (7.9±1.3 hr). Unfortunately, other studies
designed to assess the impact of sleep deprivation on the ability of physicians (usually housestaff) to perform clinical duties have generally had serious methodological flaws.

Nevertheless, a large number of non-medical laboratory and field work on sleep deprivation and performance suggest that patient care could be compromised if a fatigued or sleep-deprived clinician is allowed to administer an anesthetic, operate, or perform other medical procedures. The issue of decreased clinical performance of house officers and other physicians as a result of over-work and sleep deprivation gained media attention in the 1980’s and, increasingly, state legislatures and academic institutions are attempting to implement restrictions on house staff work schedules. Nevertheless, a survey by Howard and colleagues suggested that American anesthesia residents work an average of 73±12 hours per week (including call), although these results may be contaminated by response bias. There are still few if any restrictions on the work schedules of fully licensed practicing physicians. One wonders whether, as American health care evolves toward capitated managed care and the financial incentives associated with extended work hours diminishes, more practicing physicians will voluntarily reduce their work schedules.

CIRCADIAN CHANGES AND SHIFT WORK

Periodic, rhythmic fluctuations in bodily processes, including performance and work efficiency, have been well documented. Over 50 neurophysiological and psychological rhythms that potentially influence human performance have been identified. Most studies of rhythmic changes in efficiency have focused on cycles of about one day, called “circadian” processes. An individual's normal rhythm can be significantly influenced by environmental conditions, illness, time-zone changes, and altering shift schedules. During normal wake time, circadian-related fluctuations in performance can range from 14% to 43% (Box 18-6).

In rapidly changing schedules of regular work hours (e.g., routinely and frequently changing from day shift to night shift), performance rhythm amplitudes show variations as great as 50%. The rate and amount of adjustment to shift changes or extended workdays varies among individuals. However, in a study of nurses doing shift work, some individuals were never able to adjust and, in general, shift workers exhibit greater sleep, social, and health problems. Efficiency of permanent night-shift workers is at least 10% less than that of comparable day-shift coworkers, and minor accidents and task errors occur most frequently during night shifts and the early morning hours. On the other hand, fully acclimated night-shift workers have a realigned circadian cycle such that their best performance occurs during their normal shift. Swing-shift workers seem to have the most difficulty establishing a normal diurnal rhythm. Because adjustment to shift work takes at least several days, if shift rotations are required, the rotation should be clockwise (i.e., progressively later shifts) and never less than two weeks per shift. The implications for anesthesia
is that night-time on-call cases would be most optimally performed by anesthesia providers assigned to at least 2 weeks of night-shift only duty.

Alterations in the normal circadian rhythms cause changes in arousal as well as other mental and physical functions and play a major role in the effects on task performance of acute sleep loss, napping, and recovery from disruptions in normal sleep schedule. Phase shifts are introduced by sleep interruption. Some circadian functions are altered and normal rhythms may be disrupted even after multiple brief interruptions in an otherwise full night’s sleep. The peak and minimal performance times normally expected by the individual are similarly shifted. This can lead to a false sense of competence during “normal working hours” following acute sleep loss. For example, an anesthesiologist who has been up working most of the previous night, after recovering from sleep inertia in the early part of the next morning, may feel remarkably awake, perhaps even euphoric. Yet, studies have documented degraded performance on complex tasks in such situations (Fig. 18-3). By mid-afternoon, dramatic decreases in arousal and feelings of well-being accompany parallel performance decrements. That evening, the anesthesiologist will probably have difficulty falling asleep, especially if an afternoon nap had been taken. In fact, sleep-to-wake cycles can be disturbed for up to 36 hours, and the anesthesiologist may remain more error prone during this recovery phase 129,130.

PERFORMANCE DURING EXTENDED DUTY SHIFTS BY ANESTHESIA PERSONNEL

Recent work by Howard and colleagues suggests that anesthesia residents are chronically sleep deprived. Using standard sleep study methodology, they demonstrated that undisturbed Stanford anesthesia residents, even if they had not been on-call for two full days, had daytime sleep latencies comparable to that of patients with narcolepsy. Furthermore, often these residents denied falling asleep during the sleep tests, despite objective EEG evidence to the contrary. Post-call anesthesia residents demonstrate significant decrements on laboratory psychomotor vigilance tests. Interestingly, a recent survey suggests that sleep deprivation and fatigue may contribute to a higher incidence of automobile accidents in anesthesiology residents post-call compared with the overall U.S. population post-call.

Weinger and colleagues have recently begun to examine the task performance and workload of anesthesia residents doing actual OR cases in the middle of the night when on-call. Five senior residents performed routine general anesthesia cases at night (00:33 am ± 87 min) during a 24 hr on-call shift. The same residents were studied again during day time cases (10:30 am ±59 min) which were matched to the nighttime cases with respect to type and duration of surgery and ASA status. The residents had awakened 5±1 hr before the start of the day cases and 14±4 hr prior to the night cases. Residents reported feeling less “tired” or “drowsy” during day cases compared with night cases and,
consistent with being in different phases of their circadian cycles, tympanic temperatures were significantly higher during the day than at night.

The intraoperative activities of each resident, resolved into 35 task categories, were recorded by a trained observer. At night, more time was spent on mask ventilation and intubation while less time was spent conversing with the attending. Post-intubation, residents spent more time during the night observing their monitors and less time doing nothing at all (idle time). At night, residents also spent longer (dwell time) on individual tasks (e.g., 22±7 sec night vs. 12±4 sec day for intubation). Subjective workload was significantly higher at night vs. daytime cases. There were no differences, however, in response to a vigilance probe. These preliminary data suggest that in the sleep deprived state, anesthesia residents have higher workload and are less “efficient”, suggesting a potential for impaired performance. These results are consistent with the need at night for greater perceptual and cognitive resources to process data and accomplish tasks although additional experiments will be required to substantiate this hypothesis.

A complementary avenue of research is now underway at Stanford University where anesthesia residents are participating in a controlled randomized cross-over study designed to examine the effects on clinical performance of sleep deprivation and fatigue during realistic simulated OR cases. In the highly-fatigued condition, subjects are keep awake for at least 25 hours prior to a morning experiment. In the comparison well-rested condition, the same resident obtains an extra 2 hours of sleep every night for a week before the experiment. The simulated 4 hour routine laparoscopy cases have been designed to accentuate any effects of sleep deprivation. Interestingly, analysis of preliminary data suggest that, through the intraoperative use of a variety of counter-measures, anesthesia residents are able to overcome substantial fatigue and sleep loss to perform almost as well as during routine anesthesia cases. Unfortunately, the effects of sleep deprivation on clinical performance during serious acute critical events has not yet been examined in either simulated or real cases.

From the above discussion, it appears that work schedule can, under some circumstances, be an important factor affecting intraoperative vigilance and performance. There are significant individual differences in the response to acute or chronic sleep loss and each anesthesiologist must be cognizant of his or her own limitations. Individuals must recognize that it is neither unprofessional nor weak to admit sleepiness or fatigue when on the job and they must attempt to either make time to recuperate or seek a clinical replacement.

BREAKS

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. Short breaks have been shown to alleviate fatigue
as well as increase employee satisfaction and productivity in machine-paced jobs. For worker-controlled sedentary jobs, short breaks or a change in activity increases performance and relieves boredom. However, there is still little experimental evidence to support the widely held belief that performance will improve following a break from a prolonged complex monitoring task such as administering anesthesia.

The optimal frequency and duration of breaks is still unknown for most occupations. Warm has recommended that monitoring tasks be limited to sessions of less than 4 hours. Breaks have been required by many union contracts as well as by legislation in some countries, particularly for occupations in which impaired worker performance could endanger worker or public safety (i.e., transportation workers).

Cooper et al., in a study of critical incidents associated with intraoperative exchanges of anesthesia personnel, identified 90 incidents which occurred during a break. Twenty-eight of these incidents were deemed favorable (i.e., the relieving anesthesiologist discovered and corrected a potentially dangerous pre-existing situation) while only 10 incidents were considered unfavorable (i.e., the relieving anesthesiologist “caused” the critical incident). In some of the remaining incidents, the problem was perpetuated by the relieving anesthesiologist. Unfortunately, because of the possibility of biased reporting, the relative frequency with which relief results in favorable versus unfavorable outcomes can not be determined from this type of study. On the other hand, out of the 1,089 total critical incidents studied, Cooper and colleagues failed to identify a single relief-related incident that resulted in significant morbidity or mortality. Nevertheless, the detection of problems during a break probably depends on a systematic and comprehensive review of the anesthetic course by the relieving anesthesiologist. It has been recommended that specific relief-exchange protocols be developed and adhered to strictly (Box 18-7).

BOREDOM

Boredom is a problem of information underload, insufficient work challenge, and under-stimulation. Boredom typically results from the need to maintain attention in the absence of relevant task information and may be most likely to occur in semi-automatic tasks which prevent mind-wandering but are not fully mentally absorbing. There are substantial differences among individuals in what types of activities they find boring. Nevertheless, boredom appears to be a major problem in many complex real-life tasks. For example, boredom may be a contributing factor to human error in locomotive driving and in prolonged routine flight in high-performance and commercial aircraft. The maintenance phase of most routine anesthetics is a period of very low workload and infrequent task demands. Low workload may result in a low arousal state which can lead to impaired performance. In laboratory experiments, increased effort in the presence of boredom is necessary to suppress distracting stimuli and a generalized feeling of fatigue. The
addition of other performance shaping factors such as fatigue and sleep deprivation may augment the negative impact of boredom \(^{21}\). Boredom may be minimized by altering the sequence of tasks \(^{146}\) or by adding tasks to a monotonous job \(^{147}\). Dividing attention among several tasks (time-sharing) will, in some circumstances, improve monitoring performance \(^{148,149}\). Psychological studies suggest that some individuals may be more “boredom prone” but that behavioral interventions can improve these individual’s vigilance \(^{150}\).

Observation of experienced anesthesia providers has revealed that, during times of low workload, many add additional tasks to their routine. These secondary tasks include clinically-relevant functions such as rechecking the composition or organization of the anesthesia workspace. Alternatively, it is common to observe anesthesiologists reading, listening to music, attending to personal hygiene, or conversing with their intraoperative colleagues about matters unrelated to patient care. The choice of secondary tasks is probably less important than how those tasks are integrated with the primary tasks of caring for the patient as well as how the secondary tasks are “shed” (set aside) when anesthesia workload increases \(^{21,54,151}\). From a broad perspective, if the anesthesia task environment is optimized to minimize boredom and yet not be so continuously busy as to be stressful, the highest consistent levels of vigilance and performance will be attained.

**READING IN THE OPERATING ROOM**

Recently, a more overt discussion has occurred in the anesthesia community regarding the appropriateness of the apparently common practice of anesthesiologist reading while taking care of anesthetized patients \(^{152-154}\). Since there are yet no objective data on the effects of intraoperative reading on anesthesiologist vigilance, the opinions espoused are largely based on personal beliefs and morals (what is “right”).

Most of the time during the administration of an anesthetic, there are many patient-care tasks to perform and the diligent anesthesia provider will prioritize and undertake these tasks appropriately. Under this circumstance, if reading occurs, it will only be during “idle time” when no other tasks (other than general patient monitoring) are required. In task analysis studies, the anesthesiologist has been shown to be “idle” during up to 40% of routine cases \(^{47}\). This idle time appears to provide a reserve (e.g., spare capacity) to be called into play during high workload or critical periods when additional cognitive and physical resources must be rapidly deployed to optimize patient care. Studies suggest that more experienced providers will perform tasks more efficiently, report lower workload, and have more spare capacity at a given level of task performance \(^{53,54}\) than do less experienced providers. One might then speculate that reading during low workload periods could help to prevent boredom, sleepiness, and decreased vigilance. This hypothesis must be tested in rigorous scientific studies.
Few studies have defined the actual incidence of boredom or of reading in the operating room. A few years ago, 57 of 105 anesthesia providers at the University of California, San Diego and the San Diego VA Medical Center responded to complete a questionnaire which included questions on this topic. Almost 90% of those responding admitted to occasional episodes of “extreme” boredom. To relieve their boredom while in the operating room, 29% of the respondents read. Reading was the most common technique to relieve intraoperative boredom (other strategies included “thinking about things,” “conversing,” and “busying oneself with manual tasks”). When asked specifically “how often do you read while administering anesthesia”, 19% of the respondents stated that they “frequently” read, 46% said they “sometimes” read, and 33% “rarely” read. Only one respondent claimed that he/she never read in the OR. When they did read, two-thirds of the respondents almost always read anesthesia-related material.

Interestingly, despite its common occurrence, 49% of the respondents believed that reading detracted from anesthesia vigilance while 21% felt that reading enhanced vigilance and 30% were ambivalent. It is unclear how these data generalize to other hospitals throughout the country? These data are from a Southern California training institution in which intraoperative reading is permitted. Many residency programs throughout the country prohibit reading as a matter of policy (although I understand that middle-of-the-night OR reading may still occur. There may be significant differences between hospitals in different geographic regions or even within the same city.

Laboratory studies suggest that there is a discrete time-sharing ability which can be separated from other vigilance skills but may be able to be trained. However, anesthesia providers are not given any formal training in time-sharing techniques although “resource allocation” and “divided attention” skills are probably learned on a more informal basis. There is probably tremendous individual variability in the impact of reading on anesthesia vigilance. For some anesthesia providers, intraoperative vigilance could thus be enhanced by reading during low workload periods, while in others, the ability to detect acute events may be impaired.

One must also be cognizant of the sociopolitical and medicolegal implications of intraoperative reading. Reading will clearly have adverse impact on performance if it detracts from the anesthesiologist’s ability to do his/her primary tasks, attend to the surgeon’s and others’ requests, or to respond to new task demands. However, even in the absence of a demonstrable negative impact, reading may “look bad” and give the appearance of inattention and boredom (when, in fact, it may be serving the opposite effect). In the absence of data on the impact of reading on anesthesia vigilance and performance, it will be difficult to sustain the merits of reading during a case in which an adverse medical outcome occurred, particularly if an acute critical event was not detected or managed appropriately.
STRESS AND PERFORMANCE

Sources of stress affecting performance can be found in the work environment (social and physical)\textsuperscript{157,158}, the tasks involved (mental load and pacing), and the individual (health related, job matching, and personality)\textsuperscript{159,160}. Stress is a broad term and, depending on its type and magnitude, it can result in either degraded or enhanced performance. A subject's performance will be significantly influenced by interaction with the environment and its associated stresses, the work to be performed in this environment, and the level of incentive for performing.

Many personal interactions in the operating room can affect performance adversely (e.g., dealing with the ostensibly difficult surgeon or uncooperative nurse). Other, outside factors can also influence an anesthesiologist's performance, for example, financial worries or a recent fight with a spouse. Such domestic stresses have been shown to increase the likelihood of accidents\textsuperscript{161}.

Stressful environmental conditions impair vigilance, especially in situations of conflict\textsuperscript{162}. The level of stress can be assessed by measurement of either physiological or psychological parameters. The physiological correlates of stress generally correspond to sympathetic nervous system activity. Studies have used heart rate\textsuperscript{162-164}, skin conductance\textsuperscript{165}, respiratory rate\textsuperscript{166}, beat-to-beat variability in heart rate\textsuperscript{145,164,167}, T-wave peak amplitude on ECG\textsuperscript{145}, changes in voice characteristics\textsuperscript{145}, and catecholamine excretion\textsuperscript{168} to assess stress levels during performance of complex tasks. With increasing workload levels during simulated and real flights in high-performance aircraft, pilots who exhibited physiological signs of stress had more false alarms and exhibited more disorganized task patterns. Thus, increased workload or mental stress produces increases sympathetic nervous system activity which can lead to deleterious physiological changes\textsuperscript{169,170}.

The physiologic response of the anesthesiologist to the stress of giving anesthesia may be a crucial variable yet it has received little attention. In a preliminary study, Toung and colleagues\textsuperscript{171} measured the heart rate of anesthesiologists during anesthetic inductions. There was a 60% increase over baseline heart rate in first-year residents at the time of intubation (Fig. 18-4). More experienced clinicians had less of an increase in rate. Subsequently, these investigators showed that prior medical training, even if not anesthesia-related, was associated with a diminished stress response to the administration of anesthesia\textsuperscript{172}. Repeated exposures to a specific situation results in diminished endocrine (stress) responses if the subject has learned to cope with the situation\textsuperscript{168}. A correlation between clinical workload and the heart rate of anesthesia residents has since been documented\textsuperscript{164} and in a recent study, Mackenzie’s group not only replicated Toung’s findings but demonstrated that more emergent procedures generated a greater physiological stress response\textsuperscript{173}.

STATE OF HEALTH

Physicians, like the patients they care for, develop both physical and mental illnesses\textsuperscript{174}. The topic of the “impaired” physician has been gaining increasing attention among professional societies,
consumer groups, and government regulators. For example, how can these various constituencies be assured that an anesthesiologist infected with the HIV virus does not have neuropsychological impairment that adversely affects his/her ability to safely administer anesthesia 175? What should done with practicing anesthesia providers who are elderly, infirm, or have been involved in a previous anesthesia mishap? These are complex issues which require more discussion than is possible in this overview.

As individuals age, there are physiological and neurological changes which can adversely impact vigilance and task performance 176-178. Ample “reserve” and years of experience allows most older anesthesiologists to continue to perform at a high level under most circumstances. However, the older practitioner may be more susceptible to the performance-degrading effects of sleep deprivation, fatigue, and stress. In fact, a recent retrospective analysis by Travis and Beach suggests that older anesthesiologists are proportionally over-represented in the National Practitioner Data Bank for malpractice claims 179. Many older anesthesiologists recognize their limitations and may restrict their practice to routine daytime work or even choose to retire rather than to continue to work at night 180.

Anxiety is a major stress factor which can affect job performance. Anxiety adversely impacts attention 181 and working memory 182. Stress-related memory failures probably cause the difficulties in planning and decision-making observed in stressed individuals 85. The inability to cope with anxiety and stress is likely an important contributing factor in the development of mental illness 182 and substance abuse.

SUBSTANCE USE AND ABUSE

Data from the American Medical Association suggest that 1%-2% of practicing physicians are addicted to drugs and up to 8% may be classified as alcoholics 183. Anesthesiologists may be at higher risk for drug abuse than other physicians 184. Although the abuse of controlled substances and alcohol is obviously detrimental to job performance, a variety of other, ostensibly more innocuous drugs such as caffeine, antihistamines, and nicotine, can also affect vigilance.

Small doses of caffeine, such as that found in a typical caffeinated soft drink can have a positive effect on vigilance and task performance 185. Yet, one study suggested that even among regular coffee drinkers, caffeine ingestion can magnify the physiological consequences of stress 186. Antihistamines have been associated with performance decrements on simulated tasks 187,188 although non-sedating antihistamines may be without significant performance-degrading effects 189. Phenothiazines and perhaps other antiemetics can also impair performance on complex tasks 188.

It is well known that alcohol ingestion markedly impairs vigilance as well as psychomotor performance 190-192. In fact, pilot simulator-based training studies have documented significant impairment in performance at blood alcohol levels as low as 20 to 35 mg/dl, well below that considered legally drunk 193. Perhaps, just as important, the effects of hangover from alcohol can also
significantly affect performance\textsuperscript{194,195}, even in the absence of the perception of impairment by the affected individual\textsuperscript{194,196,197}. The implication of these findings is that individuals should wait at least 14 hours after alcohol consumption before performing such complex tasks as flying an aircraft or administering anesthesia.

Marijuana intoxication impairs performance\textsuperscript{198} and marijuana use has been implicated as a causative factor in several railroad and airline accidents\textsuperscript{199-201}. In addition, like alcohol, marijuana intoxication is associated with a hangover condition which may impair performance\textsuperscript{202}, even after 24 hours, and in the absence of an appreciation by the subjects of their impairment\textsuperscript{203}.

**PERSONALITY FACTORS**

Subjects of different personality types will perform differently on vigilance tasks\textsuperscript{167}. In fact, individual psychological or physiological differences may be the most important confounding factors in the performance of vigilance tasks\textsuperscript{204}. For example, for 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\textsuperscript{205}. Individual preferences for particular living, working, and sleeping schedules may have a substantial genetic contribution. Thus, working or sleeping at times diametrically opposed to one’s biologically rooted personality characteristics leads to performance inefficiency 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\textsuperscript{206}.

**TRAINING AND EXPERIENCE**

Training and experience are clearly important to ensuring a high level of performance on complex tasks (Fig. 18-5). Aviation accident rates directly correlate with flight experience\textsuperscript{16}. Individual practice patterns may significantly influence anesthetic morbidity\textsuperscript{207} and a recent study demonstrated a clear inverse relationship between amount of surgical training and actual complication rates\textsuperscript{208}. Additional training and experience may obviate the negative effects on performance of stress or increased workload\textsuperscript{151}. Gaba and DeAnda\textsuperscript{209} showed that more experienced residents were better able to correct simulated untoward intraoperative events yet had no faster detection times than residents with one year less training. However, individual differences, perhaps in experience or education, appeared to be much more important than amount of training. Weinger and colleagues recently showed that during routine anesthesia cases novice residents exhibited higher workload, decreased vigilance, and were less efficient than were more experienced providers\textsuperscript{53}. While experience may mitigate some of the adverse effects of other performance shaping factors such as fatigue and boredom, it is by no means complete.
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 has generally been together for a long time and is well-practiced. Team communication involves unspoken expectations, traditions, general assumptions regarding task distribution, chain-of-command hierarchies, as well as individual emotional and behavioral components. Alterations in any of these factors can impair effective team function. A recent study suggests that failures of adequate communication between care providers may contribute significantly to the occurrence of clinical errors in the intensive care unit. Not only were more than a third of all errors reported associated with (presumably flawed) verbal communication between nurse and physician but also errors seemed to occur more commonly following changes of nursing shifts (suggesting a contribution as well of faulty nurse-nurse communication). These findings suggest that the anesthesiologist who is confronted with a new surgeon, OR nurse, or anesthesia resident should be sensitive to the “new interpersonal environment” and exercise extra vigilance by making a special effort to communicate clearly and unambiguously, particularly in stressful situations. Communication may prove even more difficult when some or all of the team members are subjected to other stressors such as fatigue or sleep deprivation. Additionally, overall OR team performance can be adversely affected by dysfunctional interpersonal interactions among team members.

Workload and Task Characteristics

The specific characteristics of the task itself will interact with other performance shaping factors. An example of how workload or task requirements can influence performance comes from a 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. Under high-workload conditions, the subjects tended to decompose maneuvers into smaller, more manageable tasks. The subjects also omitted portions of the tasks which were not essential to maintain a minimum level of performance (i.e., safely flying the aircraft). Often the omission of a task component is unintentional – such as a lapse of memory during a routine, but important, procedure. Task omissions which could have dire consequences in real life, become more common in sleep-deprived individuals.

In most complex monitoring tasks, increased task complexity generally impairs performance. Human senses can be particularly inaccurate, especially in dynamic situations. 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 already taxed. Researchers have thus proposed a curvilinear relationship among performance, workload, and skill (Fig. 18-6). This relationship appears to apply to the task of administering anesthesia.

In a study of pilot performance under different workload conditions, it was shown that with increasing workload, subjects tended to stare longer at the primary (i.e., more important) instruments. In addition to attending less frequently to their secondary instruments (e.g., load shedding), when pilots did gaze at these instruments, it was for a longer time. The presumption was that with increasing workload the subjects required more processing time to perceive the information available from each instrument. The performance of more experienced pilots was less strongly influenced by workload. Thus, as task complexity increases in a busy anesthetic case, this same phenomenon may be manifested by poor record keeping, sloppy anesthetic routine, or lapses of vigilance. This is supported by recent task analysis studies. Additionally, Lambert and Paget found that intraoperative teaching during “inappropriate” times markedly detracted from patient monitoring.

**Equipment and System Factors**

The equipment that the anesthesiologist encounters in the operating room can be characterized by those devices which are primarily for the delivery of substances (gases, drugs and fluids) and those which permit the user to monitor the outcome of that delivery and the physiological state of the patient. Yet, these two groups increasingly share common attributes (e.g., microprocessor control) and associated problems. Although the percentage of anesthesia mishaps that are primarily due to equipment appears to be relatively small, the contribution of poor equipment design, maintenance, or performance to user error may be significant. Thus, one wonders about the hidden factors that might have contributed to a catastrophe, but were not elicited by the “accident” investigation. For example, did distracting alarms contribute to the end result? Or, more importantly, did poor equipment design more or less subtly influence the outcome? For example, a recent study suggested that the use of transesophageal echocardiography during coronary artery bypass graft procedures may, under some circumstances, impair vigilance for other clinical events (Fig 18-7).

**POOR EQUIPMENT DESIGN**

At least one prominent author has suggested that almost all human error is due to inadequate or inappropriate equipment or system design. Poor equipment can manifest itself in many ways, including design, device performance, user and service manuals, and maintenance. At least two factors make design of operating room equipment particularly difficult. First, the operating room places appreciable physical and environment stresses on equipment. Second, it is sometimes difficult to elicit from users precise or optimal design requirements for OR equipment. Block et al. describe the installation of one of the first computerized monitoring systems specifically designed for the operating room. Despite doing a careful survey of anesthesiologist users to determine their needs and
preferences before even designing the system, after the system was built, these users decided that they really wanted something different. This change may less reflect capriciousness than it does changing experience and evolving expectations. Nonetheless, it makes the designer’s task more difficult. At the very least, in the design and manufacture of new equipment, continuous direct contact between the designer and the user is essential.

Artifact remains a serious problem and can be a function of poor device design. For example, inadequate shielding of ECG cables can lead to motion artifact. If the software cannot handle this artifact, the displayed heart rate will either be absent, or worse yet, incorrect. Computing and displaying incorrect values can be disastrous; the clinician could easily withhold or institute therapy inappropriately, or be unable to follow the course of therapy. Fortunately, there has been a substantial improvement in artifact management software in recent years. For example, the incidence of pulse oximeter artifact has decreased considerably, such that it is no longer of significant concern to those who use automated anesthesia record keeping devices.

Poor design can be particularly frustrating, since it is often so difficult to deal with after the fact. Poor design can be hardware- or software-related. The former may show up as too many, disorganized, or inappropriate control mechanisms. Software-related design problems include confusing displays or problems navigating between display screens. Combined hardware and software problems include poor handling of artifact, disruptive display-control relationships, or irrational alarms. For a more complete discussion of anesthesia system design issues and the ergonomics of the anesthesia workspace, please refer to Chapter 17.

Optimal design of complex microprocessor-based equipment requires a delicate balance between developing a device that is too complicated for the operator to understand versus one that becomes deceptively simple. If there are too many displays, or if the displays are confusing, performance may be suboptimal, and errors can result during crisis situations. The complexity of the Aegis radar display system (and some inherent design flaws) was a major cause of the inadvertent downing of a commercial airliner by the USS Vincennes. On the other hand, well-intended attempts to simplify a device can produce equally poor results. Cook, et al. 217 describe a humidifier that had been redesigned from a manual device to an automatic one. The clinicians liked the newer device, because it was “simpler”. Yet their research showed that the users did not understand the device’s underlying operation. For example, they did not know the procedure required to reactivate the device after an alarm, nor did they know that the heating elements were turned off after an alarm. To “reset” the device after an alarm, users simply turned it off and on again. This device was not intuitive in its design or functionality.

Each individual component of a system may be well thought out, but if the system design as a whole is faulty, the result will be unsatisfactory. Often the design is appropriate for one venue, but is transferred to another without taking into account the unique attributes of the new environment. For
example, most of the original “integrated” monitors were designed for use in the ICU and provided trend displays using a scale of six or more hours. For most anesthetic cases, the resulting display was far too compressed. The needs of users in the OR can be substantially different than those in the ICU.

The ultimate performance of the equipment is the most important consideration. Poor performance may be related to poor design, implementation, construction, inappropriate use, or inadequate supporting equipment. Mosenkis suggests that excellent design should allow the clinician to use a device correctly the very first time they interact with it, preferably without reading the manual, whereas, to use that device well, practice may be required. He goes on to assert that health care providers use medical devices in the same way they use automobiles; they expect that a new device will work more or less the same as equivalent older devices. This cognitive model (of how medical devices should work) can only be supported by the ubiquitous use of user-centered design and by standardization (see below and Chapter 17).

The use of simulation may facilitate many of the design goals required for safer and more user-friendly equipment. By testing several designs under almost real clinical situations, manufacturers will be able to efficiently determine which design, if any, is the most appropriate. Simulation can also be used for training: the clinician will be able to safely and more quickly learn how to use a device, even under the most demanding conditions.

USER MANUALS/DOCUMENTATION

The user theoretically depends on the manual for many purposes: becoming acquainted with a device during its initial use, learning its finer points, and trouble shooting. Unfortunately, many manuals and other documentation for medical devices are poorly written, confusing, or incomplete. All too often, the immediately essential or desired information is impossible to find. As a result of these shortcomings, most “user” manuals are simply not used by the clinicians. The Anesthesia Patient Safety Foundation has recognized this problem and is working with industry to write better manuals. From a practical standpoint, however, most people simply do not bother reading instruction manuals except perhaps to deal with a critical or particularly confusing condition (e.g., if they can not determine how to turn on the device).

On-line real-time help systems can now be easily incorporated into microprocessor-controlled medical devices. For example, a CD-ROM or an Internet connection can provide ready access to details needed for device operation, trouble shooting, maintenance, or repair. Current implementations typically include text, line drawings, and still photographs. However, digital movies may be a more appropriate method to demonstrate how to calibrate, set-up, or trouble-shoot a device in real-time.

Another consideration is education of anesthesiologists in the use of their equipment. Is that education the responsibility of the manufacturer, the hospital, the FDA, the users themselves, or perhaps some professional society, such as the Anesthesia Patient Safety Foundation or the Society for
Technology in Anesthesia? Regardless, the technical education of the anesthesiologist is sadly
deficient at all stages, from medical student to experienced clinician. Until this educational problem is
addressed, the interaction between the user and complex machines will remain suboptimal, and
equipment-induced or system-induced errors will occur that will be inappropriately blamed on the
user.

EQUIPMENT MAINTENANCE

Anesthesia machines in particular require continual maintenance and this must be undertaken by
experienced personnel. Maintenance training has traditionally been accomplished at the factory,
usually requiring several weeks. Optimally, maintenance should either be performed by a
representative of the manufacturer itself or by a well-trained independent sales and maintenance group
(see also Chapters 23 and 24).

Maintenance errors often follow the same pattern as other types of errors: a chain of events, each
one by itself insufficient to cause a disaster, contribute to the adverse outcome. In one of the most
notorious maintenance errors, which occurred over two decades ago, the operating room medical gases
were switched. A hospital maintenance worker repaired the oxygen hose during the night -- so he
would not disrupt the operating room routine. What he did, much of it in good faith, is a classic
example of a chain of mishaps: 1) An oxygen connector was attached to one end of each of two hoses
and a nitrous oxide connector to the other end; 2) Both hoses were black, rather than color-coded; and
3) He carefully and neatly twisted the hoses around each other. In these days before the pulse
oximeter, the first patient to be anesthetized with this machine died. It was soon realized that the
second patient was undergoing the same problem, the anesthesia machine was completely
disconnected, and the patient ventilated with an independent, portable, source of oxygen. The notoriety
this case achieved was responsible both for an increased awareness of the possibility of operating room
gas switches and for the realization that continuous measurement of inspired oxygen was necessary.
Sadly enough, gas switches can still occur.

EQUIPMENT OBsolescence

Anesthesia machines are designed to be long-lasting and rugged, and their manufacturers have
largely succeeded in this goal. Thus, a large number of older machines are still in service and present a
variety of problems: 1) integral parts wear out and do not function as intended; 2) components do not
perform up to today’s standards (which can change relatively rapidly); 3) functions, available on
modern machines, are absent; and 4) some components may actually be dangerous. Examples of
dangerous components still found on older anesthesia machines include Copper Kettle and in-circuit
vaporizers as well as vaporizers without an interlock mechanism. What to do with these machines
represents a major dilemma. There will always be out-of-date machines and it is not cost effective to replace them all at once. Furthermore, some might argue that an experienced anesthesiologist is safer using customary equipment, instead of a technologically overwhelming new workstation. On the other hand, a less experienced anesthesiologist, trained only on modern equipment, who is suddenly confronted with an old piece of equipment during an emergency anesthetic is placed in a difficult and potentially patient life-threatening situation. A recent literature debate points out the issues that arise, in this era of reduced health care resources and cost consciousness, when hospitals and anesthesia providers discuss the replacement of old anesthesia machines. We would agree with Petty’s general recommendation that older anesthesia machines be replaced if they do not meet ASTM standards, are not easily upgradable, and have poor service records.

THE ROLE OF STANDARDS IN ANESTHESIA EQUIPMENT DESIGN

For a number of years, a dedicated group of clinicians, device manufacturers, regulatory agencies, consultants, and other interested parties have been developing voluntary national and international medical device standards to help ensure safe medical practice. These standards will also help assure that the devices and their integration will be similar enough to each other to permit clinicians to use different devices from different manufacturers with minimal confusion. The American contributions to medical equipment standards development are being sponsored by the non-profit American Society for Testing and Materials (ASTM), the American National Standards Institute (ANSI), and the Association for the Advancement of Medical Instrumentation (AAMI). The international standards development process includes the proposed formation of a joint working group between the International Standards Organization (ISO) and the International Electrotechnical Commission (IEC) on the topic of integrated monitors, as well as the existence of ISO/IEC Joint Working Group's for the anesthetic workstation and for medical device alarms. Standards will continue to be a driving force in the integration of the anesthetic workstation, of monitoring systems, and other medical equipment in the clinical work environment. The active involvement of anesthesiologists is essential to assure that the standards making process results in effective, safe, and easy to use devices.
ALARMS

The need to incorporate alarms into monitoring systems stems from several factors: the number of variables to be monitored have increased tremendously; the equipment used to collect and display these variables have become exceedingly sophisticated; and, as discussed above, given the complexity of the task and its attendant stress, the anesthesiologist is unlikely to be able to detect all out-of-range variables or conditions without machine assistance. In fact, if displays were easy to comprehend, presented all of the relevant information (and no irrelevant information), and if all the required clinical information were in one, easy to read, location, then perhaps alarms would be unnecessary. Unfortunately, this situation does not yet exist. In fact, with the increasing sophistication of anesthesia monitors and equipment, the number of alarms has increased almost exponentially.

The objective of any alarm system is to optimize the probability of dealing successfully with the problem at hand. Alarms actually should serve several functions: assist the anesthesiologist in the detection of adverse or unanticipated conditions in either the patient or the equipment; aid the fatigued or otherwise non-vigilant anesthesiologist; and assist in situations where stress, workload, lack of training, or other factors negatively impact on the ability of the anesthesiologist to detect or respond to undesirable conditions.

Once an activate alarm is detected, the next step is to identify the etiology of the alarm. An alarm is of no benefit if it does not also provide the user with sufficient information to correct the alarm condition (either directly, or by indicating where to look to get the necessary data). In fact, when the source of an alarm cannot be identified, it is extremely distracting and can exacerbate a potentially difficult clinical situation. Different conditions can cause an alarm condition including an unexplained change in one or more of the monitored signals, an unexpected or undesirable response of the patient to an intervention, equipment failure; or artifact.

An alarm should be more than just an indicator of an abnormal condition; it must provide some preliminary information about the condition which activated the alarm. However, too much information provided in the initial alarm state can confuse or mislead the operator, especially if the alarm is based on a single variable or if multiple alarms are simultaneously activated. The sounding (and subsequent identification) of a particular alarm narrows the focus of the user’s attention to one aspect of the system. Some alarms (such as a low circuit pressure alarm) are very specific with respect to the physical location which must be inspected and the fund of knowledge required to correct the problem. In these types of conditions, an experienced user can quickly correct the problem, often with very little conscious effort. In contrast, other alarms (such as a high PA diastolic pressure alarm or a low right hemisphere EEG spectral edge frequency alarms) may require extensive examination of multiple clinical variables and significant contemplation to determine the underlying condition which activated the alarm state.
The designer of alarm systems must consider the method as well as the consequences of the interruption produced by the alarm. An alarm system should produce an alarm signal as soon as possible after an alarm condition has been detected. It should be easy for the user to identify the source of the alarm. Accurate information about the cause of the alarm must be provided. The user’s attention must then be held long enough to ensure that the problem that caused the alarm has been corrected. Finally, interference from other, less important, alarm conditions must be minimized during the response to the original alarm condition.

Human factors principles must be applied to the design of alarms. These principles include appropriate selection of which physiological variables will have alarms, control of alarm limits, reliable detection of out-of-range events, intelligent decisions regarding which states will or will not produce alarms, provision of user-friendly output signals, appropriate application of new technologies (e.g., neural networks, fuzzy logic), and standardization across medical systems. Standardization may best be accomplished through an international multidisciplinary consensus approach such as that currently in used by the ISO/IEC Joint Working Group on Medical Device Alarms.

FALSE ALARMS

Although alarms can be useful in terms of improving recognition of critical situations, if improperly designed, they actually degrade performance. Intraoperative alarms can give misleading information as well as being distracting. Alarms may fail to provide adequate notice of a critical situation possibly due to intentional inactivation or inappropriate alarm limit adjustment. More commonly, alarms may be activated inappropriately which is called a “false alarm” and may be due to artifact or to an overly sensitive alarm limit.

False alarms continue to be a significant problem throughout the perioperative period. In one intraoperative study, at least 80% of 731 warnings occurring during cardiac surgery were of no clinical utility. In another study, 75% of all audio alarms were spurious and only 3% indicated an actual patient risk. In this pediatric study, it was noted that an alarm sounded every 4.5 minutes (with an average of 10 per case). A more recent study suggests that the implementation of integrated monitors has reduced the incidence of intraoperative false alarms. Block and Schaaf found that only 24% of auditory alarms were spurious while 23% represented a real patient risk. The majority of alarms (both true and false) occurred during induction and emergence and the end-tidal carbon dioxide monitor accounted for 42% of all alarms.

In the recovery room, individual patient’s pulse oximeters may sound more often than every 10 minutes with three quarters of these being false alarms. Apnea alarms were less frequent (about once every half-hour) but more likely to be meaningful (less than a third were false). The ECG alarmed even more infrequently yet a very high fraction of these were false.
Porciello’s survey of critical care unit physicians revealed that many found arrhythmia alarms to be inaccurate, misleading, and disturbing. O’Carroll showed that during a 3-week period in an ICU only 8 out of 1455 alarm soundings indicated potentially life-threatening problems. Forty-five percent of the false alarms were from ventilators while another 35% were from infusion pumps. Another study led the author to conclude that “over 94% of alarm soundings in a pediatric ICU may not be clinically important”.

The occurrence of a false alarm requires time and effort to verify the patient’s actual condition. This may distract attention away from other tasks or conditions. The false alarm may also lead to an inappropriate action which will take additional time and also potentially pose a risk to patient safety. Anesthesiologists routinely disable or ignore alarms which sound falsely or are annoying. Also many alarm tones are distracting or obnoxious and thereby elicit a negative affective (i.e., “make it stop!”) response. This is undesirable in an alarm because, not only will it augment stress but the subject’s primary response will be to disable the alarm as promptly as possible, perhaps without adequately investigating the meaning or significance of the alarm state. Some pilots believe that all but the most critical alarms should be silenced during high workload conditions.

ALARM NOTIFICATION MODALITY

No crucial alarm condition should be indicated via a single modality. Most experts believe that general information can be presented solely with a visual indication or message whereas warnings should be indicated by both audio and visual alarm modalities. It is best if both auditory tones and a visual indication occur simultaneously. In a complex environment with many different alarms, a proper mix of alarm notification modalities will prevent confusion and increase subject responsiveness. Consistent with their widespread use of auditory alarms in anesthesia equipment, studies have suggested that for critical information, auditory presentation leads to more rapid and reliable responses than does visual presentation. However, the auditory mode of alarm notification presents several problems. Alarm tones from different devices may sound similar, making identification of the source of the alarm difficult, or even stressful. Loeb and colleagues demonstrated that in the absence of other cues, clinicians could identify the source of alarm tones only 34% of the time. In this study, the authors recorded alarm tones and then played them back to 44 clinicians outside of the operating room. The recognition of the alarm was greater for alarms heard more frequently. There was no relationship between the complexity of the alarm tone and the ability to recognize its meaning.

Another problem with auditory alarms is that localization or recognition of specific alarm tones may require normal auditory acuity. Anesthesiologists with a hearing deficit may have difficulty determining the source of sounds in the operating room. Hearing acuity, especially above 1 kHz, decreases with age. Yet, 50% of all alarm tones in current use have much of their sound energy above
2 kHz. Thus, older clinicians may have additional difficulty identifying high frequency alarms. Higher pitched tones are also more difficult to localize.

The high noise levels in the operating room may mask or obscure some alarm tones. Using a Scott Instruments Type 450B sound meter (Maynard, MA), the peak noise level (dB_A) produced by a variety of common alarms was measured in several operating rooms at the University of California, San Diego Medical Center. Readings were obtained at a distance of one foot from the source, and the median maximum value from three successive readings was used. The sound levels of a number of common OR sounds are shown in Box 18-9. It can be seen that frequent alarm activation will contribute significantly to the high noise levels in the operating room previously reported by others.

Visual alarm lights can be coded by their color, brightness, size, location, and flashing frequency. Flashing lights are more noticeable and are traditionally used for more crucial information. Color codes have been standardized for instrument panels and alarm displays (Box 18-10). Red is used only for emergency or warning signals. Yellow indicates caution and green indicates “power on” or device activation. It must be recognized, however, that a sizable percentage of the population is color-blind and, thus, crucial alarm information must be coded simultaneously by other methods. In addition to lights, visual information can be presented as full or abbreviated text, icons, or other symbols. Coding of these visual messages should be consistent with the protocols used for simple display lights. Alarm tones and visual indications should be different for different levels of alarm priority. There are a number of applicable international standards for alarm enunciation.

Auditory tones can also be coded in several ways in addition to loudness, which is not effective because of its disruptive nature. The pattern, pitch, tone, and frequency of an alarm tone can be modified to provide distinguishing features (“which alarm is this”) and other contextual information. A good example of information coding of auditory signals can be found in the frequency modulation of pulse oximeters in which the pitch of the tone decreases as the patient’s oxygen saturation decreases. Some human factors experts have advocated more extensive use of similar “earcons”. An example of an immediately understandable alarm sound used in some advanced fighter cockpit designs to indicate “low on fuel” is the sucking noise made by the last bit of sink water going down the drain. More sophisticated types of coding of auditory alarm tones could include melody (as advocated by Block) or actual voice messages. Synthesized-voice warning messages may be particularly effective when used sparingly and only for crucial alarms. However, voice messages can be extremely disruptive if they are frequent, present information that is already known (“the car door is open”), or are spurious.

Human factors experts often emphasize the importance of consistency. In the case of auditory alarms, this would suggest that a particular alarm tone should have the same meaning regardless of where it is encountered in a given workspace. Generally, within a single clinical care environment like the operating room, no more than 10 (and preferably as few as 6) different tones should occur. Several
approaches to allocating alarm tones have been proposed\textsuperscript{243}. Traditionally, alarm tones have been “equipment-based” in the sense that each device has a different tone. However, in a truly “equipment-based” approach, all pulse oximeters would produce identical alarm tones independent of manufacturer. Similarly, ventilators, infusion pumps, monitors, etc. would all have their own unique tones. Alternatively, in a “priority based” strategy, taken by many modern integrated monitoring systems, all alarm conditions invoke one of only three tones (warning, caution, or notice). However, this approach makes it more difficult to identify the source and meaning of any given alarm.

Another approach would be based on patient risk: conditions producing a given magnitude of patient risk would produce a particular tone. The perceived patient risk could be combined with the urgency of required response. Here the problem is that patient risk and required response time can vary tremendously depending on individual patient factors and the overall clinical situation. Thus, in selected situations a “low risk-slow response” alarm tone may, in fact, represent a “high risk, rapid response” condition and the anesthesiologist could be lulled into complacency about the importance of the alarm. A fully integrated operating room alarm system should incorporate a combination of patient risk, required response time, and source (which type of equipment and what kind of physiological variable is generating the alarm) into a coherent prioritized system to optimize appropriate response. When a centralized alarm strategy is used, the system must provide as much information as possible about the source and cause of each alarm condition. The clinically most important alarm must be indicated first and other, less important alarms should be suppressed during the annunciation of the higher priority alarm. Such a system must be flexible enough to permit expansion with new technological and medical advances.

Based upon an alarm system for civil aviation in Great Britain, Patterson developed a novel series of general and context-specific alarm tones for use in the medical environment\textsuperscript{248}. Patterson’s alarm sounds consisted of well-defined, complex sequences of tones producing distinctive auditory rhythms or signatures. Each tone was composed of at least four harmonics to improve its melodic character. As described by Kerr\textsuperscript{243}, three “general” alarm sounds of increasing complexity (advisory, caution, and warning) were proposed. Six “specialized” alarm categories were also described (ventilation, oxygenation, cardiovascular, artificial perfusion, drug administration, and temperature), each with its own unique auditory signature. For each category, both a caution alarm and a warning alarm were specified. Urgency was indicated by playing the tone more quickly rather than more loudly.

The use of the Patterson alarm sounds in anesthesia remains controversial. The studies which led to the development of these sounds are more than 15 years old and may not be applicable to the OR setting, especially given recent advances in monitoring devices and technology. This approach requires individual devices to generate several complex tones, adding cost and complexity. More importantly, the operating room is a very different workspace than the cockpit of an airplane. In the cockpit, only the flight crew must listen and attend to alarms. In the OR, surgeons, nurses, and awake patients are a
captive audience who may find extraneous or excessive sounds disturbing. At a recent multidisciplinary conference, the surgeons present were adamant that they were readily distracted by the plethora of auditory alarms in the operating room [J. Hedley-White, personal communication, 1996]. There are no good data available to support the use of any particular system of alarm tones in the OR environment. Scientific studies must be performed to evaluate the impact of different alarm modes and tones on the anesthesiologist’s vigilance and on the performance of the whole OR team.

ALARM LIMITS

It is generally better to anticipate a critical condition than to respond to it. Thus, alarms would be most useful if they were activated before the deleterious condition became critical or serious. To prevent patient injury, when one sets the values (or limits) at which a particular alarm sounds, the following must be taken into account: the condition of the patient; the rate at which the variable is likely to change (deteriorate), the response time of the measurement system, the response time of the alarm system, and the response (or correction) time of the anesthesiologist. To ensure that alarms sound well before dangerous conditions occur without too frequently being spurious requires considerable “intelligence” on the part of both the system and the user. Some anesthesia monitoring devices have implemented “alert limits” a kind of pre-alarm alarm (Fig. 18-8). Systems that adjusted alarm thresholds based on each patient’s evolving condition could markedly reduce the stress and workload on the user as well as reduce the incidence of false alarms. A major area of interest for alarm designers is the development of automated intelligent alarm limit algorithms.

The criteria that determines whether or when a particular alarm sounds is called the “threshold value” or alarm limit. This limit can be set either by the equipment manufacturer or by the user. Except for a few alarm states such as “Wall Oxygen Disconnect” or “Oxygen Tank Pressure Low” whose limits are virtually fixed and rarely if ever need to be changed, other alarm conditions must be adjusted based on the particular clinical situation. The limits that are chosen will, in most situations, determine the incidence of false alarms. Thus, it is important to permit the user to easily alter alarm limits. However, if the user must frequently adjust the alarm limits to prevent false or spurious alarms, the alarm will undoubtedly be disabled. Allowing the user to adjust alarm limits to extreme values (e.g., FiO2 <15%) permits a de facto permanent disabling of the alarm and potentially could result in serious patient injury.

There are several ways to determine reasonable alarm limits for a particular variable. For example, for factory default limits, one could take a consensus of experienced users. Most clinicians would agree that a diastolic BP of over 110 or less than 40 is abnormal. Alternatively, device manufacturers might use previously collected knowledge about a particular physiological variable, perhaps based on statistical data from large numbers of similar patients. Either of these approaches would invariably result in alarm limits for some individual patients which are either too restrictive or
not restrictive enough. A more sophisticated approach would be to design the device so that it dynamically adjusts its alarm limits based on actual ongoing patient values. For example, the system could keep track patient blood pressure over the preceding 30 minutes and then set alarm limits at ±20% of the average of these preceding values. Research is currently underway on “smart” alarms which can relate several variables together, diagnose spurious alarm states, and provide additional information to the user.

CONTROL OF ALARMS

If properly designed, visual alarms do not impair critical display information. Therefore, it should never be necessary to disable them. The system must promptly recognize that the alarm condition has been corrected and immediately silence the associated alarm tone or indication. Nevertheless, it is often necessary to silence or disable auditory alarms. However, there must be a visual indication that an auditory alarm has been silenced. High priority alarm tones should only be able to be temporarily disabled for 45 seconds to 2 minutes.

It is essential that the user be able to test the alarm to assure that it will produce the expected sound at the appropriate time. Two kinds of tests should be available: a “power” test and a “limit” test. For the power test, either at “power up” or upon activation of a “test” switch, all modalities of the alarm should be activated. For the “limit” test, there should be a way for the user to adjust or modify the device and/or its alarms manually such that the ability of the alarm to trigger upon reaching the desired limit can be directly tested.

SMART ALARMS

There has been appreciable research in recent years on “smart” alarms. Theoretically, these microprocessor-based systems could provide interactive event recognition, reduce the incidence of false alarms, enhance vigilance, and aid in data manipulation. Unfortunately, thus far, commercially available alarms are not particularly intelligent. Part of the problem is that we do not understand very well the task of administering anesthesia: how do anesthesiologists make decisions and what information is important to those decisions. In addition, any given value of a monitored variable is “context-specific”. It is difficult for the system to know, for a particular patient and under specific conditions, whether an isolated value is normal or abnormal.

Thus far, investigators have employed two approaches in their attempts to develop smart alarms: rule-based expert systems and neural networks. Rule-based expert systems use elaborate “if-then” programs to set contingencies for alarm conditions or limits. Rule-based strategies work relatively well in straight-forward (and foreseeable) situations, such as those that involve the integration of several different devices with known effects on each others’ function. For example, a pulse oximetry monitor could be designed so that if a noninvasive blood pressure cuff is on the same
arm as the oximeter probe and the cuff inflates, then the SpO2 alarm would be disabled during the blood pressure reading. Pan et al. 252 described a rule-based intelligent monitoring system that incorporated the slope and minimum and maximum values of multiple monitored variables to make specific clinical diagnoses. The system was tested for its ability to diagnose problems of breathing circuit integrity and to assess adequacy of ventilation and oxygenation. The system correctly identified 91% of mechanical malfunctions within 30 seconds and 100% of adverse physiological conditions within 10 breaths.

In an alternative approach, Beinlich and Gaba 253 used a computerized representation of statistical likelihood (probabilistic) reasoning to aid the clinician in developing clinical diagnoses during critical events. Their prototype system related physiological variables with potential diseases or problems using objective conditional probability equations (the statistical likelihood that a given physiological state was caused by a particular event). In preliminary testing, their system made the correct diagnosis in only 71% of the test cases presented. Nevertheless, probabilistic techniques have gained favor in some computer-aided diagnostic decision aids 254.

A neural network is a “parallel” processor which consists of multiple nodes that are interconnected 255. A node is a site in which incoming data is processed and then the resultant outcome is presented to subsequent nodes via data flow pathways. The conditions at all adjacent nodes influence each others’ state. In this way, the information passes through the network in a wave whereby all relevant factors (including those that the programmer may not have been anticipated) impact on the result. The neural network is much more like the human brain than is a traditional serial computer and, as such, may be particularly good at tasks requiring pattern recognition or associative processing. Theoretically, abnormalities in the state of a complex system (such as the physiological state of the anesthetized patient) would be particularly amenable to detection by a neural network. The other advantages of a neural network approach are that it could provide information about the interrelationships between monitored variables and may be robust in diagnosing unanticipated or unusual alarm conditions. A neural network system designed to detect machine/circuit fault conditions was found to be highly effective and permitted a more rapid detection of underlying problems than did conventional alarms 250. Neural networks may also provide important specific diagnostic information during complicated critical events in fully integrated monitoring systems 250,256.

DESIGN OF ALARMS OF THE FUTURE

A number of factors must be considered in the design of new anesthesia alarm systems (Box 18-8). Most importantly, human factors principles must be applied. The physiological variables to be alarmed and the alarm limits chosen must be selected carefully. The clinical usefulness of alarms will be enhanced with reliable detection and identification of non-alarm states (“artifact management”). User friendly output signals, both auditory and visual, must be provided. Since the anesthesiologist can’t
always look up (e.g., during laryngoscopy), in the face of standardized alarm tones, alternative methods must be incorporated into centralized alarm systems to help the clinician identify rapidly which device is alarming.

Alarm prioritization remains important, especially in fully integrated systems. The alarm condition must correlate with the clinical level of urgency. Some organizations advocate industry-wide categorization of alarm priorities (e.g., high/medium/low) as well as standardization across medical devices. However, if standards are too restrictive, innovation or new technology may be impeded. For example, the requirements for alarm annunciation used in a personal (ear piece) audio system may be significantly different from those for general operating room broadcast. On-going deliberations of national and international standards organizations may be a good forum for attaining a consensus on some of these issues. In any case, new alarm designs must undergo rigorous clinical testing in real or accurately simulated conditions (in conjunction with other alarms and sounds that will be normally present).
INTEGRATED MONITORING SYSTEMS

HISTORY AND RATIONALE

In 1902, Harvey Cushing \textsuperscript{257} recommended that respiration and heart rate be monitored and recorded whenever anesthesia was administered. A few years later he introduced the measurement of blood pressure. It was soon recognized that the anesthetic techniques of the time were associated with labile hemodynamics. Since Cushing's time, more than two dozen clinical variables have been added to the anesthetic record. However, new variables have commonly been monitored more often because a new device or technique permitted their measurement than because a careful scientific study demonstrated that their use added significantly to patient safety. In fact, definitive studies, if done at all, usually succeeded the introduction of a new monitored physiological variable. Additionally, research in anesthesia ergonomics has not kept pace with advances in clinical anesthesia and monitoring technology. As a consequence, until the last few years, the \textit{status quo} in anesthesia monitoring was a non-integrated array of multiple monitors, often stacked on top of each other on the anesthesia machine. The location of a particular monitor was usually determined by its size and date of acquisition, with smaller or newer monitors stacked on top of older or larger ones. Each monitor had its own displays, sounds, alarm settings, cables, and methods of operation. The haphazard arrangement and complexity of sights and sounds frequently hindered the acquisition of information upon which decision-making depended. Setting up, calibrating, attaching to the patient, and monitoring these many devices required additional attention, thereby further decreasing the amount of time spent directly observing or interacting with the patient.

The recent introduction of integrated monitoring systems occurred as much for economic reasons as for the compelling ergonomics ones elucidated above. Frankly, it became significantly cheaper to produce (and thus to purchase) a single integrated monitor in which one microprocessor controlled multiple previously non-integrated physiological monitors. The resulting physical integration nonetheless addressed many of the short-comings of the older non-integrated approach. Unfortunately, the first generation of integrated OR monitors, which were hastily modified versions of intensive-care monitors, were heavy and bulky, and still wound up on top of the anesthesia machine. Second generation integrated systems (e.g., Space Labs PC2 or Hewlett Packard Merlin monitors) were more specifically designed for use in the operating room by anesthesiologists. With a few exceptions, these second generation systems, which are currently in the vast majority of operating rooms in the United States, remain physically distinct from the anesthesia machine itself. New third-generation systems facilitate integration of physiological monitoring with traditional anesthesia machine functions into a truly integrated anesthesia workstation [Fig 18-9].

Although there has been tremendous progress in the physical integration of anesthesia monitors, the integration of data displays from diverse clinical sources is just beginning in commercially
available anesthesia monitoring systems. Anesthesia equipment almost invariably now incorporates microprocessor-based intelligent systems, and this provides the ability to present large amounts of clinical information in new ways. However, as systems become more complicated and automated, they may become more susceptible to both machine error and human error. Little information exists on how monitored data are used by clinicians. The effects of the type of information, the display mode, and the relationships between them on monitoring performance are as yet unknown. A number of important avenues of research in this area are now under active investigation.

THE PROBLEM OF PHYSICAL INTEGRATION

The transition from the present, widely scattered, discrete devices to single integrated systems has been slow and painful for several reasons. There is still a large installed base of discrete devices, and the process of replacing them will require many years. The integration process itself entails many difficulties, which relate to physical, electronic, and software problems. Integration implies connection, and unless the same company makes all the components of a monitoring system, there will be incompatibilities — in cabling, in connectors, in signals, and in the software that manipulates the data and transmits them from one component of the anesthesia workstation to another. The problem of physical and electronic connections was illustrated vividly by reports of overheated pulse oximeter probes when the cable and probe from one manufacturer were connected to another's device. The software integration process involves hand-shaking, a technique that sounds easier than it is because most companies still have their own unique protocols. For example, one automated anesthetic record keeping system had to accommodate 75 different protocols to connect to all available major monitors. One full-time person in the company did little else but develop hand-shaking protocols. Integrated monitors have vastly simplified the process, especially when the same company or cooperating companies make the workstation, the monitors, and the record-keeping system. However, as technological advances lead to new monitoring devices, it can be anticipated that we will continue to find these devices stacked on top of our otherwise fully integrated anesthesia workstations. Thus, in the absence of comprehensive standards (such as those that allow all consumer stereo components to interface together relatively seemlessly), continued problems related to physical integration of discrete devices can be anticipated.

THE MEDICAL INFORMATION BUS

Bi-directional electronic data communication has been essential to enhancing labor effectiveness in manufacturing, commerce, banking, and other industries. The ability to interface medical devices with patient care computer systems has been hampered by the lack of an interface standard that meets the unique requirements of the acute patient care setting. A potential solution to many of these problems is
a series of international standards currently being developed which are collectively called the Medical Information Bus (MIB). Although all of the final standards have not yet been adopted or implemented, the MIB promises to be a boon for both manufacturers and users. It will, in essence, allow any two or more pieces of equipment that adhere to the standard to communicate with each other, more easily and at a more rapid rate.

The effort to establish the MIB standards began in 1982, when a group of hospitals recognized the problems of medical device interconnection. To meet this challenge, a committee was formed consisting of device vendors, computer system vendors, clinical engineers and clinicians. In 1984, the MIB Committee received a sanction from the Institute for Electronic and Electrical Engineers (IEEE) to work on a formal standard (IEEE 1073). The committee's mission was to develop an international standard for open systems communication in acute health care applications.

The MIB is a proposed international standard for bidirectional interconnection of medical devices and computing resources within a medical center or hospital. It specifies a local area network explicitly designed to provide connection-oriented communication services between medical devices or between medical devices and computers. The local area network that the MIB describes is distinguished from other types of data networks in that it is optimized for use in an acute patient care setting. The MIB design goals include: 1) to enable host computers to interface with medical devices in a hospital environment in a compatible, vendor-independent fashion; 2) to be highly accurate and reliable; 3) to accommodate the inevitable high frequency of network reconfiguration; 4) to provide a simple user interface including “plug and play” capabilities; and 5) to support a wide range of topologies.

Implementation of these objectives has been through a family of standards (termed layers) that define the overall architecture, electrical characteristics, network characteristics, and software language by which devices will communicate. Pre-existing international standards have been used as much as possible. Where new standards have been defined, the approach has been to facilitate future expansion of what is turning out to be a very complex system.

The pace of development of the MIB standards has, however, been frustratingly slow primarily due to national and corporate politics. A decade and a half after its inception, only two of the seven layers have been approved. In the meantime, manufacturers have filled the void with their own "standards," and the European Community is developing its own standards (CEN Technical Committee 251). For more up-to-date information on the progress of the IEEE initiative, as well as the corresponding European effort, refer to the MIB Web site at http://stdsbbs.ieee.org/groups/mib/index.html.

COMPUTERS IN INTEGRATED MONITORING SYSTEMS

A major advance in anesthesia equipment has been the incorporation of microprocessor-based “intelligent” systems. In particular, studies have shown that the precise control of ventilators
and measurement of many patient variables can best be performed with microprocessor-based systems. In the 1980’s, several institutions developed modular computer-based anesthesia delivery systems (e.g., the Boston Anesthesia System, the Arizona Program, and the Utah Anesthesia Workstation). These concepts are now being included in new commercial anesthesia workstations. An understanding of the ergonomic factors which affect anesthetic performance will enhance the ability to effectively implement automated anesthesia tasks such as drug administration and record keeping, the development of smart alarms, and novel ways of presenting clinical information. However, if integration and computerization is done poorly, without careful thought and the application of human factors design principles (see Chapter 17), their performance and the incidence of human error may, in fact, increase.

DATA MANAGEMENT IN INTEGRATED DISPLAYS

One of the major problems in anesthesia monitoring is the need to display a large amount of widely dispersed data in a way that the human mind can process efficiently. To pack a lot of information into a small space requires ingenious methods, and many integrated systems currently available do not incorporate appropriate methods to make “compressed” data easily understandable. Probably the first attempts to compress clinical information were applied to the EEG, and included the compressed spectral array (CSA), the density modulated spectral array (DSA), and aperiodic analysis. These techniques permit the compression of hundreds or thousands of pages of EEG data into just a few pages. More important, the information displayed is much more understandable than the original display. The Cerebrotrac, an early EEG monitor, was probably the first to use color in a strip-chart format on a monitor screen. The ability to scan down or across the display allowed the clinician to integrate information easily and, thereby, to assess cause and effect. An important principle learned from these early integrated displays was that the data must be packed or processed in a way that is intuitive; that is, in a way that corresponds to the “mental model” of the user about the source or etiology of the data presented. The compressed analog trend plots found in some modern physiological displays (see, for example, Fig 18-11) can be traced back to these early concepts.

Commercial anesthesia displays have traditionally used time as a variable (i.e., time-effect displays). In contrast, most cockpit displays in aircraft ignore time and simply present the continually changing data (while perhaps also providing an indication of the rate of change). Clinical display designers have only recently begun to explore time-independent display modalities. Siegel described a complex polygon-based system for displaying 11 variables in the intensive care unit. The polygon showed one node for each variable, and the distance of the node from the center of the polygon indicated that variable’s magnitude. The variables were arranged so that the shape of the polygon could assist the clinician in a quick interpretation of the state of the patient. The Ohmeda CD anesthesia machine incorporated a similar object display as one of three display options.
The Ohmeda polygon contains fewer variables than Siegel’s original implementation and, importantly, the Ohmeda CD polygon can be reset at any time to its normal, symmetrical shape. Deneault found that even without training, under simulated conditions, anesthesiologists detected some critical events as well with the polygon system as with a conventional strip-chart (time-based) format. It should be noted, however, that the Ohmeda CD’s polygon display was not designed to facilitate the use of shape changes to provide specific diagnostic information.

A more rigorous evaluation of the object displays presented on the Ohmeda CD was recently performed using a partial-task laboratory simulation. The effect of display format on the speed and accuracy of 13 anesthesia residents and 5 non-medical volunteers to detect changes in the values of the physiological variables was measured. Use of either the histogram or polygon display format by the anesthesia residents significantly improved detection time and accuracy compared with the numeric display. In contrast, display format did not significantly affect detection time or accuracy in the non-medical volunteers. The results of this study suggest that graphical displays may enhance the detection of acute changes in patient physiological status during the administration of anesthesia. More generally, object displays appear to improve detection and recognition of visual patterns thereby allowing the observer to determine more rapidly the system’s overall state. This research also demonstrates the importance of assessing clinical device performance by studying actual users rather than random subjects.

The results of these clinical studies are consistent with non-clinical display research. In laboratory studies, object displays were superior to bar graph (histogram) displays when the task involved the integration of several individual data values. In contrast, histogram-type displays may provide for faster responses when a change in a single variable must be detected. Object displays appear to be processed “holistically” whereby the perception of the whole takes priority over perception of individual parts. In process (system) control tasks, especially those involving system uncertainty, graphical displays appear to be superior to numeric displays. The relative disadvantage of numeric-type displays in these situations may be a consequence of slower serial processing of each individual display element. Thus, properly designed object displays may permit more rapid situational assessment and thus enhance performance under time stress, particularly when a unique display configuration has specific diagnostic and/or therapeutic implications. Recent studies support a role for object displays in clinical diagnosis of complex critical situations. For example, Blike’s work suggests that the use of emergent features (graphical features which act as a metaphor for the user’s mental model of the underlying system being represented) facilitate the pattern recognition task required to diagnose the etiology of shock.
DESIGN CONSIDERATIONS FOR INTEGRATED DISPLAYS

There is a large body of literature on methodologies that optimize complex visual displays. Moray enumerates several design priorities for complex display systems: for example, the number of displays and the time required to perceive information should be minimized. The time required to perceive information can be shortened by use of display integration, analog or graphic rather than digital visual displays, sound and color signatures, highlighting, and poignant visual or audible messages instead of vague, cryptic warnings. Some data suggest that analog displays of information may be easier for the mind to process than digital displays of the same information, especially in high workload situations. Novel methods of displaying critical information such as rate-of-change functions may also improve performance. Integrated displays may be most effective when the displayed variable represents a physiologically relevant interaction of the underlying inputs (e.g., the relationship between heart rate and ejection fraction). The ultimate integrated display may be the line-drawing face developed by Fukui whereby a few simple lines indicate the patient’s status in a format that incorporates everyday experience.

THE MODERN INTEGRATED OPERATING ROOM MONITOR

Until recently, these concepts were only sporadically applied to anesthesia monitors. However, modern anesthesia monitors now incorporate most if not all of the important physiological variables into a single integrated display. These monitors often include ST segment analysis, cardiac output calculations, both respiratory and cardiovascular parameters, real-time on-screen HELP, and even access to clinical information. Portable monitors are equally sophisticated. Monitoring equipment manufacturers have strived to design their clinical monitors to interface relatively smoothly with existing anesthesia machines. In addition, the software for many modern physiological monitors run on off-the-shelf computer hardware thereby facilitating integration and lowering cost. Finally, most modern OR monitoring systems are networked together, usually via a non-proprietary architecture. This not only allows centralized printing and data archiving but also facilitates communication with other hospital computers and with other facilities, possibly via the Internet.

Unfortunately, while a major improvement over previously available non-integrated monitors, many current devices still have significant shortcomings from an ergonomics standpoint. For example, displays may be crowded and difficult to read, especially during high workload situations. In the most common menu-driven schemes, crucial waveform and other clinical data may disappear when the user is performing other, secondary tasks, such as cardiac output measurements.
At a higher level of integration, all of the major anesthesia machine manufacturers have now either introduced or will soon introduce state-of-the-art integrated anesthesia workstations which include not only gas and drug delivery systems (and monitoring of these systems) but also fully integrated comprehensive clinical monitoring systems (Figs. 18-20, 18-21). This next generation of anesthesia workstations appear to have paid more attention to the human-device interface issues. The importance of incorporating human factors into monitors, anesthesia workstations, and other medical devices has been recognized by the federal government. FDA regulations effective June 1997 now require all manufacturers to incorporate human factors into the design and development of all medical devices. Chapter 17 contains a more complete discussion of the human factors issues in medical equipment design.

Further Issues in Complex Integrated Systems

One advantage of fully computerized systems is that each piece of data can be presented in the context appropriate to the system’s current state and the operator’s immediate needs. However, when microprocessor-controlled system is used, hundreds or thousands of different displays (or menus) are potentially possible and a hierarchical organization may be inadequate to provide guidance to the operator attempting to navigate through the display system. Unfortunately, design guidelines for the relationships between multiple interrelated computerized displays are generally lacking.

With the introduction of integrated displays, the critical design pitfalls partially shift to the relationships and interactions between displays. Design errors at this level can lead to new kinds of problems, including having to navigate through too many useless or inefficient displays, getting lost in the display network, tunnel vision or “keyhole“ effects (restricting oneself to a small subset of displays), and mental overload related to management of the data presented. Woods et al.’s statement regarding displays in nuclear power plant control rooms applies equally well to the anesthesia domain: “Given that one of the problems in existing control centers is data overload in rapidly changing circumstances, the shift to more computer-based systems can exacerbate this problem as well as mitigate it”. Perhaps paradoxically, the use of rapid prototyping by designers can lead to a proliferation of display screens (“since we can do it, why not include it?”) without adequate consideration of the navigational requirements between displays. Another problem with rapid prototyping is that the same design mistake can be promulgated on a larger scale.

The amount of potentially displayable data is always much larger than the amount of physically available screen space. In complex integrated display systems, the user will have difficulty maintaining a broad overview of system status, especially when required to navigate frequently through multiple displays. One commercially available operating room monitor has over 150 different menu display
screens. It is, therefore, important to provide “overview displays” which rapidly present crucial aspects of system status.

The ultimate goal of the integrated clinical monitors of the future will be to present only the data the anesthesiologist actually requires at precisely the time they are required. Information overload must be minimized. Clinical decision-making will be enhanced if the relationship between individual physiological variables is readily apparent. Thus, to accomplish these goals, future displays will employ a variety of techniques including display integration, graphical rather than digital display, sound and color signatures, animation, highlighting, and poignant visual or audible messages. Novel methods of displaying critical information including rate-of-change functions may also be employed. A promising approach, validated in the military setting, is the use of sophisticated object displays containing animated iconic representations which mirror the anesthesiologist’s mental model of human physiological processes (Fig. 18-22).

CONCLUSIONS

This chapter has discussed ways in which the interface between the anesthesiologist and the anesthesia equipment can play a crucial role in influencing the outcome of the anesthetic administered. The administration of anesthesia incorporates a complex monitoring task and, as such, requires vigilance. Human error has been claimed to be a major cause of most anesthetic mishaps. However, poorly designed equipment certainly contributes to the occurrence of error in anesthesia practice. Human performance is often less than optimal, and is particularly susceptible to degradation by a variety of human, environmental, equipment, and system factors. Therefore, designers of anesthetic equipment must assist the anesthesiologist by incorporating devices and technologies to augment vigilance and monitoring performance. Alarms, intended to notify the operator of potential critical situations, are effective only if properly designed and implemented. The completely integrated anesthesia workstation containing “smart” alarms and other types of automated decision aids is on the horizon. Their successful implementation will require a more complete understanding of the task of administering anesthesia and of the factors that affect performance of the anesthesiologist in this complex task environment.
ACKNOWLEDGMENTS

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## TABLES

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</tr>
<tr>
<td>Description Error</td>
</tr>
<tr>
<td>Capture Error</td>
</tr>
<tr>
<td>Faulty Activation or Triggering</td>
</tr>
<tr>
<td>Data Driven Error</td>
</tr>
<tr>
<td>Fixation Errors</td>
</tr>
<tr>
<td>Confirmation Bias ‡</td>
</tr>
<tr>
<td>Representational Errors</td>
</tr>
</tbody>
</table>

‡ Note errors may also occur due to a variety of other types of cognitive bias such as availability, representativeness, similarity, framing, anchoring, etc. (see, for example, 24,25,294).

* After Norman 32 and others
## Box 18-2. Some Typical Causes of Human Error in Anesthesia

<table>
<thead>
<tr>
<th>Cause of Error</th>
<th>Representative Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HUMAN FACTORS</strong></td>
<td></td>
</tr>
<tr>
<td>Task Complexity</td>
<td>Not ventilating when coming off cardiopulmonary bypass</td>
</tr>
<tr>
<td>Lack of Training or Experience</td>
<td>Rapid administration of vancomycin or protamine</td>
</tr>
<tr>
<td>Stress</td>
<td>Drug syringe or ampule swap during critical situation</td>
</tr>
<tr>
<td>Ill Health</td>
<td>Under the influence of opiates or other substances</td>
</tr>
<tr>
<td><strong>ENVIRONMENTAL FACTORS</strong></td>
<td></td>
</tr>
<tr>
<td>Noise/Miscommunication</td>
<td>Misheard surgeon, gave wrong antibiotic</td>
</tr>
<tr>
<td>Workplace constraints</td>
<td>Circuit disconnect due to moving equipment or personnel</td>
</tr>
<tr>
<td><strong>EQUIPMENT &amp; SYSTEM FACTORS</strong></td>
<td></td>
</tr>
<tr>
<td>Poor Equipment Design</td>
<td>Light bulb goes out on laryngoscope while trying to use it</td>
</tr>
<tr>
<td>False and/or Noisy Alarms</td>
<td>Failure to recognize critical situation after disabling alarms</td>
</tr>
<tr>
<td>Mismatch of Man-Machine Functions</td>
<td>Failure to detect ongoing event while manually recording</td>
</tr>
<tr>
<td></td>
<td>vital signs onto record</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Perception</td>
<td>To attain awareness or understanding, usually via the senses.</td>
</tr>
<tr>
<td>Attention</td>
<td>A conscious effort to remain alert, and to perceive and select information.</td>
</tr>
<tr>
<td>Vigilance</td>
<td>A state of readiness to detect and respond to changes in the monitored environment, a state of “sustained attention”.</td>
</tr>
<tr>
<td>Monitoring</td>
<td>A vigilance task involving the observation of one or several data streams in order to detect specified changes, often occurring at random intervals.</td>
</tr>
<tr>
<td>Anesthesia vigilance</td>
<td>A state of clinical awareness whereby dangerous conditions are anticipated or recognized.</td>
</tr>
<tr>
<td>Judgment</td>
<td>The formation of an opinion or evaluation, based on available information.</td>
</tr>
<tr>
<td>Cognition</td>
<td>The act or process of knowing, including both awareness and judgment.</td>
</tr>
<tr>
<td>Decision making</td>
<td>The act of choosing between alternative diagnoses or possible actions, based upon judgments.</td>
</tr>
<tr>
<td>Situation awareness</td>
<td>A coherent mental model (or picture) of the current state of a complex dynamic system including an understanding of prior conditions and the implications of on-going processes to future states.</td>
</tr>
</tbody>
</table>

(After Swain and Weston 295, Weinger and Englund 21, Mackworth 35, and others)
Box 18-4

Factors Affecting Vigilance and Performance

1. Environmental Factors
   a. Noise
   b. Temperature and Humidity
   c. Environmental Toxicity
   d. Ambient Lighting
   e. Workspace Constraints

2. Human Factors
   a. Human Error and Cognitive Biases
   b. Fatigue
   c. Sleep Deprivation
   d. Circadian Effects and Shift work
   e. Breaks
   f. Boredom
   g. Substance Use/Abuse
   h. State of Health and Stress
   i. Training and Experience
   j. Psychosocial Factors
   k. Personality Factors

3. Task/Information Factors
   a. Primary Task Load
   b. Secondary Task Intrusion
   c. Misinformation or Distracting Information
   d. Alarms and Warnings
   e. Interpersonal/Team Communication

4. System/Equipment Factors
   a. System-Induced Errors (e.g., latent errors)
   b. Equipment Failure
   c. Equipment-Induced Errors
   d. Faulty Mental Models of Equipment Design/Function
   e. Clumsy Automation

After Weinger and Englund 21
Box 18-5

**Some Potential Effects of Sleep Deprivation on Vigilance and Performance**

1. Decreases in reaction time
2. Increases in response variability
3. Decreases in work rate
4. Difficulties making choices
5. Increases in omission errors
6. Impaired working memory
7. Failure to appropriately allocate attention
8. Difficulty setting task priorities
9. Failure to evaluate potential faulty information

Box 18-6

**Some Potential Problems with Night and Shift Work**

1. Circadian-related fluctuations in performance
2. Some individuals are never able to adjust
3. Difficulty establishing a normal diurnal rhythm
4. Sleep deprivation
5. Exacerbation of other performance shaping factors
6. Health problems
7. Social and Interpersonal problems
8. Increased incidence of on the job errors and accidents
Box 18-7

**Recommended Standard Relief Protocol** *

1. The relieving anesthesiologists must establish familiarity with:
   a. the patient’s preoperative status
   b. the course of the anesthetic
   c. the course of the surgical procedure
   d. the overall anesthetic plan
   e. the arrangement of the equipment, apparatus, drugs, and fluids
2. The two anesthesiologists must communicate the relief plans with the surgeon(s).
3. The original anesthesiologist must not leave the room until the relieving anesthesiologist is in control of the situation and has all of the necessary information to continue with the anesthetic
4. The original anesthesiologist should not leave the room if the patient is unstable or the anesthetic is not likely to remain in a steady-state condition for at least 5-10 minutes.
5. Care must be taken to communicate all special information which is not recorded or may not be readily evident.
6. Under normal circumstances, the relieving anesthesiologists should not appreciably alter the course of preexisting anesthetic management.
7. Before resuming control, the original anesthesiologist should carefully go through these same steps with the relieving anesthesiologist.
8. If the relieving anesthesiologist is to finish the case, special care should be taken to explain the anesthetic plan.

* (After Cooper et al. 140)
Box 18-8

**Some Principles of Good Alarm Design**

1. Human factors principles must be applied (see Chapter 17).
2. The physiological variables to be followed and the alarm limits (with appropriate user control) must be carefully selected.
3. There must be reliable detection and device intelligence regarding non-alarm states (good “artifact management”).
4. Alarms must be prioritized (consider industry-wide standards).
5. Alarm states must correlate with clinical urgency.
6. The use of different alarm modalities (e.g. audio, visual) and their integration must be considered.
7. The user must be able to, at least temporarily, silence alarms.
8. Output signals must be user-friendly and not produce a negative affective response (“turn it off!”).
9. Designers must consider, on a case-by-case basis, the clinical usefulness of incorporating clinically-relevant data into alarms.
10. Alarms should be standardized across all medical devices likely to be used in the same clinical environment.
Box 18-9. Some Common Alarm and Other Sounds in the Operating Room *

<table>
<thead>
<tr>
<th>Sound</th>
<th>dBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet ventilator</td>
<td>120</td>
</tr>
<tr>
<td><em>Hewlett-Packard Merlin monitor</em> (all alarms; at highest setting)</td>
<td>91</td>
</tr>
<tr>
<td>Fisher Pakel humidifier (temperature probe not plugged in)</td>
<td>86</td>
</tr>
<tr>
<td>Aspen Labs ATS tourniquet (disconnect)</td>
<td>84</td>
</tr>
<tr>
<td><em>Narkomed 2 anesthesia machine</em> (loss of oxygen supply)</td>
<td>84</td>
</tr>
<tr>
<td>Narkomed 2 anesthesia machine (circuit disconnect)</td>
<td>78</td>
</tr>
<tr>
<td>IVAC 560 infusion pump (bottle clamp)</td>
<td>77</td>
</tr>
<tr>
<td>Surgical instruments against each other in sterile basin</td>
<td>75</td>
</tr>
<tr>
<td><em>Hewlett-Packard Merlin monitor</em> (all alarms; at “standard” setting)</td>
<td>74</td>
</tr>
<tr>
<td>Aspen Labs Electrocautery Unit (return fault)</td>
<td>74</td>
</tr>
<tr>
<td>Intercom</td>
<td>72</td>
</tr>
<tr>
<td>Tonsil tip suction</td>
<td>70</td>
</tr>
<tr>
<td>Nellcor pulse oximeter (maximum volume)</td>
<td>66</td>
</tr>
<tr>
<td>Surgeon’s conversation (at patient’s ear)</td>
<td>66</td>
</tr>
<tr>
<td>“Background” music at patient’s ear</td>
<td>65</td>
</tr>
</tbody>
</table>

* See text for details

Box 18-10. Example of Alarm Hierarchy

<table>
<thead>
<tr>
<th>Alarm Priority</th>
<th>Meaning</th>
<th>Desired Response From Operator</th>
<th>Visual Indication</th>
<th>Auditory Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH PRIORITY</td>
<td>Emergency, Warning</td>
<td>Immediate</td>
<td>Flashing</td>
<td>Complex tone,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RED</td>
<td>continually</td>
<td>at fast pace</td>
</tr>
<tr>
<td>MEDIUM PRIORITY</td>
<td>Caution</td>
<td>Prompt</td>
<td>FlashingLess</td>
<td>complex tone,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>YELLOW</td>
<td>less frequently</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alert</td>
<td>Increased</td>
<td>Continuous</td>
<td>None or simple tone,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vigilance</td>
<td>YELLOW</td>
<td>infrequently repeated</td>
</tr>
<tr>
<td>LOW PRIORITY</td>
<td>Notice</td>
<td>Information, Confidence</td>
<td>Awareness,</td>
<td>GREEN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Confidence</td>
<td></td>
<td>None</td>
</tr>
</tbody>
</table>
FIGURE LEGENDS

Fig. 18-1
There is a curvilinear relationship between task performance and task duration whereby increasing task duration results in impaired performance. This curve is shifted to the left as the complexity of the task increases.

Fig. 18-2
The mean response time (ordinate, seconds) to a vigilance light is plotted against case segment (abscissa, induction and maintenance). Response latency during induction was significantly delayed compared with the maintenance period (p<0.001). In addition, novices were significantly slower in their response (p<0.02) than were experienced practitioners both during induction and over the whole case. Reprinted from 53.

Fig. 18-3
This figure depicts the mean performance of 40 volunteers on a hand-eye coordination task (Left-side Y-axis; expressed as a ratio of baseline performance) while remaining awake continuously for over 24 hours beginning at 8:00 am (X-axis; in hours). In addition, the magnitude of performance impairment on the same test in the same subjects was tested, on a different day, after consumption of cumulative doses of alcohol at 30 minute intervals until a blood alcohol concentration (BAC) of 0.10% was obtained (Right-side Y-axis; in %). The magnitude of cognitive psychomotor impairment after remaining awake for 24 hours was roughly equivalent to that produced by acute inebriation with a BAC of 0.10% (at or above the legal limit for operation of a motor vehicle) 100.

Fig. 18-4
The heart rate of anesthesiologists increases above baseline during the induction of anesthesia. This increase in anesthesiologist heart rate, a physiological correlate of stress and workload, is greatest in first-year anesthesia residents and diminishes with increasing experience 171.

Fig. 18-5
As in aviation, in medicine there appears to be a strong correlation between experience and clinical performance. See and colleagues studied urological surgeons and demonstrated a significant inverse correlation between the number of laparoscopic procedures (X-axis) performed within 12 months of formal training in this surgical technique and the reported rate of complications (Y-axis) 208.
Fig. 18-6
For most complex tasks including anesthesia, there appears to be a curvilinear relationship between task performance and workload. Performance begins to deteriorate as workload increases. There may also be a less apparent performance decrement at low workload levels, presumably due to boredom or inattention. Increasing skill on the task will shift the performance-workload curve upward and to the right while increased stress will have opposing effects.

Fig. 18-7
Intraoperative vigilance, as measured by the response latency to an alarm light positioned within the anesthesia monitoring array, was decreased during use of the transesophageal echocardiography (TEE) device when compared with the performance of other anesthesia tasks. The minimum and maximum values in each group is shown by the upper and lower bars while the rectangle contains 50% of all of the data and the dark line depicts the median value in that group. The response latency (in seconds) was significantly slower when observing or adjusting the TEE when compared with record keeping, observing monitors, or adjusting IV’s (*; P<0.05). Subjects detected the vigilance light more quickly when observing the monitoring array (†; P<0.05 compared with all three other tasks). Modified from 54.

Fig. 18-8
The use of “alert” limits (dashed lines) may provide a more sensitive threshold for detecting adverse trends in patient vital signs thus allowing intervention prior to the attainment of a full “alarm” condition. Such alert zones would be particularly useful if they were modified based on the individual patient’s actual on-going physiological responses to surgery and anesthesia. Photo courtesy of Ohmeda.

Fig. 18-9
The Datex AS/3 is an example of a state-of-the-art fully integrated anesthesia workstation which seemlessly incorporates a traditional anesthesia machine (including gas delivery systems, volatile anesthetic delivery systems, and mechanical ventilators) and comprehensive physiological monitoring. Note the use of two data displays; the one on the left primarily provides information on gas delivery parameters and anesthesia machine function while the one on the right displays more traditional physiological cardiovascular and respiratory data.
Fig. 18-10

The Medical Information Bus (MIB) is an evolving international standard for hardware and software communication protocols for bi-directional interconnection of medical devices. Not only monitors, but computers, record keepers, laboratory equipment, and other devices could easily communicate with each other using the MIB protocol.

Fig. 18-11

This figure demonstrates an advanced physiological display developed by Westenskow and colleagues at the University of Utah. The display is organized into functional windows representing different aspects of the “system” (i.e., the anesthetized patient) and includes (clockwise from the upper left corner) ventilator function, cardiovascular performance, anesthetic agent concentrations, muscle relaxation, temperature, fluid balance, blood pressure, oxygen saturation, and ventilation. Advanced display attributes include compressed analog trend plots, alert limits, integrated object display elements in which shape provides additional information (e.g., the product of stroke volume and heart rate is cardiac output), and drug time/concentration plots. Reproduced with minor modification with permission of Dwayne Westenskow.

Fig. 18-12

The polygon display on the Ohmeda Modulus™ CD anesthesia machine is an example of an integrated configural display which graphically relates a number of key physiological variables. Deformation of the hexagon rapidly indicates a deviation from the predefined “normal” physiological state of the patient. These kinds of displays may be useful for the detection of acute changes in physiological variables. The use of object displays as an aid to the recognition of evolving clinical conditions in anesthesia is a subject of on-going research. Photo courtesy of Ohmeda.

Fig. 18-13

Like many modern integrated physiological monitors, the DINAMAP MPS employs a modular plug-and-play architecture and permits simultaneous display of multiple physiological waveforms and their corresponding digital values. Photo courtesy of Johnson & Johnson Medical, Inc.

Fig. 18-14

The Marquette Solar 9500 is a new integrated physiological monitor that incorporates a full spectrum of cardiovascular and respiratory variables and performs secondary computer processing to display valuable additional clinical information such as ST segment analysis (18-14a) and
cardiac output calculations (18-14b). Data are presented in multicolor displays in both analog and digital display formats.

Fig. 18-15
Most integrated monitors provide real-time on-screen HELP. In this example from a monitoring system by Marquette, HELP is provided for a problem with pacemaker rhythm detection.

Fig. 18-16
Many modern OR monitors incorporate off-the-shelf commercial software and hardware. The use of a commercial computer operating system such as Windows NT or UNIX facilitates the addition of valuable features by other developers. For example, the Space Labs PC2 system can run optional software modules which provide the clinician with valuable clinical information and other reference materials.

Fig. 18-17
Sophisticated multiparameter monitors are now available throughout the hospital. In fact, portable monitors such as the Datascope Passport XG are capable of providing high level display and processing functionality in a relatively lightweight and compact package.

Fig. 18-18
Electronic anesthesia recordkeeping devices, such as this one by Criticare, may increasingly incorporate traditional physiological displays including digital values, analog waveforms, and trend plots.

Fig. 18-19
The collaboration between different manufacturers such as those making monitors and those making anesthesia machines has resulted in unprecedented interconnectivity to produce well-integrated anesthesia workstations. Pictured here is the Hewlett-Packard Merlin™ system integrated into an Ohmeda EXCEL anesthesia machine. Many manufacturers now recognize the potential value of the “open architecture” approach. Photo courtesy of Ohmeda.

Fig. 18-20
This Drager anesthesia workstation takes advantage of modern technological innovations to fully integrate traditional anesthesia machine functions with physiological monitoring and electronic recordkeeping.
Fig. 18-21  
The Siemens KION anesthesia workstation incorporates a number of ergonomic innovations in its fully integrated design. Unique features include physical and functional modularity, a revolving arm/turntable (for optimal positioning), a rotating vaporizer magazine, and a physiological monitor display which can be easily removed and used as a transport monitor.

Fig. 18-22  
The integrated anesthesia workstation displays of the future will take advantage of powerful microprocessors and improved understanding of the human physiological response to anesthesia to present clinical data in a more intuitive and relevant manner. In this depiction, display integration, clinically relevant object displays, color signatures, and highlighting are employed to yield iconic representations which mirror the anesthesiologist’s mental model of human physiological processes. Note the logical positioning of redundant information. Animation could be used (e.g., a beating heart) to provide increased information content which would obviate the need for waveform displays. Trending of data (not shown) could also be readily incorporated into the display. Reproduced with permission of Dr. Weinger.
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