CASE STUDY

Peer-Reviewed

PATIENT SAFETY

Hospital Technicians & Information Overload

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THE STUDY PRESENTED IN THIS ARTICLE was undertaken because risk managers in this hospital system became concerned about the number of alarm-related deaths occurring in the healthcare industry and commissioned the study. The monitoring technician position and the work setting studied are similar to industrial operations such as oil and gas processing operations, pharmaceutical manufacturing, paper manufacturing, specialty chemical manufacturing and power plant operations. A technician sits at a monitoring station watching the feedback from the operating system and responds accordingly depending upon what the feedback from the system indicates (or, in this case, what patient monitoring data indicate).

This article presents the results of an analysis of the cognitive information processing workload of patient monitoring technicians in the cardiac floor central monitoring units (CMU) at five U.S. hospitals. The researchers conducted the analyses during a physical visit to four of the hospitals and through conversations with the management team, nurses and technicians at all five hospitals June 1-2, 2016. The study's objective was to determine whether technicians' information processing (IP) workload was too high for error-free operation.

While data or study results do not appear to be available in the literature for healthcare applications to determine whether changes in error rates occur as a function of changes in IP load, the authors suggest that an increased IP load or length of exposure to a high IP load will increase error rates among technicians. In this study, errors are defined as events such as missed alarms, late response to alarms, misinterpretation of alarms, missed interpretation of electrocardiogram (EKG) strips and missed alarm notifications of nursing staff. Where the existing IP workload appears to exceed accepted limits, the researchers made recommendations to hospital management to help reduce the risk to patient safety.

KEY TAKEAWAYS
- Cardiac hospital monitoring technicians monitor 800,000 alarms per month and vital signs for 30 patients per day.
- These healthcare professionals are exposed to many distractions per shift and are expected to act on too much information.
- The authors make recommendations to reduce information processing load on technicians.

The alarm processing load for any one technician is derived from a measured number of alarms in a nearly month-long period collected at one hospital (from Dec. 23, 2015, to Jan. 19, 2016, 748,150 alarms were recorded). The number of alarms at the other hospitals may be fewer; however, fewer technicians on duty make the processing load per technician similar across all hospitals. This yields a 31% probability that an alarm will activate in any one operational second (0.31 alarms/second). A measure of the rest of the IP load was derived from the amount of data analyzed and cognitive tasks conducted by the technicians such as EKG interpretations, hospital admission and discharge processing, and phone calls made to nursing staff. The IP load per technician was calculated to be approximately 7 to 8 bits/second [a bit is the amount of information necessary to decide between multiple situation alternatives, each with a different probability of occurring (Freivalds, 2014)]. This is compared to the recommended IP load limit of 3 to 4 bits/second suggested in the literature for visual information processing (Miller, 1955).

Due to the high IP load, 2- to 4-hour rotations should be considered (Chewning & Harrell, 1990; Goldstein & Gigerenzer, 2002; Marois & Ivanoff, 2005; Nadav-Greenberg & Joslyn, 2009). Even mindful (meaningful) task-vigilance decrement over time occurs in all people without exception (Greir, Warm, Dember, et al., 2003). Technicians' ability to manage that much information without error, consistently over the long term is of concern and the probability of error increases as the shift progresses (Murayama, Blake, Kerr, et al., 2016).

Monitoring System Description

The subject hospitals monitor the health status of their patients via telemetry and portable bedside monitoring units. An example of a staffed monitoring workstation is shown in Photo 1 (p. 26).

These telemetry and bedside monitoring devices transmit signals from the patients to the CMUs where technicians monitor the data (Photos 2 and 3, p. 26). Technicians look for alarms triggered by patient conditions that require attention from the floor nurses. They spend the entire shift monitoring dynamic input data from patients. They must understand what the data mean so they can communicate accurate preliminary assessment information to the nurses. The technician role requires significant technical, medical knowledge, strong communication skills and a high level of vigilance to be able to watch a large volume of data over a full shift. It is a cognitively demanding job.

If an alarm indicates that a patient needs medical attention, the technician calls the nurse assigned to the floor on which the patient is located, informs the nurse of the alarm condition and explains what the quantitative data show. The nurse addresses the problem while the technician goes back to monitoring the other patients. On a regular basis, the technicians

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also receive EKG results and provide an interpretation of the results to the nurse in charge of each patient. This alarm condition is determined by an out-of-acceptable-range measured parameter (sometimes referred to as vital signs) detected by the system. These acceptable ranges are medically defined and are different for each variable. The biometric parameters monitored include heart rate, respiration rate, pulse oxygen level, mean arteriole blood pressure, central venous pressure, premature ventricular contraction and continuous real-time blood pressure, as well as several others (all parameters are not monitored on all patients throughout their entire stay). Technicians monitor the measured parameters 24 hours a day at the CMUs, each working 8-hour shifts (12-hour shifts at one hospital).

Photo 3 (p. 26) shows an example of workstation layout, which has five screens of dynamic data and one reading screen where EKG wave signals are read.

The monitoring system recognizes acceptable ranges for each biometric parameter monitored. As noted, these ranges are medically determined and vary between patients depending on their age and medical condition. Upon development of a potentially adverse health condition in which one or more monitored parameters drops below or exceeds the predetermined acceptable limit, an alarm is generated and becomes visible on one of the CMU screens. Depending on the magnitude of the out-of-range parameter, the alarm will be either yellow, indicating the development of a critical condition (categorized as either "yellow arrhythmia" or "yellow parameter") or red, indicating a potentially life-threatening condition ("red arrhythmia" or "red parameter"). Each is recognized by its own distinctive tone and yellow- or red-colored light activating on the applicable screen. When an alarm condition develops that requires a response, the technician notifies the patient's nurse, who delivers the necessary medical response and treatment.

Cognition Description & Context

The brain has a tremendous amount of processing power, but even though few dispute this power, significant research supports a claim that the brain is limited in the amount of information it can process at any one time (Nadav-Greenberg & Joslyn, 2009). According to Marois and Ivanoff (2005), the brain can store as much as a billion bits of information over a lifetime, but its processing power appears to be acutely limited by three significant bottlenecks:

1) attentional blink (the inability to process a second visual target when presented within a half second of a first target, in this case, a second alarm coming in within a half second of a first alarm);

2) visual short-term memory limitations;

3) psychological refractory period phenomenon (processing of a second piece of visual information is slowed because the brain is still processing the first).

Perhaps surprisingly in our multitasking world, these limits along with other complexities make it difficult for us to effectively and accurately do more than one thing at a time (Marois & Ivanoff, 2005).

The literature does not definitively quantify an information processing limit, but enough research has been found to allow generalized determinations depending on which information input channel is used (e.g., visual, auditory, tactile). In general, a strong indication exists that increasing the volume of information from which the technicians draw their interpretations and make their decisions can be detrimental to both their decision-making quality and their situational awareness (Chewning & Harrell 1990; Goldstein & Gigerenzer, 2002; Nadav-Greenberg & Joslyn, 2009). Even if there are essentially no demands placed on short-term memory (meaning the data are maintained on visual computer screens and do not require being remembered), significant processing limitations exist (Norman, 2013). Endsley (1995) suggests that the processing limitations affect "our ability to perceive, comprehend and make projections" or, in the hospitals' case, the ability to make determinations and decisions about the alarms. Endsley (1995) also suggests that this processing load erodes situational awareness.

Traditionally, to quantify information to process we use the term *bit* (i.e., amount of information necessary to allow a person to decide between equally likely alternatives. For some cases in which alternatives are not equally likely, a different calculation is used). The term comes from the *binary digit* terminology and concept used in computer and communication sciences (Freivalds, 2014).

Miller (1955) suggests that we are only capable of processing visual information in the 3 to 4 bits/second range (meaning we can only effectively consider that much information when making critical decisions about alarm indications on the screen). However, he suggests that we are seemingly able to manage much more information than that due to our ability to select salient information and only process what we consider to be important. Even though we can manage (remain aware of) much more information than we can actively process, we are still limited in the amount of information that we can actually respond to and act upon (Miller, 1955). The downside of this is that interpretations and decisions do not readily come from this managed information. The information must be further processed before it can inform interpretations and decisions.

So, while it is suggested that the information is manageable, concerns are still associated with the IP load faced by these monitoring technicians. Each element of concern is calculated, quantified or identified in the results section and is reflected in the recommendations.

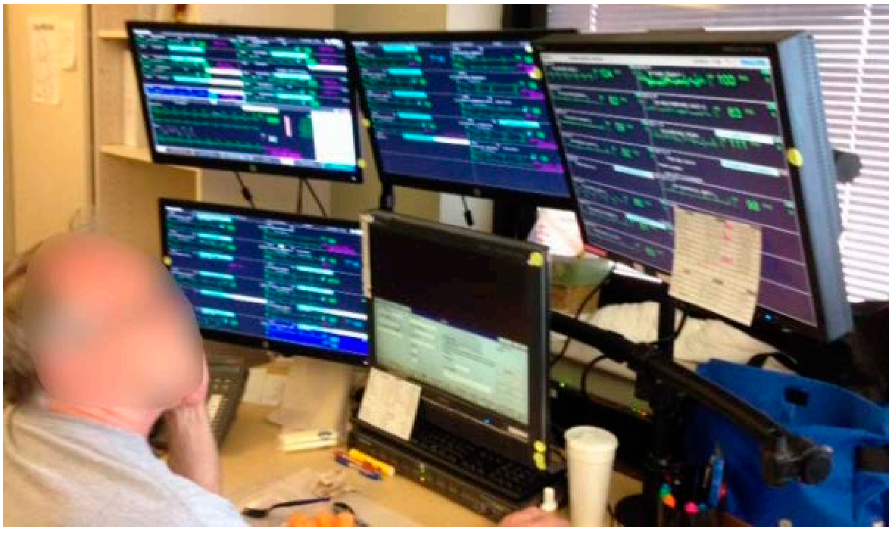
Experimental Methodology

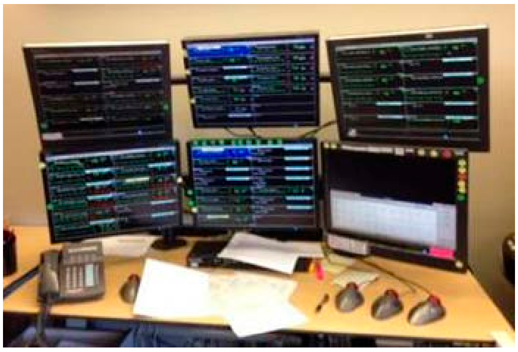
The analysis involved gathering monitoring system operating data, alarm activation data, equipment information (e.g., capacity, operating parameters) and non-alarm-related information with respect to technician activities to better understand the operation, equipment, technician capabilities and demands, screen layout and content, and communication processes. The researchers also toured CMUs and patient rooms in four hospitals and discussed the monitoring tasks and operations with monitoring technicians, chief nursing officers, the director of patient safety and the risk manager. The researchers conducted interviews (open-ended questions about specific duties, cognitive load, responsibilities, fatigue level, distractions and any other difficulties) with 10 on-duty technicians (four at one hospital, two at each of three other hospitals), each interview lasting about 45 minutes. Interviews (involving open-ended questions about their impression of the same as was addressed with the technicians) were also held with the monitoring unit directors at each hospital, and with floor nurses at three hospitals, all over two shifts. The researchers also observed operations in the CMUs over 8 hours during the 2 days of hospital visits.

Many hospitals in the U.S. and beyond use this type of monitoring system, but this concentrated study was conducted in one hospital system as it was the system that commissioned the study. The results are generalizable to other hospitals and any other monitoring system technician position with similar demands.

The researchers analyzed the cognitive processing load on monitoring technicians (i.e., amount of information they monitor, number of alarms they experience, interpretive expectations they have for each alarm, additional duty expectations, such as calling nurses and printing/sending strips to nurse stations, and how the technicians integrate these into their primary objectives of keeping patients safe). Additionally, the study also addressed shift length and fatigue. The researchers observed the actual monitoring equipment in three hospitals during operation and compared the process and operations with recognized and generally accepted good engineering practice at similar types of operations for layout, displays, lighting, activity level, task and information processing, and distraction loads.

The study included an analysis of monitoring system output and alarm status reports to help determine and quantify each technician's information processing demands. The results of these analyses were compared with findings





(Clockwise from top) Photo 1: One CMU workstation. Photo 2: Monitoring and transmitting device. Photo 3: Workstation with five data screens and one reading screen for viewing and managing EKG results.

in existing published literature. This part of the analysis was conducted to identify and quantify gaps between the existing IP load and what is considered accepted limits (Marois & Ivanoff, 2005; Miller, 1955; Petersen, 1996; Turmell, Coke, Catinella, et al., 2017).

This cognitive processing workload is addressed in the analysis by quantifying the amount of data to be monitored by each technician, the number of data points they are responsible for monitoring, the number of alarms to which they respond, and the additional duties and distractions to which they are exposed. The cognition process involves information input through visual and auditory channels (as well as other channels, but visual and auditory are the primary ones here); interpretation of what that information is and what it means (i.e., its criticality, the actions it evokes, the type of actions); and selection of an appropriate response (e.g., acknowledge the alarm, call floor nurse). This process takes time, which is identified as *response time* or *information processing time* (IP time) (Equation 3). As one might expect, IP load is influenced by the amount of information one must process. IP load increases as the amount of information to process increases and the number of decision alternatives to be considered increases. The study captured and quantified this amount of information. Each technician interviewed explained that the amount of information they processed during the analysis was typical of any day or month. Therefore, the analysis, interpretation, conclusions and recommendations are based on the alarm data collected over 1 month and that which was determined by 2 days of observation and interviews.

Technicians must make decisions about whether a critical alarm has activated and, if so, where and what type of alarm. Once the technician makes these determinations and decisions, s/he must then decide what actions to take (another decision). It is this information processing workload that the researchers quantified along with determining its impact on decision time, reaction time, choice reaction time and the need for prospective memory (the need to remember to go back to readdress an alarm that had not yet established its full meaning when first detected) (Freivalds, 2014; Wickens, Lee, Liu, et al., 2004).

Analytical Methodology

As noted, the information is traditionally defined as bits. If the alternatives are equally likely, the amount of information needed or used is calculated as the log_2 of the number of decision alternatives, as shown in Equation 1 (Freivalds, 2014; Wickens, et al., 2004):

$$H = log_2\, n$$

Where H = the number of bits of information; and
n = the number of decision alternatives

If the alternatives are not equally likely, the calculation is more complex. With disparity in likelihoods, the result is a reduction in the number of bits that the technician must process because s/he can focus more attention on the more likely alternatives. This amount of information is calculated by Equation 2:

$$H = \sum p_i \; x \; log_2 \,(1/p_i)$$

Where H = the number of bits; and
p_i = the probability of the ith alternative being selected or the likelihood of it occurring

The concept of redundancy in information processing can be considered as a measure of reduction in the amount of information that must be processed to make the decision when alternatives are not equally likely to occur. An engineer designing a task that requires significant information processing can use redundancy as a design goal. Essentially, more redundancy means that less attention capacity is needed. It is calculated by Equation 3:

$$R = (1 - H/H_{max}) \; x \; 100$$

Where R = % redundancy;
H = number of bits processed when different occurrence likelihoods exist; and
H_{max} = maximum information to process if all alternatives are equally likely

From this information, the researchers determined decision-making or information processing time. Minimizing decision-making time is important in a cardiac unit. To minimize this time, a task designer can minimize the number of alternatives from which technicians must choose so they can make decisions more quickly and carry out appropriate responses to alarm conditions. This is calculated by Equation 4:

$$IP = a + b \; log_2 H$$

Where IP = information processing time (seconds); and
H = number of bits of information

The numerical values are constants derived from research data distribution plots (a = y-intercept; b = slope of the curve) (Freivalds, 2014; Wickens, et al., 2004).

In the first step, the researchers determined that each technician can be expected to monitor as many as 130 data points every second (each monitored value can change from one second to the next). This is estimated by 30 patients at a time and four variables per patient (even though the number of variables can be much higher at times, a lower estimate is used as being more representative of an average over time). While each technician does not have to make a decision about every data point every second (an impossible task), s/he does have to continually monitor those data; this consumes attention capacity and must be considered in decision-making time determinations.

The 130 data points are not exclusively or explicitly used in the calculations because that amount of information and the attention capacity it consumes is tempered by an alarm system. The alarm system allows the technician to quickly dismiss any change in the monitored data from one second to the next if the change stays within the medically acceptable range of values. In fact, without the alarm system, the technicians would be faced with a difficult information processing task. The bit value of 130 alternatives would be $H = log_2$ 130 = 7.022 bits. This places significant importance on the reliability of the alarm system. Although those 130 data points must be considered in the IP calculations, processing only the alarms in categories and the number of response alternatives significantly reduce the required IP load. The alarm choices (e.g., category, type, location, criticality) become the decision alternatives.

From the January 2016 alarm report, more than 240 alarm types exist; this number would be impossible to process every second. The fact that only the top 20 alarm types (all greater than 10,000 alarm activations in a month) would be expected to consume the greatest attention capacity makes managing this phenomenon more possible. Therefore, for alarm type, the researchers assume 20 alternatives (Freivalds, 2014; Wickens, et al., 2004).

Even with alarm limitation, demand distractions that consume attention capacity increase the information processing load. Technician attention capacity is directed away from important monitoring tasks by the admission and discharge process. While not the case at all evaluated hospitals, leaving the workstation to print out and fax EKG strips to floor nurses also consumes significant attention capacity. The need to make and answer phone calls about a patient's status or to ask questions about an alarm also consumes attention capacity. Interpreting each EKG strip requires significant information processing as well, especially given that technicians determine 15 or more conditions from the EKG wave form. Even though more possible interpretations exist, a technician performs a bit calculation based on an average of 15 alternatives.

Results

Each technician must manage as many as 130 to 180 data points that can change from one second to the next. From these data, technicians determine whether and what response actions are needed. The job would be impossible if each technician had to evaluate every data point and interpret its status every second. It is made more possible by the categorizations that have been developed and the existing alarm system that activates (i.e., colored light and audible tone) for five different conditions: when a device is removed or becomes inoperable, or when a measured parameter exceeds its medically acceptable range in four different categories. These categories are labeled *red arrhythmia*; *red parameter*; *yellow arrhythmia*; *yellow parameter*; and *inoperable*. This narrows the identification process to a decision about the category and then type of alarm, the location where the alarm is occurring, then a decision about the criticality of the alarm. There is still significant information to process, but it is a more achievable expectation. Only the salient information is selected for processing, minimizing the demand on attention capacity.

In nearly one month (27 days between December 2015 and January 2016) 748,150 alarms were registered at the largest hospital's CMU. If one extends that to a full 30-day month, approximately 801,250 alarms would have been registered. An alarm will activate on any one parameter at a rate of 0.31 alarms per operational second. This means that a roughly 0.31 (31%) probability exists that in any one second an alarm will activate. The researchers observed an average of about four or five alarms at any one workstation at any one time, sampled during observational work sampling. Because so many monitored units exist (12 units total at the largest hospital, each technician/station monitors about three at a time), five different alarm categories with more than 200 different alarm types, a significant amount of information must be processed to successfully make appropriate decisions about patient care.

In general, we should seek to maximize redundancy when designing tasks involving cognitive processing. In the current decision-making process, the amount of information that must be processed is as follows:

1) The first decision (decision whether an alarm is critical) information processing quantification results show:

If one technician decides between critical or not, that is two alternatives yielding 1 bit ($H_{max} = log_2 2$; H_{max} = 1 bit), but if both types of red alarms are considered most critical, the probability of a critical alarm would be 17,015 + 18077 = 35,092 critical alarms/748,150 total alarms = 0.047 or 4.7% critical red alarms. If both types of yellow alarms are considered critical, the number of yellow alarms is 535,114/748,150 total alarms = 0.715 or 71.5%. Therefore, the number of bits processed in the first decision is: $H = 0.047 \times log_2 (1/0.047) + 0.715 \times log_2 (1/0.715) = 0.552$ bits.

2) The second decision (alarm location) information processing quantification results show:

Each technician monitors the patients in an average of three units. Decisions as to the location in which the alarm occurs would involve a maximum information load of $H_{max} = log_2 (3) =$ 1.58 bits if all units are of equal likelihood. Each unit does not have the same alarm load, so this dynamic distribution of units to technician is determined with a random number generator and the information load for each and the likelihood of an alarm coming from any one unit is determined by dividing the number of alarms in each unit by the total number of alarms. The results are as follows: Technician 1 (units 901, 601 and 9 East) = 0.774 bits; Technician 2 (units 6 East, 9 West and dialysis) = 0.5999 bits; Technician 3 (units 701, 8 East and 8 West) = 1.185 bits; Technician 4 (units 501, 801, and burn) = 0.6463 bits: The researchers conservatively selected the highest of 1.185 bits as being representative.

3) The third decision (alarm category) results show:

Each technician faces five alarm categories (i.e., red arrhythmia, red parameter, yellow arrhythmia, yellow parameter, inoperable) to determine a response. This part of the process involves a possible information load of $H_{max} = log_2 (5) = 2.329$ bits, but here, too, each alarm category has a different likelihood of occurrence, so the bit totals are reduced: $H_{redA} = 0.1245 \times log_2 (1/0.1245) = 0.3753$ bits; $H_{redP} = 0.1302 \times log_2 (1/0.1302) =$ 0.384 bits; $H_{yellowA} = 0.5320 \times log_2 (1/0.5320) = 0.4858$ bits; $H_{yellowP} = 0.5300 \times log_2 (1/0.5300) = 0.4869$ bits. Total bits for alarm location = 0.3753 + 0.3840 + 0.4858 + 0.4869 bits = 1.732 bits.

4) The fourth decision (alarm type) information processing quantification results show:

Each technician then must determine the type of alarm so that s/he can respond appropriately. Considered here are only the top 20 alarms because each of these alarm types showed more than 10,000 activations during the data collection period. The maximum information load from this is $H_{max} = log_2 (20) =$ 4.32 bits, but each alarm type occurs with a different probability, so bits are reduced to $H = (0.125) \times log_2 (1/0.125) + (0.095) \times log_2 (1/0.095) + (0.093) \times log_2 (1/0.093) + (0.062) \times log_2 (1/0.062) + (0.046) \times log_2 (1/0.046) + (0.037) \times log_2 (1/0.037) + (0.028) \times log_2 (1/0.028) + (0.033) \times log_2 (1/0.033) + (0.028) \times log_2 (1/0.028) + (0.027) \times log_2 (1/0.027) + \ldots = 4.218$ bits.

So, the total bit load that each technician must process is ∑H. Four decisions must be made in the process of interpreting the saliency, location, category and type of alarm; therefore, we sum the bit load:

$$\sum H = 0.552 \text{ bits} + 1.185 \text{ bits} + 1.732 \text{ bits} + 4.218 \text{ bits} = 7.687 \text{ bits}$$

Response time $RT = a + b\ log_2 H$ (we assume the reaction time takes a minimum of 2 seconds to reach for a phone and place a call, so this becomes the y-intercept; the slope is estimated to be linear at 0.5 slope)

$$RT = 2 + 0.5\ log_2 (7.687 \text{ bits}) = 3.02 \text{ seconds}$$

Comparing this to the visual information processing limit of 3 to 4 bits/second suggests that an information load reduction or change to the task should be sought.

•Information processing load: approximately 7 to 8 bits/second for each technician (research literature indicates more appropriate load of 3 to 4 bits/second).

•Fatigue: 8 hour-shifts in three hospitals and 12 in one hospital. Information and alarm fatigue and vigilance (a rapidly deteriorating commodity) is of concern.

Technicians have several opportunities to recognize an alarm condition associated with artifacts (movement-generated signals not associated with a heart condition) or a condition that would generate a meaningful alarm. To establish this, technicians often allow time for the signal to stabilize, clear or become more definitive. They must go back to the signal in a few seconds or a few minutes to ascertain its true meaning. This uses a capacity referred to as prospective memory, akin to putting a pot of water on the stove to boil, then leaving to attend to other matters and having to remember to return later to turn off the heat. Prospective memory is considered a highly unreliable form of memory and the need to use it should be minimized in task design. This problem at the hospital should be studied further (Salvendy, 2012; Wickens, et al., 2004).

Recommendations

Since the number of alarm-related deaths in hospitals reported from 2005 to 2010 is quite high with 566 deaths occurring during this period (Turmell, et al. 2017), system changes are worth considering. Processing as much information as was determined here presents challenges to the ability of the technicians to manage critical information for a full shift without error. The ability could be improved with lower likelihood of error if changes are made to the task, environment, schedule or patient load. The authors offer the following recommendations, which can be considered at any hospital with a similar system (Clemens & Simmons, 1998; Petersen, 1996; Salvendy, 2012):

•Reduce patient load per technician to a maximum of 25 patients per technician (will reduce to roughly 100 the average number of data points to monitor).

•Reduce or eliminate the need to print out and fax EKG strips (a significant distraction). The existing electronic systems at two hospitals are much improved (i.e., more efficient, less distracting) over the largest hospital's process of printing out and faxing paper copies.

•Consider a rotation schedule that allows technicians to rotate to other nonmonitoring functions every 2 to 4 hours (especially important for the 12-hour-shift technicians).

•Maximize the use of headphones with one-button activation for calls to floor nurses.

•Automate the interpretation of EKG results as much as possible to reduce the interpretation load for technicians.

•Automate the admission and discharge process as much as possible so technician attention is not taken away from alarm monitoring. Much is currently automated, but the authors suggest considering whether enough is automated.

•A high percentage of inoperative alarms occur (e.g., transmitter battery dead, connection dislodged). Reduction of inoperative alarms would help to reduce the information load on each technician.

Seeking to reduce information processing load should be considered in all task design for overall system performance.

Conclusion

As noted, the monitoring technician position and the work setting studied are similar to various industrial operations. In terms of attention, memory and information processing limits, humans are the same no matter what the industry, so these recommendations (or variations thereof) can apply in any industry where technicians monitor operational information with the expectation of responding to upset conditions. **PSJ**

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