Advanced Patient Monitoring Displays: Tools for Continuous Informing

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We reviewed the use of advanced display technologies for monitoring in anesthesia. Researchers are investigating displays that integrate information and that, in some cases, also deliver the results continuously to the anesthesiologist. Integrated visual displays reveal higher-order properties of patient state and speed in responding to events, but their benefits under an intensely timeshared load is unknown. Head-mounted displays seem to shorten the time to respond to changes, but their impact on peripheral awareness and attention is unknown. Continuous auditory displays extending pulse oximetry seem to shorten response times and improve the ability to timeshare other tasks, but their integration into the already noisy operative environment still needs to be tested. We reviewed the advantages and disadvantages of the three approaches, drawing on findings from other fields, such as aviation, to suggest outcomes where there are still no results for the anesthesia context. Proving that advanced patient monitoring displays improve patient outcomes is difficult, and a more realistic goal is probably to prove that such displays lead to better situational awareness, earlier responding, and less workload, all of which keep anesthesia practice away from the outer boundaries of safe operation.

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Recent advances in display technology offer new ways to present information about patients to anesthesiologists. Some research focuses on identifying information that needs to be conveyed and has led to configural graphic displays that show relations between sensed measures and physiological functions. Other research focuses on improving information delivery to the clinician. For example, head-mounted displays (HMDs) present monitored information directly to the anesthesiologist's field of view and may be a more effective way of monitoring patients. Alternatively, sonification, a nonspatialized auditory display[1] that represents relations in data as relations between the dimensions of sound, may serve a similar purpose. The technology for all these advances is increasingly affordable and customizable for the end-user, but the ideas behind them are only starting to be rigorously evaluated.

In this paper, we discuss the relative merits of configural graphics, HMDs, and sonification in supporting the anesthesiologist's work. Issues that still need resolving are whether attention will be directed to configural graphic displays at the right time, whether attention will sometimes be inappropriately captured by HMDs or auditory displays, and whether HMDs and auditory displays might even complement each other in helping the anesthesiologist maintain situational awareness.

Key Monitors

Patient monitoring is ultimately intended to help anesthesiologists meet high-level goals of anesthesia rather than to track low-level information. Examples of high-level goals are managing the major side effects of surgery (pain, awareness, movement, etc.), managing the patient's coexisting diseases, and maintaining and supporting homeostatic control of oxygenation, ventilation, and perfusion to core organ systems. Because such goals cannot always be directly sensed or

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displayed, anesthesiologists usually monitor variables that, when integrated, indicate whether the goals are being reached. American Society of Anesthesiologists minimal monitoring standards include measures of oxygenation, ventilation, circulation, and temperature (1). In anesthesia closed-claims cases and incident reports, pulse oximetry, capnography, electrocardiogram, and arterial blood pressure (BP) are cited as the most useful monitors, with pulse oximetry and capnography usually topping the list (2–4).

Until instrumentation provides direct feedback on how well an anesthesiologist is reaching higher-level critical care goals, as may be the case with bispectral index monitoring of depth of anesthesia (5), anesthesiologists must integrate lower-level data from multiple monitors to determine whether the goals are being met. However, monitors should provide this information in a manner that does not compromise anesthesiologists' management of their attention and workload (6). An important challenge is to find the best way to deliver information so these objectives can be achieved.

From Alarms to Continuous Informing

The need for a more effective way to convey information motivates much research on patient monitoring displays. The anesthesiologist is usually free to look at the monitors, but when tracheally intubating or extubating a patient, inserting an IV cannula, drawing up syringes, or handling an infusion device, the anesthesiologist may have to turn away from the monitor. Turning back to view it may be awkward. At such moments, the anesthesiologist relies on clinical observation for monitoring, backed up by auditory alarms. As has been well documented, alarms are often noisy, distracting, and uninformative and are often silenced (7–9). The long-standing struggle to reduce the intrusiveness of medical equipment alarms and the failure to resolve it satisfactorily suggests that novel solutions may be required. Few intelligent alarm-monitoring systems have reached clinical practice (10), and many groups now prefer to support clinicians with advanced displays (11).

One research direction in advanced display design is to determine exactly what information, at what level of description, should be presented to the user and how the information should be designed so that its meaning or significance is observed with minimal workload (12). Some outcomes are configural visual displays (13–15) and so-called "ecological interfaces" (16) that are already being explored for anesthesia. Most of this research still focuses on visual monitors, which may not provide users with information in the most appropriate format.

A second research direction is to find the human information processing bottlenecks and to seek ways to avoid them (17). Several new display technologies exploit the fact that humans work more effectively when information is delivered more directly. Examples are the use of speech synthesis, head-up displays (HUDs) and HMDs, auditory icons and earcons, spatial audio, tactile displays, and combinations of the above as virtual, augmented, or mixed reality (18). Such technologies are increasingly cost-effective and are being rapidly introduced into the workplace, such as in the cockpit, on the factory floor, and in maintenance workshops.

Visual and auditory displays each have strengths and limitations that should inform display design decisions. Visual displays are directional (can be viewed from only a limited range of positions) and optional (can be eliminated by reorienting visual attention). However, auditory displays are ubiquitous (usually audible from any point) and obligatory (cannot be eliminated by reorienting auditory attention) (19). In simplest terms, we do not have earballs and earlids that work the same way as eyeballs and eyelids (20). An HMD converts a directional, optional visual stimulus (patient monitor) into a ubiquitous visual stimulus that is always seen, thus reducing the time to seek information. An auditory display creates both a ubiquitous and obligatory auditory stimulus that is always heard, thus significant changes attract attention. In theory, both make information continuously available.

Field research suggests that anesthesiologists sometimes tailor auditory alarm systems to give themselves continuous background information or periodic reminders about a patient (8,21,22). Anesthesiologists respond faster to auditory alarms than to visual alarms (23) and may also respond faster with auditory displays or visual displays such as HMDs, both of which are ubiquitous. For example, Lampotang et al. (24) performed a large simulator study in which anesthesiologists were allocated randomly to conditions where variable-tone pulse oximetry and capnography were present or absent. Participants handled one of four incidents with a simulated anesthetized patient. Anoxic oxygen supply was detected faster with pulse oximetry and capnography present, but there were only nonsignificant trends for the three other incidents. However, the three other incidents were the only ones in which end-tidal carbon dioxide ($ETco_2$) changed, but $ETco_2$ does not have an auditory display. Detection might have been faster for the other three incidents if there had been continuous auditory $ETco_2$ monitoring alongside pulse oximetry or if key variables had been presented continuously on an HMD.

In the next sections, we review advanced visual displays, HMDs, and auditory displays, noting their advantages and disadvantages for anesthesia monitoring.

Advanced Visual Displays

Researchers have developed ways to move beyond so-called "single-sensor, single-indicator" displays to displays that integrate data graphically in a way that shows higher-order system properties (12–16). Similar developments have been seen in the anesthesia domain in attempts to present integrated representations of an anesthetized patient's state. Drawing on contemporary developments in theories of interface design, results have been characterized as metaphor graphics (25), configural and emergent features displays (26–29), or ecological interfaces (30,31). All share the goal of showing higher-order physiological functions or states by graphically configuring lower-level measures in a manner that makes the higher-level properties emerge.

Advantages

Graphing directly-sensed variables in a way that shows emergent properties can speed responses to events. In an early study, Cole and Stewart (25) showed tidal volume (V_T) and respiration rate (RR) as the height and width of a rectangle whose area was proportional to minute volume. Using this rectangle display, clinicians interpreted respiratory status twice as fast as with a tabular display. Furthermore, Michels et al. (26) compared anesthesiologists' ability to detect and diagnose four anesthesia events either with the Body™ simulator interface or with a graphical interface that integrated 30 sensed variables. With the graphical interface, two of four anesthesia events were detected faster and three of the four events were identified faster. Overall benefits were between 2.4 and 3.1 min—important gains given the time frame of anesthesia.

Later studies have shown benefits of representing not just directly-sensed variables, but also higher-order variables such as preload, afterload, contractility, and drug concentration through emergent features of graphical displays. Blike et al. (27) developed a configural display for hemodynamic monitoring that included five measured variables: heart rate (HR), BP, central venous pressure (CVP), pulmonary artery pressure (PAP), and cardiac output (CO); two derived variables: systemic vascular resistance (SVR) and stroke volume (SV); and four relationships: mean arterial BP (MAP) $-$ CVP $=$ CO $\times$ SVR, CO $=$ HR $\times$ SV, left ventricle end diastolic volume $\sim$PAP, and right ventricle end diastolic volume$\sim$CVP. Anesthesiologists recognized the signs of clinical shock earlier and made fewer errors classifying the kind of shock than when using a conventional digital display.

Agutter et al.'s (28) cardiovascular display incorporated CVP, pulmonary vascular resistance, HR, MAP, ST segment, SV, PAP, left atrial pressure, SVR, arterial oxygenation, and CO in a pipe-like image. Anesthesiologists detected changes faster and initiated more effective interventions with the cardiovascular display than with a more conventional control display. Similarly, Wachter et al.'s (32) graphical pulmonary display integrated fractional inspired oxygen, RR, V_T, $ETco_2$, upper and lower airway resistance, and fractional alveolar oxygen. Anesthesiologists readily recognized the graphical elements of the display, and subsequent simulator trials indicated that participants recognized pulmonary events 1.6 min faster with the graphical display. Finally, Syroid et al.'s (29) drug display presented the anticipated concentration over time of sedatives, analgesics, and muscle relaxants. When anesthesiologists were asked to keep drug concentrations at 95% effective concentration, there was more accuracy and less variability in effect-site concentration with the drug display than with a standard monitor, workload was rated lower, and own performance was rated higher.

Advantages persist when individual configural displays are combined. Jungk et al. (30) combined configural displays for respiratory mechanics, respiratory gas exchange, hemodynamic status, oxygen status, and depth of anesthesia into one interface. A first interface not only led to longer trials and more control actions than with the Body™ default screens, but also to the most effective restoration of patient status to normal. With a final version of the interface, however, anesthesiologists identified cuff leakage and blood loss events significantly faster than with the Body™ default monitors (30,31). Similarly, Zhang et al. (33) showed that an integrated display provides better support for maintaining awareness of patient state than a traditional display.

Disadvantages

There are several potential disadvantages of advanced integrated displays. First, there is conflicting evidence on whether advanced integrated displays take longer to use and require more attention, even if they lead to better outcomes. Second, an advanced integrated display on a monitor still needs to be attended but at busy times may not be. Although such displays have been tested in full-scale patient simulator environments, they have not yet been tested in a controlled fashion with timeshared tasks representative of operating room (OR) tasks. Third, advanced integrated displays require a large array of measured and derived variables. Researchers have not yet examined whether inadequate instrumentation might jeopardize the effectiveness of advanced integrated displays. Such displays rely upon data points becoming coordinates for integrated graphics that may take an uninterpretable shape if instrumentation sends a bad signal. This danger has already been demonstrated for process control (34).

Finally, although some advanced displays have been called ecological interfaces (30,31), authors do not report using all principles and tools of ecological interface design as it has been practiced in other domains (16), such as power plant control, chemical refining, and aviation. As also noted by Blike et al. (35), closer use of ecological interface design principles might accelerate progress towards effective design. Handbooks are appearing that will provide guidance (36).

HMDs

Apart from patient monitoring, demands on the anesthesiologist's attention may include inserting invasive lines, charting, drawing up drugs, taking calls, and giving reports. Some researchers have proposed that HMDs can reduce attentional conflicts by keeping patient variables in the field of view (37,38). HMDs provide displays that are either monocular or binocular and either transparent or opaque. Although aviation research shows that HUDs and HMDs represent inherently spatial information effectively, less is known about their performance for more abstract, functional information.

Advantages

Using a full-scale patient simulator (with a patient manikin and OR equipment), Ormerod et al. (38) and Ross et al. (39) compared anesthesiologists' pattern of visual attention with and without the use of a HMD that displayed key patient vital signs in digital format. They found that when using the HMD, participants spent 48% more time looking towards the patient, 29% less time performing tasks, 89% less time looking at the normal visual monitor, and had 54% fewer switches of visual attention. All participants agreed that the HMD made it easy to perform operative tasks without having to look back at the monitor, and it increased their confidence in their clinical decisions.

In similar studies, Via et al. (40,41) demonstrated subjective and objective benefits from an HMD displaying patient vital signs. Their HMD not only provided read-outs of vital signs, but also provided the waveforms expected on a standard monitor. In the first study, 12 anesthesiologists used the HMD for two busy parts of an operation. Almost all agreed that the HMD was of value, despite some minor problems, and they liked having vital signs continuously available rather than having to look around for them. In their second study using a full-scale patient simulator, 15 anesthesiologists conducted anesthesia scenarios with and without HMDs. With the HMD, anesthesiologists required 29%–34% less time to recognize critical events compared with the standard visual monitor, which meant they could reduce the resulting deviations in patient vital signs. Clearly, the HMD provides continuous information with low workload to the anesthesiologist. These kinds of results, coupled with rapidly decreasing prices for HMDs, should encourage the anesthesia community to adopt HMD technology, as many others have done. As we will see, however, auditory displays offer similar advantages.

These results are promising, but research with similar devices in aviation indicates that having information in the field of view does not mean it is attended (42), and cognitive tunneling can result when workload is high (43). HMDs are not necessarily the best solution to how patient monitoring can be time-shared with other tasks.

Disadvantages

There are several potential disadvantages of HMDs for use in anesthesia. First, the different kinds of HMDs may have different practical drawbacks. In a thorough comparative study, Laramee and Ware (44) reported that when a transparent monocle is used in combination with binocular viewing, and the monocle images are superimposed on a dynamic background scene, detection times are significantly delayed compared with other conditions. However, if an opaque monocle is used, the view of the world is monocular, binocular cues to depth perception are lost, and only pictorial and parallax cues preserved. This makes perceptual-motor manipulations more difficult.

Second, even if information is in the visual field, it is not necessarily noticed. Research on visual selective attention indicates that when users focus primarily on one aspect of a visual scene they sometimes miss events in another (45). Events in the world may distract a viewer from noticing events in a display and *vice versa*. This can happen even when stimuli are so important, bizarre, or safety-critical it seems quite improbable that they would be missed—a phenomenon dubbed "inattentional blindness" (46). In aviation, for example, pilots using HUDs can miss runway incursions by other traffic (42,43), especially when a HUD is cluttered and even when warned that such events might happen.

Third, HUDs can amplify the tendency for high workload to cause cognitive fixation (42). Despite the common use of HMDs in military and surgical contexts, less empirical evidence has reached the open literature about whether the above phenomena are seen in HMDs. It is important to test whether such phenomena generalize to the use of HMDs in the medical domain.

Finally, even though HMD technologies are increasingly lightweight, they will not necessarily be tolerated by all anesthesiologists. Depending on the kind of HMD, problems can include weight and fit of the unit, restriction of head mobility, and restriction of peripheral vision (47).

Auditory Displays

Most research on patient monitoring systems focuses on visual displays or auditory alarms (11,48) and tends to ignore the potential for auditory displays to inform rather than to alert. Although we know that 3D audio can very effectively guide people's attention to locations in space, we know less about how nonspatialized audio might convey information about functional or abstract properties of a system or process. Auditory displays may reduce demands on the anesthesiologist's visual attention, allowing patient variables to be monitored in the background—so-called "eyes-free monitoring". Naturally occurring continuous sound will often move into focal awareness if it signals an unexpected state (a change in ventilator noise may indicate a problem) but recede into peripheral awareness if it signals an expected state (21,49).

These properties, coupled with the success of variable-tone pulse oximetry in clinical monitoring, have encouraged several research groups to investigate patient monitoring using sonification or earcons (50,51). Earcons are short discrete sounds or sound patterns that carry information about the status of a variable. Sonifications are distinct from so-called "audifications." The esophageal stethoscope is an audification that, because it amplifies naturally occurring sound, does not convey inherently noiseless variables, such as the results of gas analysis, which must be sonified.

Advantages

Sonifications have been developed for patient monitoring using various combinations of HR, O_2, BP, RR, V_T, and $ETco_2$, among other variables. Fitch and Kramer (50) showed that nonanesthesiologist participants could identify physiological events better when the events were sonified than when displayed in a traditional visual form. In a later study, Loeb and Fitch (52) reported that anesthesiologists could identify six anesthesia events effectively with a two-stream sonification of the above six variables. Events were detected faster with a combined visual and sonified display but more accurately with a visual display than with a sonified display. Using a similar sonification, Seagull et al. (53) found that nonanesthesiologists detected changes in patient variables faster with a visual display, but a time-shared manual-tracking task was performed most accurately when patient variables were sonified only.

Watson and Sanderson (54) developed a respiratory sonification that combines information about RR, inspired:expired ratio, V_T, and $ETco_2$ into one sound stream. Flow of gas is represented by relatively pure tones distinguishing inspiration and expiration, rather than the breath-like sound used by other researchers. Using the Body™ simulation and 11 anesthesiologist participants, Watson and Sanderson (54) showed that anesthesiologists can monitor RR, V_T, and $ETco_2$ as accurately with the respiratory sonification as they can monitor HR and oxygen saturation (Spo_2) with variable-tone pulse oximetry. In a series of 10-min scenarios based on reported incidents, the anesthesiologists identified clinical conditions as accurately with auditory monitoring (pulse oximetry plus respiratory sonification) as they did with visual monitoring. Moreover, when the anesthesiologists performed an unrelated time-shared task (simple arithmetic) in parallel with patient monitoring, they monitored the simulated patient as effectively with auditory monitoring as with visual monitoring, but with auditory monitoring they performed the time-shared task better (54).

In a further experiment, nonanesthesiologist participants using auditory monitoring gave faster responses and looked less often at visual monitors, but they seemed to trade off performance between patient monitoring and the time-shared task (55), much as Seagull et al.'s (53) participants had. However, when a perceptual-motor time-shared task was used, the trade off disappeared, indicating that sonification can help even nonanesthesiologists sustain both patient monitoring and time-shared task performance at the highest levels (56).

Disadvantages

There are several potential disadvantages of auditory displays. First, participants may habituate to abnormal pitch and volume levels or may fail to notice slow changes if no auditory standard for comparison is provided, making visual backup or other cues essential. Second, anesthesiologists may become overreliant on continuous signals (compared with other less salient or more intermittent clinical signs) and may over-treat as a consequence. Third, attentional capture can occur, similar to that found for visual displays (57). Fourth, although pilot studies suggest that respiratory sonification may be less vulnerable to interference from music than from having to perform time-shared tasks (58), there may be some acoustic masking from other ambient noise, regardless of whether the sound is delivered free-field or via an earpiece. Fifth, without the symbolic labels available in a visual display, participants may misinterpret the mapping of vital signs to the different auditory dimensions of a sonification.

Finally, a continuous auditory display may not always be well tolerated by clinicians, coworkers, or patients. Despite the success of the pulse oximetry tone, anesthesiologists are concerned about the potential annoyance of further sound in the OR. Anesthesiologists would have to decide whether to play an auditory display in free-field, so all could hear it, or whether to listen to it through a personal earpiece, so that only he or she could hear it. If team coordination is required, then free-field delivery might be better, otherwise earpiece delivery might be better. Given circumstances and personal preferences, an anesthesiologist would need to make a determination, which may not be to everyone's liking.

Combining Technologies

Clearly, HMDs and auditory displays share many advantages. Both remove important attention bottlenecks, and the information they provide can be processed in parallel with other activities. If each by itself yields performance advantages, would both together compensate for some of the disadvantages? Would either or both enhance the use of configural displays on traditional monitors? Alternatively, are configural displays suitable for use in HMDs? Such questions should be considered cautiously because, as Spence and Driver (59) have noted, "adding input channels in other modalities may ... incur considerable performance costs unless the appropriate design decisions are made."

Human performance theory suggests that performance can improve if the load of processing information is divided across modalities (20). However, performance does not improve if the information first needs to be integrated for a person to act on it. Clearly, to understand fully the state of a patient, the anesthesiologist must integrate information from several vital signs. Is there any benefit then to using HMDs and auditory displays together? In previous research, we found that responses to verbal probes about a simulated patient's status are fastest with sonification alone, slower with a visual monitor, but slowest of all when both the visual monitor and the sonification are available, suggesting that people experience response interference or another modality incompatibility effect (55).

Research indicates that the benefits of multimodal monitoring are usually highly conditioned by the task to be performed (60). Rather than providing redundant information, the auditory channel may be of more use if it provides continual background awareness and prompts a visual search of the HMD when required. An auditory display could keep the user informed so that attention will be captured if there is a significant change. For example, in the field of aviation, where the auditory information space cannot be further crowded, recent experiments have tested vibrotactile wristbands and peripheral visual cues (61,62) to alert pilots to Flight Management System mode changes that might otherwise go undetected. An HMD may be best for finer-grain inquiry and for examining trend information.

Evaluation and Challenges

An important issue is how benefits from any new display combination should be evaluated. We should consider the impact on clinician workload and situation awareness, the effects on patient variables related to critical care goals, and the contexts in which auditory monitoring and respiratory sonification might fail, and then determine the implications of such findings.

Badly designed interfaces can jeopardize patient outcome (63). Forms of human interaction with medical devices that have produced fatal consequences in clinical contexts have been demonstrated in relatively simple but representative laboratory experiments (64). In contrast, it can require almost unobtainable statistical power to demonstrate that any single monitor produces better patient outcomes. For example, despite pulse oximetry's well documented role in providing early warning of emerging problems and reducing hypoxic events, researchers cannot produce clear scientific evidence of better patient outcomes (less morbidity or mortality) when it is used (65,66). It is claimed that no single monitoring technology leads directly to better patient outcomes (67) because clinician vigilance and interpretive skills, coupled with multiple monitors, already ensure high levels of patient safety (6,68).

Given the above, we will most probably see the advantages of new monitoring technologies in (a) how quickly and accurately clinicians maintain situational awareness and detect and identify emerging incidents (24), (b) how workload is reduced, (c) how easily clinicians manage incidents and compensate for unexpected problems, thus operating further inside safety boundaries (69,70), and, (d) how monitors might help reduce over-treatment and so eventually reduce risks and costs of patient care. Ultimately, monitors should help clinicians avoid incidents rather than detect them when they emerge.

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