Patient Monitors in Critical Care: Lessons for Improvement

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Abstract

Unexpected incidents are common in intensive care medicine. One means of detecting, diagnosing, and treating these events is use of physiologic displays that show the patients' vital signs. Monitors currently in use in intensive care units (ICUs) provide information in numerical and waveform formats, but most such displays originated in patient monitors developed for use by anesthesiologists. The present study focused on problems related to patient monitoring and needs of ICU nurses. Semistructured interviews of 26 experienced ICU nurses were employed to identify monitor usability problems. Among their comments, interviewed nurses mentioned that monitors now in use make it difficult to access vital sign trends and do not permit marking of events or interventions on trend displays. The present results indicate that patient monitoring in the ICU could be improved, but that such improvement will require identification of the tasks nurses perform and the development of new monitoring tools that fit their specific needs.

Introduction

The last three decades have seen significant effort and resources expended toward improving data display design in high-risk fields, such as aviation and power plant control. These efforts have yielded marked improvements in the safety and efficiency of airplane and nuclear power plant operation. Among the commonalities of these two domains are engineered systems. All monitored systems are designed by engineers, and consequently, they are well understood by their designers and to a certain extent by their operators. Sometimes the systems are designed with the goal of making system monitoring less complex. Engineered systems can be contrasted with situations where the task involves the monitoring of a natural system, that is, a patient.

One of the very first technical approaches to monitor patient physiology was the strip chart electrocardiogram (ECG) recorder developed by Sir Thomas Lewis in 1912. Interestingly, even some of today's most innovative monitors still employ elements of Lewis's original strip chart, with some numerical information added.

Development of patient monitors grew out of anesthesiologists' need to improve intraoperative patient monitoring. The complexity of the monitoring task is reflected by the fact that anesthesia monitors currently in use display more than 36 critical physiologic patient variables—often in real time—visualizing them through a combination of numerical data and waveforms.

Physiologic monitoring displays were introduced into the ICU in the 1970s, and they have not changed substantially since then. Patient monitors still employ a conventional format rooted in anesthesiology to present physiologic variables. The design format for these displays is based on a single-sensor-single-indicator (SSSI) approach, which provides a single indicator for each individual sensor connected to the patient. This approach to monitoring is founded in the domain of engineered systems[1] and has been applied to patient monitoring without significant modification.

The physiologic parameters currently displayed on ICU monitors include blood pressure, acquired from an arterial catheter and external pressure cuff; oxygen saturation of the blood, acquired from a pulse oximeter; heart rate; and respiratory rate, acquired from external transducers and the electrocardiogram waveform. Critically ill patients may also require hemodynamic monitoring using a pulmonary artery (PA) catheter. The parameters obtained from a PA catheter—including central venous pressure, right atrial pressure, PA pressure, cardiac output, and other calculated parameters—are also typically displayed.

ICU nurses monitor physiologic patient parameters on a regular basis to assure the patient's stability. Among the most common problems they face is detecting changes in one or more physiologic patient parameters. Timely detection of a change becomes a potential problem when detection is viewed in the context of all the patient's physiologic parameters and disease history and then must be interpreted and compared with parameters stored in the nurse's recent memory or the patient's records.

Nurses sometimes have to integrate 10 or more rapidly changing physiologic parameters into a clear and qualitative mental representation of a patient's current state. To make matters worse, in the case of an unexpected and potentially life-threatening event, the cognitive demands increase as the clinician must interpret new data for problem detection and rapid intervention.[2] The high cognitive demand for data integration reduces available cognitive resources for other important tasks (e.g., taking corrective actions, documentation, communicating with physicians and/or nurses). This can lead to other problems or a cascade of errors, such as interrupted tasks or deviations from the treatment plan or necessary interventions.[3]

Providing nurses with information about the patient's physiologic status in a manner that is easy and fast to interpret should reduce the time needed to detect changes. However, currently available monitors are not explicitly designed as cognitive aids for facilitating the rapid detection of changes in patient status.[4]

Current ICU monitor displays are also deficient in their ability to facilitate an integrated assessment of the patient's status that would enable nurses to develop a high level of situation comprehension.[5] Designs that follow the SSSI approach tend to yield data in a sequential, piecemeal form that makes it difficult and time-consuming for nurses to develop a coherent understanding of the relationships and underlying mechanisms of the displayed parameters.[6, 7] However, this situation flies in the face of the fact that a coherent understanding of a system's function and patients' physiologic mechanisms is a necessary precondition for optimum performance.[8, 9]

In their paper on medical errors in the ICU, Donchin and colleagues[10] reported that nurses performed 87 percent of all patient-oriented activities. Overall, nurses contributed to more than half the errors observed during the data collection period in this study. One plausible explanation for this high occurrence of error is that nurses have to rely on monitoring equipment that is not optimized for the specific tasks they have to perform. This mismatch between the required task and the cognitive aids available to deal with the task may be partly responsible for the relatively high occurrence of error in the ICU.

A user-centered approach might help optimize the design of physiologic ICU monitoring equipment. For example, iterative, user-centered design strategies for the development of graphic displays in health care have been suggested.[4, 11, 12]

Despite these problems, very few researchers have actually evaluated new designs for nursing monitors. For example, Effken, et al.,[13] developed a graphic, etiologic display to support hypothesis testing and treatment. The monitor incorporated elements of ecologic interface design to show causal constraints among key hemodynamic variables.[9, 14] In their study, critical care nurses and student nurses administered simulated drugs to correct hemodynamic disturbances in simulated patients. Compared to a traditional monitor, the graphic display reduced the time to initiate treatment (i.e., administer drugs), reduced the total number of drugs used, and increased the percentage of time that variables were in the optimal range. Interestingly, the etiologic display did not help clinicians understand the underlying physiologic effects. In fact, student nurses were better than experienced critical care nurses at returning the hemodynamic state to normal by simply focusing on returning the display's shape to normal and ignoring the underlying physiologic models. This display seemed to support treatment but not diagnosis.

The Cognitive Task of Controlling Patient Physiology

To conceptualize the control of a critically ill patient's physiology, several aspects of the control task must be taken into account. Hollnagel's Contextual Control Model (COCOM) provides some guidance and also allows predictions of potential problems that are associated with patient monitoring.[15] COCOM is based on three main concepts:

- Competence—which is what the human-machine system can do based on the recognized needs, the available information, and the range of available actions. It is the combination of information and ability to act on that information.
- Constructs—which are conceptualizations of the situation; also referred to as mental models.
- Control—which characterizes the application of competence in relation to constructs. Control modes correspond to different processes of decisionmaking that vary in several dimensions, including:
    - Determination of outcome—which refers to the operator's ability to detect and interpret a change in system state.
    - Subjectively available time—which refers to the time pressure the controller perceives.
    - Number of simultaneous goals—which is related to the number of objectives a person can maintain.
    - Availability of plans—which is related to an individual's ability to generate an action based on available information. Plans can be generated based either on fast pattern recognition processes or on slow, cognitively demanding problem analysis.

- Event horizon—which refers to the amount of prior information an individual uses in making a decision about an intervention and how that individual extrapolates information into the future based on the current situation.
- Mode of execution—which refers to the type of feedback that influences future behavior; some actions may be executed in a "ballistic" fashion, while others rely on feedback.

Operator control can range between the extremes of absence of control and the highest level of control. Hollnagel[15] outlined four regions of control as areas on this continuum:

- Scrambled control mode. This is the lowest level of control, which is characterized by the absence of any control. An operator acting at this level shows random actions that are characteristic of a trial-and-error approach and the absence of any cognitive schemata that could potentially guide behavior. Consequently, cognitive stress and time pressure experienced by an operator "controlling" at this level are extremely high.
- Opportunistic level of control. This is the next level on the control continuum. The operator at this level has some limited ability to control the system (i.e., actions are not random) but still faces high subjective time pressure. A central characteristic of opportunistic control is the ability to recognize and act on cues in the environment, allowing for feedback that can guide actions. Because the operator is slightly familiar with the environment, it is also possible to apply some cognitive schemata that direct action.
- Tactical level of control. This is the next highest level, in which the operator is capable of short-range planning. An expanded event horizon is available, and the subjective time pressure is less than at the lower levels of control. The user is experienced in acting in this context, making it possible to apply rules and procedures and to anticipate action requirements in the near future. The user operating at this level is able to maintain several goals simultaneously and relies on feedback.
- Strategic level of control. This is the highest level of control. Interaction with the system produces high levels of system stability, based on effective and robust control input. Because operators at this level do not experience time pressure, they can spend more time planning actions, allowing anticipation of future events while integrating past information. Due to the high cognitive load, operation at the strategic level is usually possible only for limited periods of time.

Monitoring Physiologic Parameters

Monitoring patient physiology, as well as planning and executing interventions to stabilize an unstable patient, can be conceptualized as control tasks.[16] Often, nursing activities go far beyond these tasks and include such tasks as assessing patients' functional and cognitive state. Other necessary activities, such as vital signs assessment and auscultation, require hands-on data acquisition. In addition to these tactile tasks, a significant number of activities involve the acquisition and interpretation of data that are displayed on patient monitors.

Based on a combination of observations and interviews with nurses, Aitken[17] analyzed the nurses' use of hemodynamic data and developed "concept maps." These "maps" showed that the nurses were integrating a wide range of physiologic data—e.g., information from the patient's medical history and current treatment regimens—into concepts to describe the patient's state.

In another interview study (13 ICU nurses) of hemodynamic monitoring, Doig[18] identified six cognitive tasks that nurses typically perform (Table 1). The concept maps identified in interviews can be used to make inferences about the control of patients and the level of control that is possible based on current monitoring technology.

Table 1. Tasks and issues

Tasks	Examples for issues with tasks
Selective data acquisition	• Limited by ability to understand and/or conceptualize variables
Data interpretation	• Visualizing the big picture • Understanding relationships between variables
Controlling hemodynamics	• Titrating medications and intravenous fluids to achieve a physiologic goal
Independent interventions	• Anticipating the needs of the health care team during emergent situations
Monitoring trends in numerical data	• Defaulting to memory for trend assessment
Use of current technologies	• Trusting the accuracy of computer-acquired data

Source: Doig A. Graphical cardiovascular display for hemodynamic monitoring [dissertation]. Salt Lake City: University of Utah; 2006.

In the current study, we used a contextual adaptation of the concept maps developed by Aitken[17] and Doig[18] to identify challenges involved in ICU nurses' monitoring of physiologic patient parameters. The goal was to identify the central issues and to relate them to the dimensions of control as identified by Hollnagel.[15]

Methods

Semistructured interviews were used to assess issues and challenges related to the use of currently available physiologic monitors in the ICU. Interviews lasted approximately 1 hour and were conducted individually with 26 ICU nurses (Table 2). Most interviews were conducted at the Department of Psychology, University of Utah. The study was approved by the University of Utah Institutional Review Board.

To recruit nurses, we posted advertisements at several ICUs in Salt Lake City, UT. To participate, nurses had to be active Registered Nurse license holders, currently working in an ICU, and have at least 1 year's experience working in critical care.

The mean age of the 26 participants (19 females, 7 males) was 39 years (range 22 – 64, sd = 13.2). Nurses had an average of 10 years working in a critical care setting (range 1-38, sd = 9.86). Most of the nurses were currently working in the medical ICU (65.4 percent); other workplaces included the thoracic ICU (11.5 percent), the surgical ICU (11.5 percent), the neurological critical care unit (7.7 percent), and the burn-trauma unit (3.8 percent).

Interviews were recorded digitally and professionally transcribed (see Table 3 for interview questions). Data analysis began with the identification of themes that emerged in the interviews concerning monitoring of physiologic patient parameters (see Table 4). Analysis was performed according to the guidelines for theme extraction, as per Ryan and Bernard.[19] Category generation was based on prior research regarding general concepts about nurses' use of physiologic monitors.[17, 18] Emerging themes from the interviews were then identified and consolidated with the list of themes. This was followed by an additional analysis of the data, which focused on identifying individual elements that fit into the theme categories.

Table 2. Demographics of participating ICU nurses

Total ICU nurses participating	26
Age (years)	
Mean (±SD)	39 (14)
Range	22 - 64
Years in critical care nursing	
Mean (±SD)	10 (10)
Range	1 - 38
ICU workplace (%)	
Medical	65.0
Thoracic	11.5
Surgical	11.5
Neurologic critical care	7.7
Burn-trauma unit	3.8

Table 3. Interview Questions

- Which monitored variables are the most confusing ones?
- Think about information that would make patient monitoring more effective. Which information is currently missing on physiologic monitors?
- What are your main concerns with current patient monitors in general and, in particular, with the specific monitor you are using?
- Think about a situation when you and your colleagues work under serious time pressure. Are there errors you observe in others that are related to or caused by patient monitors?
- Which are the parameters on physiologic monitors for which trend information is, or would be important?
- Is all the trend information that you want available?
- Think about the way trend information is currently displayed. Is this mode of information presentation optimal?
- In order to get other data, you have to go through menus. When you do this, what is the information you are looking for, and how easy is it for you to get through the menus?

Results

The list of themes (task column) that emerged from the interviews is shown in Table 4. Examples of statements concerning these themes are listed in the second column. We will discuss the themes and the issues in more detail in following sections.

Data Acquisition and Processing

False alarms. Some nurses mentioned issues regarding data acquisition of physiologic parameters and data processing of parameters. One frequently described problem in this category is the high frequency of alarms sounded by ICU-based patient monitors, most of which are false alarms. Due to the high workload of ICU nurses (e.g., nurse-to-patient ratios ranging from 1:1 to 1:3), nurses often do not respond to alarms, assuming they are false, with the obvious consequence of missing a real alarm.[20]

Table 4. Important themes and issues abstracted from interviews with ICU nurses

Themes	Issues
Data acquisition/processing	• Data processing leads to frequent false alarms.
Data/event integration	• Marking events as an explanation for changes in vital signs. • Only contextual information allows for detection of artifacts. • Clutter makes data extraction and integration difficult.
Data interpretation	• Applying meaning to variables. • Understanding interrelationships among variables.
Monitoring trends in numerical data	• Trend functions are not routinely used, not accessible. • Need to visualize interrelationships between intervention and physiologic variables. • Defaulting to memory for trend assessment.
Usability issues	• Variables were difficult to read due to small font size. • Color coding of variables is not consistent between manufacturers or even within same manufacturer models. • Cables should be color coded for ease of use and troubleshooting.

Nurses also expressed a desire to adjust alarm thresholds for individual patients. They often stated that, due to the monitors' complex menu structure and a lack of training, they did not know how to change alarm parameters. The absence of a standardized alarm menu structure increases monitor complexity. Nurses cited this inconsistency as the reason they tend to use default alarm settings, which are based on population parameters and are more likely to produce false alarms in critically ill patients. The application of such broad parameters to a specific patient in the ICU inevitably results in a high percentage of false alarms.

Data Integration

Appropriate assessment of a patient's status requires cognitive integration of physiologic patient parameters, as displayed on monitor screens. The nurses identified several issues regarding current monitor technology.

One category of issues involved data artifacts (i.e., when measurements of physiological parameters are incorrect, for example, due to sensor-related problems). Nurses mentioned in the interviews that they are frequently confronted with these artifacts; correct interpretation of these artifacts requires an assessment of the overall context in which they have occurred. At present, there is no display technology available that would allow nurses to assess a patient's status in a fast and integrated manner. As a result, nurses are forced to process individual physiologic parameters, both past and present, in a piecemeal fashion and then identify any inconsistencies between the patient's history and current status.

The nurses provided the following example that illustrates the shortcomings of currently available monitors: Oxygen saturation monitors are frequently associated with false alarms. When a patient's blood oxygen saturation drops too low, the oxygen saturation monitor sounds an alarm to notify the nurses that an intervention is needed to restore blood oxygen to an acceptable level. When such an alarm sounds, it is only natural for nurses to gravitate toward the alarming monitor. Based on the monitor reading of blood oxygen levels alone, it might be reasonable to assume that an intervention is necessary. However, it is common for an oxygen saturation monitor to report deceptively low blood oxygen saturation levels if the patient's body temperature is low.

It might well be that the patient's blood oxygen saturation values are actually low. However, because the sensor measuring blood oxygen saturation only operates accurately within an optimal temperature range, it is more difficult to obtain an accurate reading of oxygen saturation if the body temperature falls below that range. In the absence of an integrated display, a nurse faced with a low oxygen saturation alarm must remember to first check the patient's body temperature and then create a comprehensive mental model integrating both the patient's blood oxygen saturation levels and body temperature. The benefit of a display that integrates both pieces of information in one location is obvious here.

ICU nurses also expressed a need for information about recent interventions (e.g., drug administration) to be better integrated into trend displays on physiologic monitors. They pointed out that, when looking at trend data to assess the variability of parameters over time, information about recent interventions is not directly available; instead, it is recorded on the paper records or electronic charts, which are not integrated into or accessible on the data monitor display.

Data Interpretation

Interviewed nurses frequently reported observing novice nurses focusing on individual parameters rather than on the overall pattern of physiologic parameters. According to the interviewees, novice nurses experienced difficulties integrating information from available parameters and, consequently, tended to overemphasize the importance of individual parameters. This phenomenon, in which there is too strong a focus on individual parameters, has been termed "cognitive tunnel vision."[21]

To help alleviate "cognitive tunnel vision," some nurses recommended data monitors that integrate individual variables into graphic representations of the data, which would allow an immediate, more holistic assessment of patients' status. At the same time, some nurses mentioned that they also need the ability to focus on individual parameters, with the goal of identifying artifacts and assessing the patient's status.

Interviewees also mentioned two other factors that can influence their data interpretation: the formation of expectations regarding potential problems that facilitate data interpretation, and long years of experience, which allow them to quickly (although not necessarily effortlessly) assess a patient's status, despite problems with monitors.

Monitoring Numerical Data Trends

Almost all of the interviewees mentioned the relevance of information about physiologic patient parameter trends. As one nurse put it, "Trends kill people." The nurses viewed trend information as being relevant in a wide range of situations, from regular monitoring to critical events, or "code" situations, where access to trend information can be crucial when making rapid assessments about the cause of a problem.

Nurses frequently stated that trend information is only available on the main station monitors, and that they can only access the information from there. Many nurses also stated that trend information, despite its importance, is not used often enough, which some nurses attributed to a lack of formal training on the monitors. In addition, they stated that nurses were often unaware that they could access trend information on patient monitors, and that the menu structure on these monitors is too complicated and counterintuitive.

Nurses' suggestions about making trend information more readily available focused on their ability to review alarms and alarm setting changes over time, as well as on their ability to assess trend information. Additionally, nurses mentioned that they would prefer a monitor that allows them to visualize both trend information about physiologic parameters and information about interventions (e.g., drug administration). Such an integrated monitor would help them develop a more comprehensive understanding of both the effectiveness of interventions and the patient's response to them.

Finally, nurses also indicated that it would be helpful, in allowing for artifacts, for them to have the ability to mark events (e.g., "patient is supported in leaving bed temporarily") on a monitor that provides trend information. The nurses said a graphic representation of data over time would be best for displaying trend information.

Usability

The largest group of issues identified by the nurses involved problems with monitor usability. In the following section, we apply the criteria outlined by Drews and Westenskow[22] to categorize the usability topics mentioned in the interviews.

Affordance. Nurses frequently mentioned issues of affordance,[a] which gives them clues about which interaction with a monitor's interface is required to perform a particular operation. For example, many nurses complained about the difficulties they encountered in finding and selecting various functions on display menus and screens, which often resulted in many of the

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[a] Affordance is a term used in human-computer interaction to describe the quality of an object or environment that allows an individual to perform an action.

monitor's functions not being used. In a similar vein, nurses mentioned problems with the visibility of certain functions. For example, information about alarm settings was not always directly accessible. The issue of visibility was also mentioned in the context of the clarity of monitor function activation, where it was not always obvious whether a particular function had been activated or deactivated by a previous user.

Clutter. Nurses stated that novice nurses were often overwhelmed by the amount of clutter on the monitor display, making it difficult for them to use the monitors effectively.

Discriminability. Nurses complained about excessively small font sizes used on monitors, which increased the likelihood that numbers would get misread. Abbreviated labels were also likely to be misread, potentially leading to an incorrect assessment of patients' status and certainly to an increase in the time spent interacting with the monitor.

Knowledge. Nurses found fault with the discrepancy between information provided on the monitor to guide nurses vs. knowledge that nurses needed to have previously acquired in order to navigate successfully through a menu (knowledge in the world vs. knowledge in the head[23]). They mentioned that the menu structure was often too "deep," making it difficult to find the desired information or menu item. They also complained that some patient monitor models did not provide help menus or a booklet of quick reference functions.

Consistency. Nurses pointed out that monitors were inconsistent in their use of color coding and the organization of menu structures. In some monitors, menu structure changed based on settings, and color mapping of variables varied with different settings, violating the principle of consistency.

Hardware modifications. Most nurses expressed a desire for touch screens to allow a direct manipulation of the displayed information, potentially removing, or at least reducing, the number of complex menu structures. They also pointed out that easy-access buttons would allow them to directly access important information without having to go through menus. Finally, they mentioned that it is essential to always display the alarm status on the main monitor.

The interviewees consistently pointed out that, as a result of these and other usability deficits, it takes a long time for nurses to feel comfortable interacting with physiologic patient monitors. Also, many monitor functions did not get used on a routine basis, possibly depriving nurses of important information.

Discussion

The current study revealed a number of issues related to the monitoring of physiologic patient parameters in the ICU. Nurses experienced a high number of false alarms, which they attributed to alarm settings not adapted to individual patients and to a lack of knowledge about how to change alarm settings, among other problems.

The nurses in this study emphasized the fact that currently available display technology does not allow them to rapidly integrate individual parameters into a coherent, holistic assessment of the patient. Instead, it forces them to process individual parameters in a piecemeal fashion. This is consistent with the fact that the current data displays were developed using an engineering-based SSSI approach, which provides a single indicator for each individual sensor connected to the patient and makes data integration difficult.

The task of data integration is further complicated by the suboptimal information arrangement on patient monitor displays. Nurses complained about the presence of clutter on monitors. They also expressed a desire for information on physiologic trends, which they do not acquire from currently available monitors because they do not know how to access it.

By far the largest number of complaints about ICU monitor problems fell into the category of usability. In terms of software, nurses mentioned issues of affordance, visibility of functions, accessibility, discriminability of information, and violations of the consistency principle. Also mentioned were issues with current hardware, including a desire for touch screens, easy-access buttons, and clearly displayed alarm status.

These findings strongly suggest that nurses' information needs in the context of patient monitoring are not being completely met. Currently available monitoring equipment seems not to be based on an analysis of nurses' information needs. Information, such as event markers and trend data, often is either not available or not easily accessible.

According to COCOM, these findings suggest that competency is not being fully realized when nurses interact with current physiologic data displays, since competency is a function of the combination between information available and the ability to act.

Hollnagel[24] has described the levels of control based on several dimensions. Given the limitations identified in our interviews, it is clear that ICU nurses are not being supported optimally in the determination of outcome of an intervention due to a lack of information integration. This situation could be remedied by making available event markers that indicate the timing of an intervention in the context of physiologic trend information. Better integrated information displays would also help. These changes would also increase the likelihood of available plans, since pattern recognition processes would be better supported.

It is likely that ICU nurses' cognitive load is also increased by the requirement that information be gathered piecemeal, thus limiting the number of simultaneous goals that can be represented cognitively at one time. Moreover, because trend information is difficult to access and consequently rarely used, expansion of the event horizon is not supported. Finally, optimizing the feedback that nurses receive would also allow for a more feedback-based mode of execution.

Future development of physiologic monitors should follow the principles of usability outlined by Drews and Westenskow[22] among others. It is also important to emphasize that the task of monitoring a patient differs from monitoring a technical system. If approaches from technical system monitoring are blindly applied to patient monitoring, progress is bound to be short-lived. Thus, only careful application of lessons learned from other domains to health care in general and patient monitoring in particular will lead to improved patient safety.

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