

## Intelligent Alarms Reduce Anesthesiologist's Response Time to Critical Faults

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The proliferation of monitors and alarms in the operating room may lead to increased confusion and misdiagnosis unless the information provided is better organized. Intelligent alarm systems are being developed to organize these alarms, on the assumption that they will shorten the time anesthesiologists need to detect and correct faults. This study compared the human response time (the time between the sounding of an alarm and the resolution of a fault) when anesthesiologists used a conventional alarm system and when they used an intelligent alarm system. In a simulated operating room environment, we asked 20 anesthesiologists to resolve seven breathing circuit faults as quickly as possible. Human response time was 62% faster, decreasing from 45 to 17 s, when the intelligent alarm system was used. The standard deviations in response time were only half as large for the intelligent alarm system. It appears that the computer-based neural network in the intelligent alarm system diagnosed faults more rapidly and consistently than did the anesthesiologists. This study indicates that breathing circuit faults may be more rapidly corrected when the anesthesiologist is guided by intelligent alarms. (Key words: Alarms: critical events, response time. Anesthesia safety. Computers: artificial intelligence. Monitoring.)

ALARM SYSTEMS ENHANCE safety by warning of impending danger.<sup>1,2</sup> Present threshold alarm systems are, however, very nonspecific and a considerable amount of time is required to diagnose some problems.<sup>#,13</sup> For example, the low airway pressure alarm can be caused by any one of 12 events, including disconnection, internal machine obstruction, ventilator failure, and tracheal extubation.<sup>4</sup> Once the alarm has sounded, steps taken to

diagnose the cause of failure may include any or all of the following: switching to manual ventilation, instigating an oxygen flush, observing the reservoir bag filling, and adjusting fresh gas flow. These tasks can be time-consuming.

Intelligent alarm systems generally use artificial intelligence to provide automatic diagnosis of faults.<sup>\*\*††‡‡§§5-9</sup> These computer systems collect data from sensors in the patient breathing circuit and use artificial intelligence (rule-based and/or neural network) to review the data and to automatically diagnose the problem. The applied assumption is that automatic diagnosis will shorten the time between the occurrence of a fault and the correction of the fault.

This study measured human response time (the time between the sounding of an alarm and the resolution of the fault) when using a conventional anesthesia alarm system and when using an intelligent alarm system. We also measured alarm activation time (the time from the occurrence of a fault to the announcement of that fault by the alarm sound) to compare the speed of the two alarm systems in identifying critical events. Our null hypothesis was that there is no difference in human response time and fault detection time for conventional *versus* intelligent alarm systems.

### Methods

We asked ten faculty and ten resident anesthesiologists from the Department of Anesthesiology, University of Utah, to work in a simulated operating room environment. Five residents were in their third year of training, two were in their second, and three were in their first. Each subject sat between the simulated patient and the anesthesia machine, with his or her back to the simulated patient (fig. 1), and answered ASA self-exam questions expecting the exam to be scored and rated. We told each subject that several breathing circuit faults would be cre-

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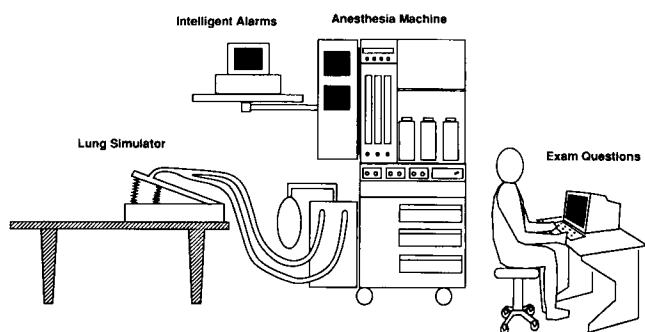


FIG. 1. Simulator environment.

ated without their knowing about them. When an alarm sound was heard, the anesthesiologist was asked to turn and give full attention to resolving the critical event. Half the anesthesiologists used the conventional monitors. The other half used the information shown on the intelligent alarm computer screen. For this second group, the conventional monitors and alarms were disabled.

A test lung (Vent-Aid TTL, Michigan Instruments, Grand Rapids, MI), placed at the head of a gurney, simulated the patient. The test lung compliance was set at 0.05 L/mmHg. Airway resistance was created with a series resistor (Rp 7.7, Michigan Instruments), in the central airway, and two (Rp 5.6) resistors, one in each bronchi. Carbon dioxide was delivered to the test lung to simulate a normal  $\dot{V}CO_2$  of 250 ml/min. A 15-cm-long silicone tube (15 mm ID) was connected to the test lung and intubated with a 7.5-mm ID cuffed endotracheal tube (Malkrodt, St. Louis, MO). The lung was ventilated with a 6 L/min minute volume at a rate of 10 b/min with an I:E ratio of 1:2, and a fresh gas flow of 7 L/min. A sampling adapter for the CO<sub>2</sub> analyzer was placed between the endotracheal tube and the breathing circuit of an Ohmeda Modulus II anesthesia system (fig. 2).

Critical events were created in random order using computer-controlled pneumatic actuators developed by the Technical University in Lübeck, Germany (Fach-

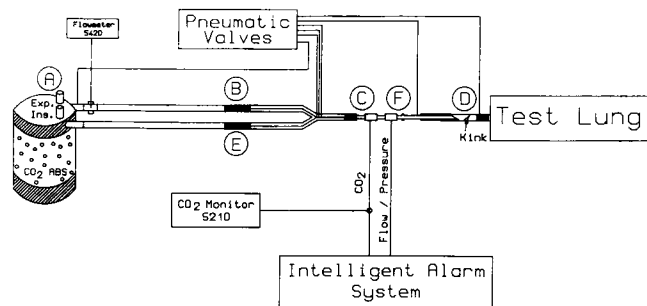


FIG. 2. Block diagram of the anesthesia breathing circuit and lung simulator, showing the location of the six fault actuators.

hochschule-Lubeck; fig. 3). Actuator lettered "A" lifted the expiratory valve leaf to create an expiratory valve failure. "B" pushed one end of the expiratory breathing hose off its connector, causing an expiratory hose disconnection. "C" either pushed the CO<sub>2</sub> sampling adapter partially off the connector, causing an airway leak, or all the way off, causing an airway disconnection. "D" twisted the intubated silicone tubing, simulating airway obstruction. "E" partially separated the junction between two sections of the inspiratory hose, causing a hose leak. "F" opened the check valve on the endotracheal tube cuff, causing a cuff leak. The actuators and the pneumatic tubing were hidden within the breathing hoses. The pneumatic tubing lines connected each actuator to a central control unit where computer-activated solenoid valves triggered each event.

A computer operator observed the simulation environment and initiated each event. He waited at least 2 min between events to be certain that the simulation was in steady state. Each critical event was randomly selected and a timer started when the solenoid valve was activated. The operator recorded the time when the alarm system auditory signal sounded and the time when the critical event was found (correct verbal description of the problem), or when 2 min had elapsed from the sounding of the alarm. If the anesthesiologist compensated for the fault (e.g., by increasing fresh gas flow to override a leak), he or she was still asked to attempt to identify the cause of the fault.

Using a restricted randomized assignment table, ten anesthesiologists (five faculty, five residents) used the intelligent alarm system and another ten used the Ohmeda Modulus II monitors and alarm system (Ohmeda, Madi-

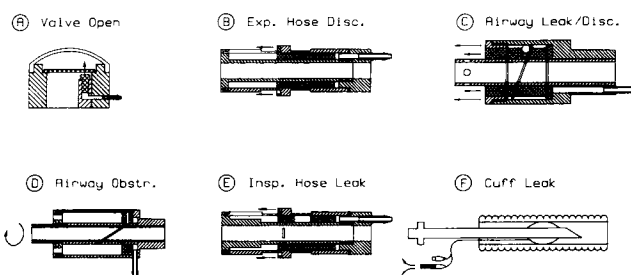


FIG. 3. Pneumatically driven actuators used to generate breathing circuit faults. The piston in Device A moves upward to hold the valve leaf open. Device B forces the expiratory hose off the connector to create a disconnect. Device C forces the CO<sub>2</sub> sampling adapter off the connector, creating a disconnect or forces it partially off to create a leak through an orifice. Device D rotates the silicone tubing, causing a kink in the simulated trachea. Device E forces the inspiratory hose partially off the connector, opening an orifice to create a leak. The opening or exposed section of the device is painted black to camouflage the leak. Device F forces a piston into the check valve of the endotracheal tube cuff filling device, thereby emptying the cuff, causing a cuff leak.

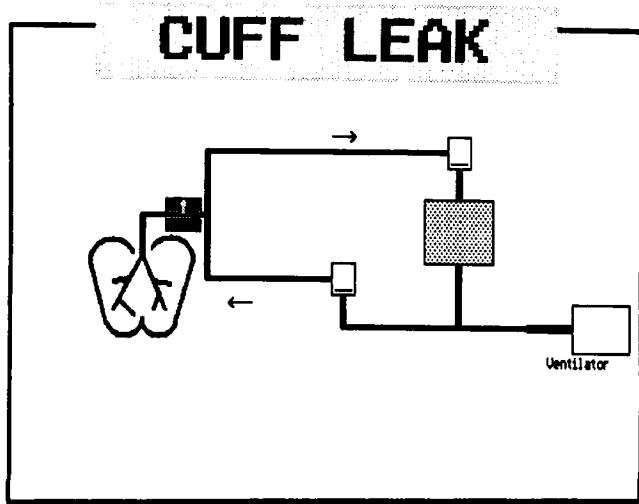


FIG. 4. Intelligent alarm system display. The failed component in the breathing circuit is animated in the block diagram display, using inverse video to change its color from white to red once per second.

son, WI). The conventional alarm system included the Ohmeda 5210 CO<sub>2</sub> analyzer with its default alarm thresholds at 3.0 and 6.5 vol% CO<sub>2</sub>, the 5420 expiratory flowmeter with the low minute volume alarm threshold set at 4.0 L/min, and the 7000 ventilator with its internal low and high airway pressure alarms.

The intelligent alarm system used data from a variable orifice flowmeter (Carlsbad International, Carlsbad, CA), an inline CO<sub>2</sub> analyzer (model 1260, Novametrix Medical Systems, Wallingford, CT), and a solid state airway pressure sensor (Model SCX05, Sensym, Sunnyvale, CA; fig. 2). This prototype system used neural network-based artificial intelligence to process the CO<sub>2</sub> and flow and pressure signals to detect and identify critical events.<sup>§§10</sup> When an event was detected, a breathing circuit diagram was drawn on the computer video display and the failed component was animated and highlighted in red (fig. 4). A sound was generated and one of the text messages in table 1 was displayed. The CO<sub>2</sub> monitor and flowmeter displays were hidden when the intelligent alarm system was used. The time between the creation of the event and the alarm sound (alarm activation time) and the time between the alarm sound and the event recognition (human response time) were tabulated. Statistical significance was measured by multivariate analysis of variance, using Hotelling *t* square tests with significance at  $P < .05$  (BMDP software).

### Results

Figure 5 shows the alarm activation time, the time between the creation of a fault and the sounding of the

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TABLE 1. Messages Displayed by the Intelligent Alarm System

Cuff leak
Airway obstruction
Expiratory valve stuck open
Inspiratory hose leak
Expiratory hose disconnection
Airway disconnection
Airway leak

alarm. Activation time averaged  $21 \pm 19$  s (mean  $\pm$  SD) for the conventional alarm system and  $25 \pm 9$  s for the intelligent alarm system. The intelligent alarm system detected "airway leak" ( $P = .046$ ) and "cuff leak" ( $P = .0003$ ) sooner than the conventional alarm system. The conventional system detected "airway disconnect" ( $P = .0001$ ), "expiratory hose disconnect" ( $P = .0001$ ), and "expiratory valve open" ( $P = .0001$ ) sooner than did the intelligent alarm system. Variability in activation time occurred because events were created randomly and were out of phase with the ventilator cycle.

The "expiratory valve open" was the event that the conventional alarm system detected most rapidly. It was announced by a "reverse flow" message, usually within one breath. The conventional system responded to "cuff leak," "airway leak," and "airway obstruction" with a "low minute volume" alarm only after the expired minute volume decreased from 6.0 to 4.0 L/min. Because the flowmeter (from which minute volume is calculated) has a long integration time, it took as long as 37 s before the threshold was crossed. "Airway disconnect," "expired hose disconnect," and "inspiratory hose leak" were signaled by the "low airway pressure" alarm on the ventilator, about 13 s after these events started.

Figure 6 shows the human response time, the time between the sounding of an alarm and the time of event

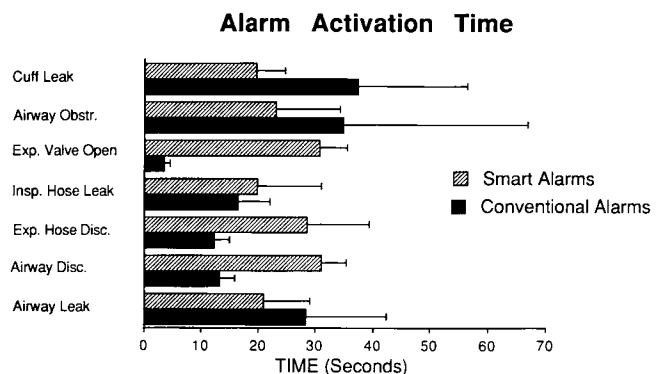


FIG. 5. Alarm activation time (time between fault creation and alarm sound) for the Ohmeda Modulus II conventional alarm system (solid color) and the smart alarm system (shaded bar). Each bar indicates the mean value and one standard deviation. Text describes significant differences.

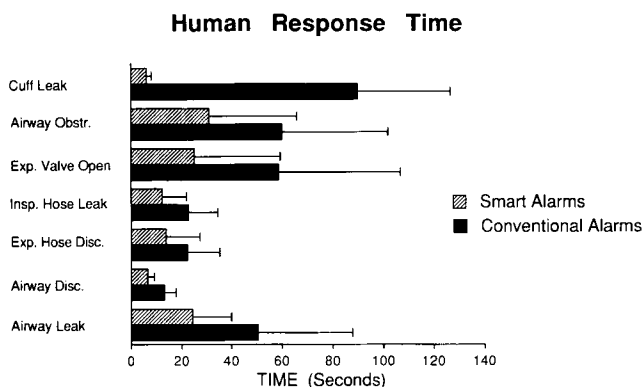


FIG. 6. Human response time (time between the alarm sound and fault identification) for the Ohmeda Modulus II conventional alarm system (solid color) and the smart alarm system (shaded bar). Each bar indicates the mean value and one standard deviation. Text describes significant differences.

resolution. The human response time averaged  $17.1 \pm 21.4$  s (mean  $\pm$  SD) for the intelligent alarm system and  $45.2 \pm 39.7$  s for the conventional alarm system ( $P = .0043$ ). Human response times were significantly shorter when the intelligent alarm system was used to resolve, "airway disconnect" ( $P = .003$ ), "inspiratory hose leak" ( $P = .04$ ), and "cuff leak" ( $P = .0001$ ). Times were not significantly shorter for the other four events.

Figure 7 shows the alarm activation time plus the human response time. This total resolution time, the time from the occurrence of a fault until its resolution, averaged  $41.0 \pm 22.7$  s for the intelligent alarm system and  $65.7 \pm 47.3$  s for the conventional alarm system. Total resolution times were significantly shorter when the intelligent alarm system was used for "cuff leaks" ( $P = .0001$ ), "airway obstruction" ( $P = .02$ ), and "airway leak" ( $P = .03$ ). The time was significantly shorter for the conventional alarm system for "airway disconnect" ( $P = .002$ ).

There was not a statistically significant difference between the response times of residents and faculty. For the conventional alarm system, the residents' average response time for all faults was  $40.6 \pm 35.0$ , and the faculty's was  $49.9 \pm 43.9$  s. For the intelligent alarm system, the residents' time was  $14.9 \pm 13.1$  and the faculty's was  $19.3 \pm 27.4$  s.

When the conventional alarm system was used, 11 events were never correctly diagnosed: five times the endotracheal tube cuff leak was not found within the allotted two minutes; three times the patient airway obstruction was not found; and three times the open expiratory valve was not found. When anesthesiologists used the intelligent alarm system, only two events were missed. A resident, who had been in training for only 2 months, did not detect the open expiratory valve and the airway obstruction.

However, these differences were not statistically significant.

### Discussion

Results from this study suggest that "intelligent alarms" improve the anesthetist's ability to detect faults. Our study found that human response times to breathing circuit faults averaged 28 s less when using the intelligent alarm system. Although these measurements were made for only seven breathing circuit faults, and in a simulation environment that was somewhat unrealistic, this study demonstrates a concept that could help greatly to reduce the confusion and potential misdiagnosis caused by the proliferation of monitors and alarms in the operating room.

An important question may be: Is an average response time of 45 s for finding breathing circuit faults adequate, and is the savings of 28 s important? The savings may not be important for faults such as disconnections, valve failures, and leaks. Yet, the time savings may be important for expiratory hose occlusion, where there is potential for barotrauma. Also, if a fault occurs while the anesthetist is dealing with other complications, a little time saved on each event could make a difference. Perhaps the real advantage of intelligent alarms is not the average time saved but the avoidance of tunnel vision or fixation error, where an extraordinarily long time is taken to find a fault and the fault has time to progress to a more serious event.

When the intelligent alarm system was used, it appears that human response time was less variable. The standard deviations of the human response time were only half as large when the intelligent alarm system was used. The neural network in the intelligent alarm system was faster and less variable than the anesthesiologists in diagnosing breathing circuits faults. The neural network examines 30 features from the breath-to-breath flow, pressure, and CO<sub>2</sub> waveforms to make its decisions. Processing this

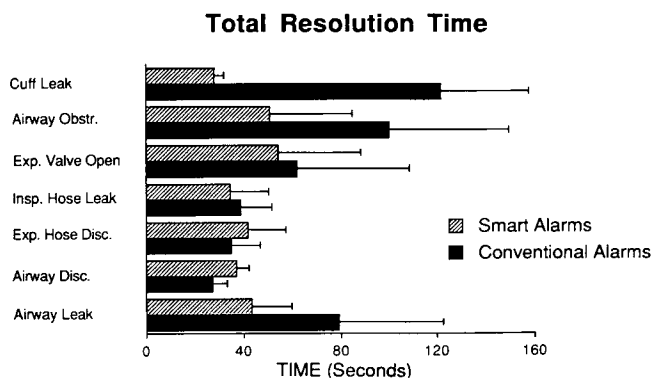


FIG. 7. Alarm activation time plus human response time for the Ohmeda Modulus II alarm system (solid color) and the smart alarm system (shaded bar). Each bar indicates the mean value and one standard deviation. Text describes significant differences.

amount of data breath-to-breath would be extremely tedious and nearly impossible for an anesthesiologist. The anesthesiologist, on the other hand, looks at a much broader picture and considers many variables that the neural network does not. The anesthesiologist's focus is toward protection of the patient, not just finding a breathing system fault. In future alarm systems, it may therefore be appropriate to include machine intelligence to watch the details of the anesthesia machine while the anesthesiologist is freed to observe the patient and the clinical environment.

Our measurement of human response time is an estimate of the time required by an anesthesiologist to diagnose faults. To resolve a fault, the anesthesiologist must recognize that an event has occurred, diagnose the fault, and then repair the fault.<sup>#3</sup> Assuming that the recognition times and repair times were the same when using either alarm system, the difference in human response times between the two alarm systems (28 s) is an approximate measure of human fault diagnosis time. Although several seconds should be removed from this estimate to allow for the time to read and interpret the computer message and to verify it by direct observation, 28 s seems to be a reasonable amount of time to find a fault manually, where one must switch from ventilator to rebreathing bag, squeeze the rebreathing bag several times, and look and listen until the fault is found.

Our results are similar to those of another simulation study.<sup>11</sup> DeAnda and Gaba's "experienced" anesthesiologists corrected an airway disconnection in  $18 \pm 10$  s; ours took  $13 \pm 6$  s. Their residents took  $15 \pm 6$  s; ours took  $13 \pm 4$  s. Given that the Gaba simulation is much more realistic and operating room-like than ours, the similarity of the results adds validity to our study.

The most clinically important time may be the total resolution time, the time between the occurrence of a fault and the fault resolution. This time includes both the alarm activation time and the human response time. Total resolution time was, on the average, 24 s shorter when the intelligent alarm system was used. For three of the seven faults, the total resolution time was statistically significantly shorter for the intelligent alarm system. The standard deviations indicate that total resolution time was less than half as variable when the intelligent system was used.

Unfortunately we obtained these results using simulation, rather than actual clinical testing. Our patient simulator lacked tracheal sounds and gurgling, which could have helped in diagnosing airway obstruction and endotracheal tube cuff leak.<sup>4,12</sup> In our study, however, the anesthesiologists found airway leaks after hearing a whistling through the leak, which was realistically simulated. They detected airway obstructions and disconnections from the "feel" of the breathing bag, which was also re-

alistically simulated. Not a single participant in the study used the CO<sub>2</sub> waveform to diagnose faults, thus, our concern for its realistic simulation was not important.

Some faults were easier to find in our simulation than they would be in the operating room. For example, we told the anesthetists they could lift the drape over our test lung to observe tracheal obstruction, and many did so. Our simulation was free of clinical clutter, and the room was quiet. Because of this simulator bias, the human response times we report are probably less than the actual times expected in a clinical environment, although any difference is hard to predict.

Fortunately, human response times were least for the most critical faults. Airway and expired hose disconnections were diagnosed in  $13.0 \pm 4.9$  s and  $22.4 \pm 12.8$  s, respectively (conventional alarm system). The longest time for a disconnection was 42 s. The less critical faults of cuff leak, airway leak and airway obstruction (which caused a 50% decrease in tidal volume), were diagnosed in  $90 \pm 36$  s,  $50 \pm 38$  s, and  $60 \pm 42$  s (conventional alarm system). It is still a concern that for 20 of the 70 events, response times exceeded 1 min, especially in the quiet simulation environment, where there are no other tasks or distractions.

The expiratory valve that was stuck open was especially difficult to diagnose with the conventional alarm system. The response time averaged  $58.3 \pm 48.4$  s, with a range from 9 to 120 s. The anesthesiologists usually saw this fault by observing the lack of fluttering action of the valve leaf, not by noting the change in the CO<sub>2</sub> waveform. The Ohmeda flowmeter always displayed a "reverse flow" alarm message, usually one breath after the fault occurred. If the participant saw and understood the "reverse flow" message, the response time was extremely short.

The expiratory hose disconnection seemed to us to be such an obvious fault, that it would provide no challenge. The hose was obviously separated and the separation was easily observed. The human response time, however, ranged from 7 to 42 s (average  $22.4 \pm 12.8$  s) for the conventional alarm system. Experts who discuss optimal response to alarms recommend a quick visual inspection of the breathing circuit as the very first step.<sup>4,13</sup> This step did not always occur in our study, otherwise the disconnection would have been obvious. This is an example of fixation error, where attention is incorrectly focused in one area, to the exclusion of more important, outside information.<sup>11,14</sup> Perhaps a significant advantage of the intelligent alarm system is its objective and untiring search through all of the data; it may help the user avoid this error.

The anesthesiologists in our study were frustrated if they could not find a fault within 2 min. When faced with the endotracheal cuff leak, most switched to manual ventilation and increased the fresh gas flow, which compen-

sated for the leak. Although the inspired/expired tidal volume difference and tracheal whistling were still noticeable, the anesthesiologists continued to look elsewhere, without any obvious direction or order to their searching. No one took the quantitative approach, using information from the flow, pressure, or CO<sub>2</sub> monitors.

The resident who failed to diagnose the open expiratory valve and airway obstruction, when using the intelligent alarms, must not have understood our succinct messages nor been familiar enough with the machine to understand the breathing circuit diagram. He told us at the beginning of the study that he had been in training for only 2 months and was not familiar with the Ohmeda anesthesia machine. Perhaps a display that is more pictorial than that shown in figure 4 would help the new user. Another option would be to expand the succinct message to a lengthier explanation, if it is not understood.

The intelligent alarm system misdiagnosed the fault, and displayed the wrong message, 6 of 70 times. (We designed the intelligent alarm system for use in patients in the operating room and its performance was degraded when used with the lung simulator.)<sup>§§</sup> For these six occurrences, the human performance time averaged  $21 \pm 18$  s, which is not much longer than the average for all events for the intelligent alarms ( $17 \pm 21$  s). Four of the incorrect messages were "Y-piece disconnect" when, in fact, an expiratory hose disconnection occurred. The resulting message led the participant to the correct type of event, but the wrong location. The fault was still found quickly. A potential disadvantage of the intelligent alarm system is that incorrect messages may lead the operator astray, if there is a high level of confidence in the intelligent alarm system. General distrust in our prototype-looking instrument may have been to our advantage.

This study shows that breathing circuit faults are more rapidly diagnosed and corrected when the anesthesiologist is guided by intelligent alarms. Intelligent alarms may help avert fixation error by directing attention toward the real problem area. The additional information content in intelligent alarm messages also may allow an alarm arbitrator to assign alarms priority, thus reducing the alarm nuisance

factor. For intelligent alarms to have their full impact, they should be applied on a much broader scale, with careful attention paid to artifact rejection, to keep the false positive alarm rate low.

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