MetaMonitor: a system for patient monitoring in intensive care units

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by Benjamin Fineman

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MetaMonitor: a system for patient monitoring in intensive care units

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the problem: ICU patient monitoring

My motivation in choosing this topic was simple: hospitals are fascinating places, with their combination of cutting edge technology and a diversity of roles and activities. Monitoring and alarms in particular matched my interests in the themes of attention and interruption.

the environment

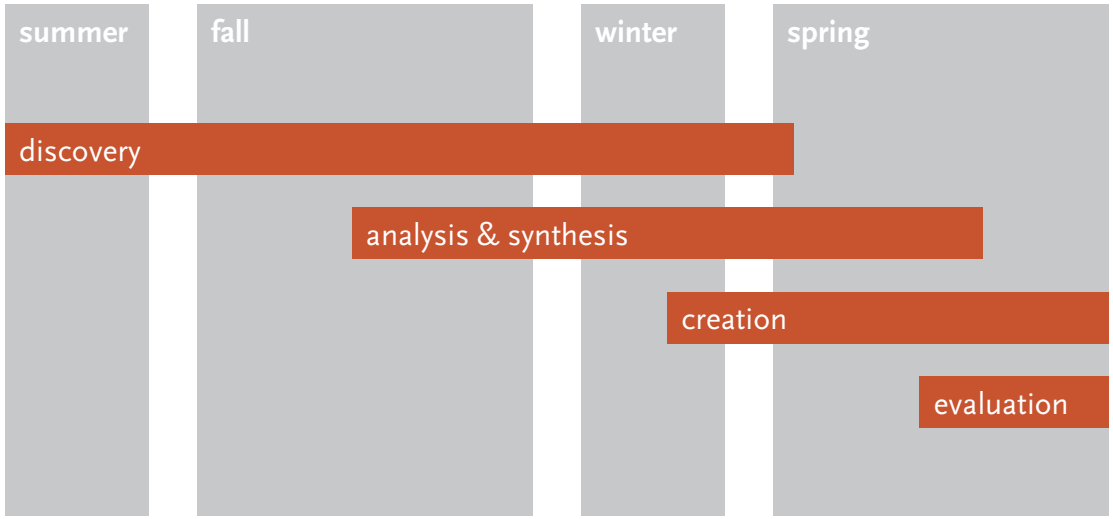
- Unstable patients
- Lots of technology
- Hundreds of alarms
- High stress
- Complex web of roles & responsibilities

the problems

- High number of false alarms
- Alarm noise causes stress for both nurses and patients
- Alarms not standardized, nurses have to learn each new piece of equipment

process overview

My process can be broken down into four fuzzy and overlapping phases.

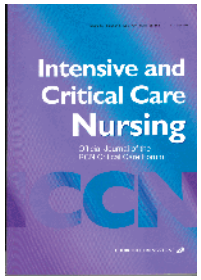


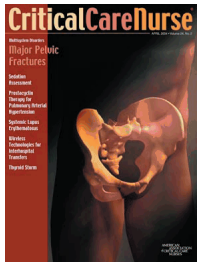
DISCOVERY

- Medical literature review
- Monitoring devices
- Nursing basics
- Interviews & observations
- Summary of research findings

medical literature review

Medical journals publish extensively on the subject of ICU patient monitoring, especially problems with patient monitoring alarms. I started my discovery phase with a literature review.





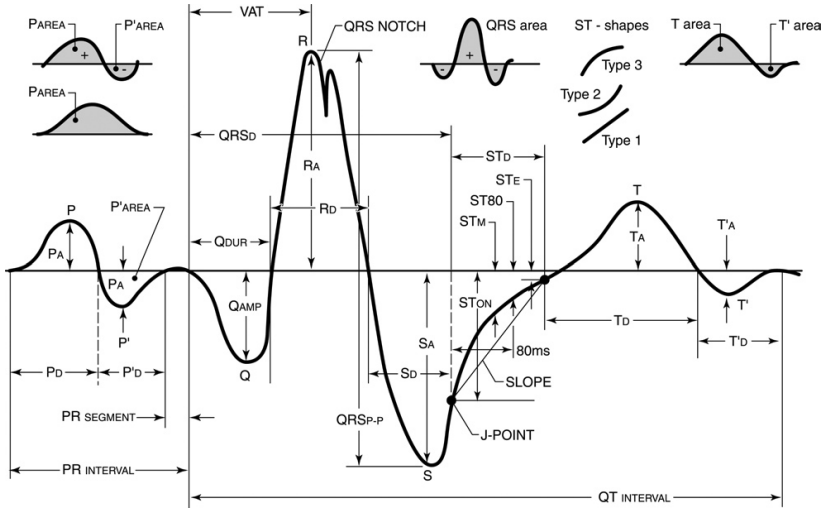
For more information, see Appendix A: bibliography and Appendix B: summary of research findings.

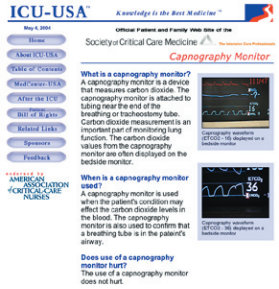
monitoring devices

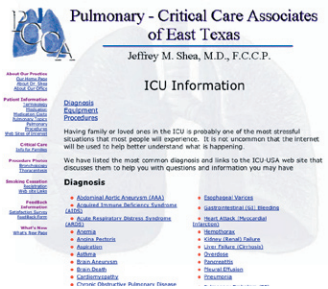
I studied how monitoring devices work, what kinds of data they collect, and how that data is displayed, paying particular attention to alarms—types, triggers, and notification mechanisms.

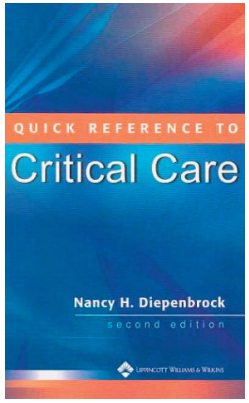
nursing basics

From websites, books, and a former ICU nurse, who served as an expert advisor on my project, I learned the basics of what nurses do and the types of patient interventions that occur in an ICU.









Diepenbrock, Nancy H. 2004. Quick reference to critical care. 2nd ed. Philadelphia: Lippincott Williams & Wilkins.

interviews & observations

Primary research consisted of interviews with ICU staff as well as observations of ICUs and other medical units. Getting access to nurses and ICUs proved to be a challenge, but well worth the effort.

Interviews

I interviewed nurses, unit directors and doctors to find out:

- Who does what in an ICU
- Problems with current monitoring and alarm systems
- Perceived differences between different monitoring systems
- Whether problems in the literature were recognized by practitioners in the field

ICU observations

I observed several different types of intensive care units to discover:

- How nurses actually respond to alarms
- How the space of the ICU affects monitoring and alarm response
- Unarticulated needs and problems
- How devices are actually used in the field
- Whether problems in the literature were evident to an observer

Comparative observations

I observed a respiratory unit and a dialysis unit to compare:

- Different monitoring and alarm technologies
- Different monitoring activities and alarm responses
- Practices from one environment that might benefit the other

summary of research findings

Midway through my project I paused to summarize my research in a poster.

	Research questions	Summary of detailed findings	Resulting artifacts
activities	• How do nurses respond to alarms? • What information do they use to make decisions? • What other routine tasks do nurses perform?	• Alarms are less significant during patient intervention • The patient is often a better source of information than numbers or alarms • Nurses need trend information and context to interpret numbers	• Task list • Alarm response model
environments	• How does the space of the ICU affect monitoring? • What is the level of noise, light, traffic, and activity? • What are the differences between types of ICUs?	• Information is spread out in many different locations • It's difficult to locate the source of some alarms • With the curtain closed, it's difficult to tell if there's a nurse in a room	• ICU environment observation notes • Space sketches
interactions	• How do nurses interact with other people? • How do nurses interact with devices and technology? • When are alarms disabled or silenced?	• Tacit knowledge is exchanged verbally, including advice, stories, and opinions • Nurses don't use all of the features of the technology • Nurses play a significant role in managing visitors	• Relationship diagram
objects	• What are the devices present in the ICU? • What alarms do they have? For what problems? • Who sets and modifies alarm limits?	• Only the newest systems integrate many devices • There are about 70 different alarms associated with monitoring patient status • Any alarm could point to serious problems, but some predict better than others	• Device list • Alarm taxonomy • Display library
users	• Who are the people in an ICU? • Why are they there? What are they doing?	• Respiratory technicians may assist with ventilator alarms • Patients have many people associated with them, including assistants, doctors, respiratory therapists, dialysis technicians, social workers, visitors, and priests	• Role / task list • Relationship diagram

Insights

- Nurses should spend their time worrying about patients, not how to deal with alarms
- The space of the ICU is underutilized as a means of both input and output by monitoring systems
- Alarms are poor indicators of patient health
- In making decisions, nurses rely on examining the patient, talking to other people, patient stories and history, and their own knowledge and experience in addition to the information given by the alarm

Design implications

Awareness
Monitoring systems could be aware of
- Who is in the room
- Who is closest to the patient
- Where all the people associated with the patient are
- Which devices are in use
- Which procedure is being performed on the patient
- The alarm status of other patients

Display
An improved information display could
- Integrate patient health data values with trends and alarm limits
- Better use the space of the ICU
- Integrate information about the patient's condition,

Consolidation
Information and alarms from multiple devices could be consolidated in one location

Communication
Monitoring systems could facilitate communication with the various people associated with patients

Agency
Monitoring devices function like agents, and could benefit from new research and technology in the field

Practicality
- Due to the mix of technology, the new system should be modular, working with a range of other devices

ANALYSIS & SYNTHESIS

- Alarms
- Activities
- Space
- Alarm response model
- Generative scenarios
- System requirements

alarms

The first step in analyzing my research data was to create a taxonomy of alarms. Only by understanding the details could I hope to communicate with, much less empathize with nurses.

Patient health			
• Temperature	Numeric	Hi, lo	Arterial, core, esophageal, venous, nasopharyngeal
Cardiopulmonary			
Blood pressure	Waveform		Arterial, venous, atrial, ver aortic, pulmonary arterial, arterial, umbilical venous,
• Systolic	Numeric	Hi, lo	NBP, arterial line, Swan-Ga
• Diastolic	Numeric	Hi, lo	NBP, arterial line, Swan-Ga
• Mean	Numeric	Hi, lo	NBP, arterial line, Swan-Ga
• Disconnect	Boolean	Disconnect	Arterial line only
• Heart rate / pulse rate	Waveform (ECG/pressure), numeric	Hi, lo, extreme tachycardia, extreme bradycardia	NBP, arterial line, Swan-Ga pulse oximeter, ECG
• Asystole	Boolean	Asystole	NBP, arterial line, Swan-Ga pulse oximeter, ECG
• ST value	Waveform (ECG), numeric	Hi, lo	ECG
Arrythmia	Waveform (ECG), numeric		ECG

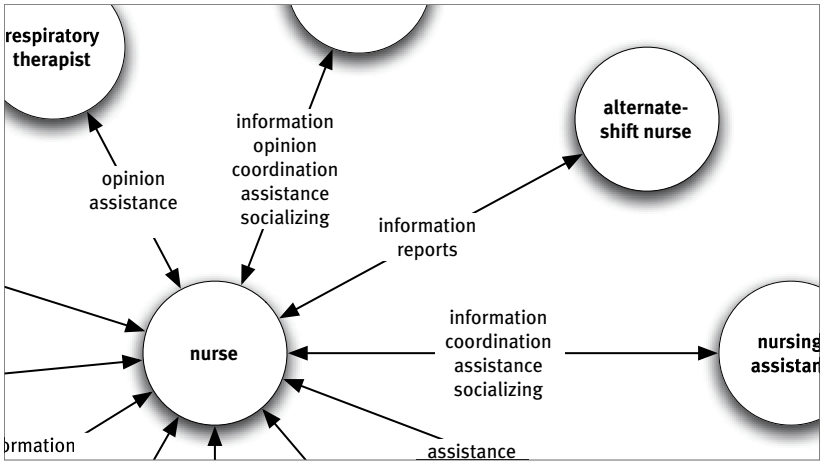
Detail from alarm taxonomy, showing different patient health measurements, the type of data collected for each, possible alarms, and sources of the data. The taxonomy contained over 70 patient health alarms. In addition to patient health alarms, each device has specific device-malfunction alarms.

activities

The next step was a structured understanding of nurse's activities, through an activity categorization and a mapping of relationships with other people in the unit.

	Activities	Observations	Opportunities & implications
Routine patient interaction	• Turning • Suctioning • Changing bedclothes • Physical therapy • Respiratory therapy • Medicating • Diagnostics (NBP)	• Many routine patient interactions have no reminder or alarm • Many activities involve either assisting or getting assistance from others • Recordkeeping not standardized for these activities • Patient intervention often causes clinically insignificant alarms	• Extend monitoring and alarming capabi include routine patient interactions not currently monitored (eg, turning, chang linens). But don't overdo it, too many a already • Improve, standardize, and/or automate recordkeeping • Reduce intervention-related alarms thr context awareness
Non-routine patient interaction	• Admitting/discharging • Changing rooms • Surgery • Diagnostics (CO) • Adding/removing lines • Emergency/code	• Sometimes involves modifying alarm limits or setting up new alarms • Patient intervention often causes clinically insignificant alarms	• Reduce intervention-related alarms thr context awareness
Recordkeeping	• Charting • Shift report	• Recordkeeping systems are often separate from monitoring systems, don't import data • Alarms don't appear on recordkeeping displays, only monitoring displays	• Integrate recordkeeping and monitorin systems • Make monitoring information more visi during recordkeeping activities

Detail from nurse activity taxonomy, showing activities by category along with relevant insights from ICU observations and implied opportunities

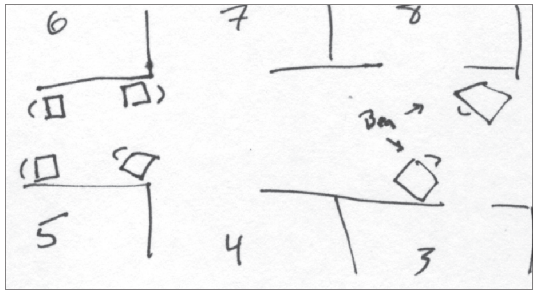


Detail from nurse relationship map, showing nurse's interactions with others in the unit

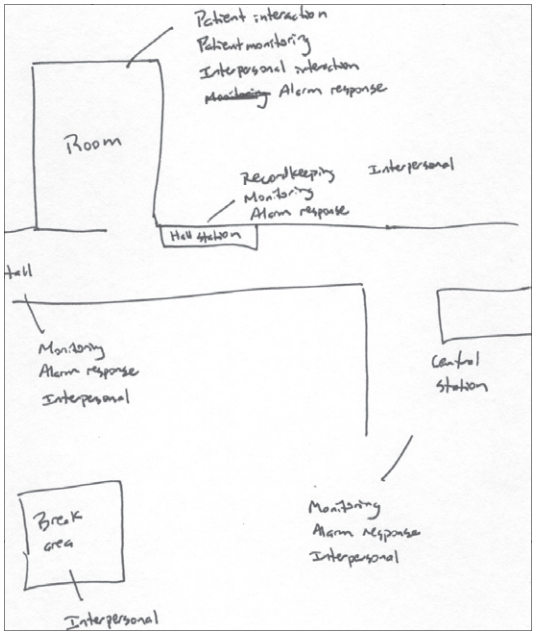
space

Although the architecture differs from unit to unit, all of the ICUs I observed had similar functional spaces. None of the current devices make the best use of these spaces.

Detail from space sketch made during an ICU observation



Sketch of opportunities for using the physical space of the ICU more effectively



A preliminary sketch mapping nurse activities to abstracted functional spaces

alarm response model

When nurses hear an alarm, they make a number of decisions quickly and almost reflexively. I broke this reaction down into a four-stage process which was invaluable later in designing my alarm notifications.

alarm

information needs

orientation

what type of alarm is it?

- Which patient?
- Which device?
- What alarm?

evaluation

do I need to act immediately?

- My patient?
- How serious?
- How urgent?

information

what exactly happened?

- Patient data
- Examination
- Knowledge of patient history
- Expert knowledge

action

what should I do?

- Expert knowledge
- Knowledge of patient history
- Second opinion/ stories

generative scenarios

Based on the activity taxonomy and alarm response model, I developed a set of scenarios which imagined activities within each activity category. Those activities then suggested requirements or opportunities for a system to support those activities.

	Scenario	System requirements
routine monitoring	*Nurse at hall station* • Can see summary info for both patients, including trends • Gets status of / reminders for routine tasks • Quick access to detailed patient info: orders, charts, records, monitor data, pharmacy • Quick access to constellation contact info *Nurse in room* • Sees summary info for patient, including trends • Sees more detailed information for patient • Can see device information if desired • Gets status of / reminders for routine tasks • Quick access to detailed patient info: orders, charts, records, monitor data, pharmacy • Quick access to constellation contact info	• At-a-glance patient summary, easily visible from hall, charting workstation, or room • Routine task status/reminder system • Integrated record system • Contact mechanism • Detailed patient monitoring display • Patient records display • Device information display
alarms	*Nurse at hall station* • Alerted to alarm, patient, and alarm type • Sees summary info for patient, including trends • Sees more detailed information for alarm condition • Silences alarm • Quick access to detailed patient info: orders, charts, records, monitor data, pharmacy • Quick access to constellation contact info • When nurse enters room, alarm silenced, condition info remains	• Alarm system capable of alerting individual nurses • Indication of patient and alarm type • Alarm condition display, easily visible from hall, charting workstation, room, different room, and possibly elsewhere • Silencing mechanism • Location awareness • Public indication of alarms and response status

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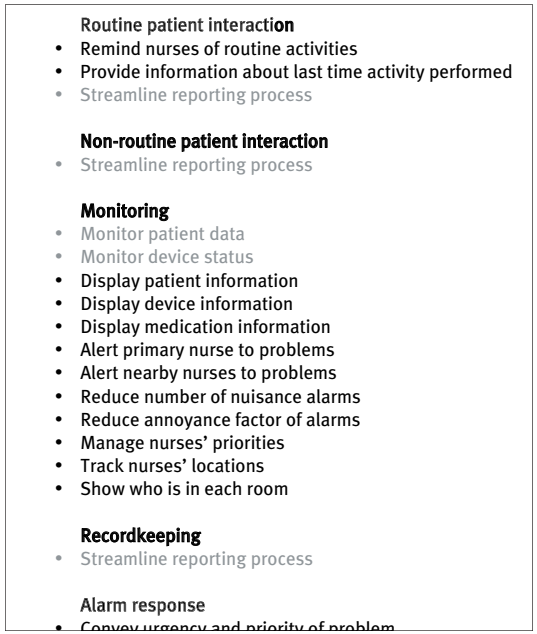
Detail from generative scenarios, showing nurse activities and information needs in the left column, and system requirements to support those needs on the right

system requirements

Based on the generative scenarios, a list of possible system features and functions emerged.



Routine patient interaction
- Remind nurses of routine activities
- Provide information about last time activity performed
- Streamline reporting process

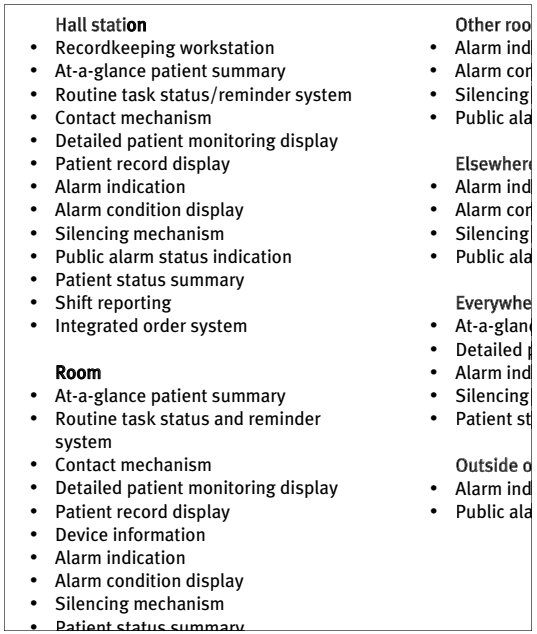
Non-routine patient interaction
- Streamline reporting process

Monitoring
- Monitor patient data
- Monitor device status
- Display patient information
- Display device information
- Display medication information
- Alert primary nurse to problems
- Alert nearby nurses to problems
- Reduce number of nuisance alarms
- Reduce annoyance factor of alarms
- Manage nurses' priorities
- Track nurses' locations
- Show who is in each room

Recordkeeping
- Streamline reporting process

Alarm response
- Convey urgency and priority of problem

Detail from list of possible system functions, organized by activity category



Hall station
- Recordkeeping workstation
- At-a-glance patient summary
- Routine task status/reminder system
- Contact mechanism
- Detailed patient monitoring display
- Patient record display
- Alarm indication
- Alarm condition display
- Silencing mechanism
- Public alarm status indication
- Patient status summary
- Shift reporting
- Integrated order system

Room
- At-a-glance patient summary
- Routine task status and reminder system
- Contact mechanism
- Detailed patient monitoring display
- Patient record display
- Device information
- Alarm indication
- Alarm condition display
- Silencing mechanism
- Patient status summary

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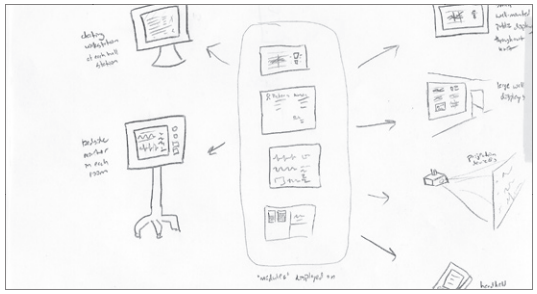
Detail from list of system features, organized by location within the functional spaces of the ICU

CREATION

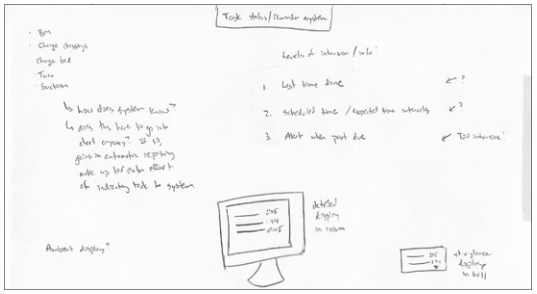
- Opportunity identification
- Devices
- Monitoring
- Notification

opportunity identification

From the large list of requirements, I sketched the outlines of a system that would accommodate most of them. From this wide-angle view, I chose to focus primarily on alarm response, with a secondary focus on patient monitoring.

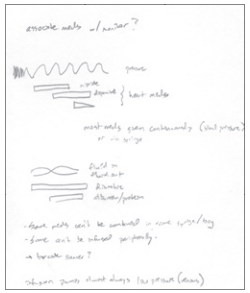


Sketch for a modular infrastructure that would enable many of the other opportunities

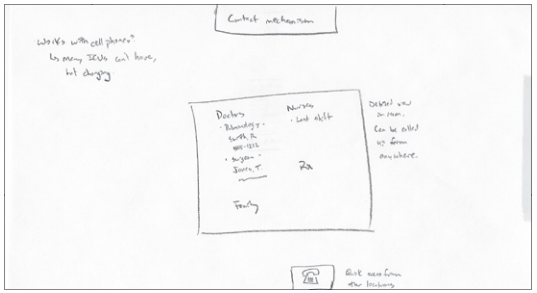


Unexplored opportunity: routine task status & reminder system, possibly using an ambient display

Unexplored opportunity: medication tracking system integrated with monitoring display



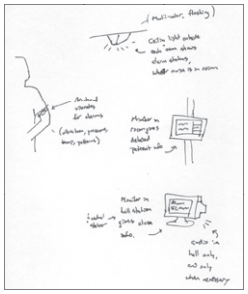
Unexplored opportunity: device management system, collecting information about all devices for a given patient

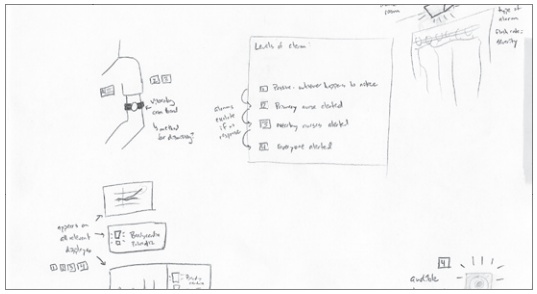


Unexplored opportunity: quick contact mechanism, allowing nurses to quickly reach doctors, family members, pharmacists, social workers, and others connected with a given patient

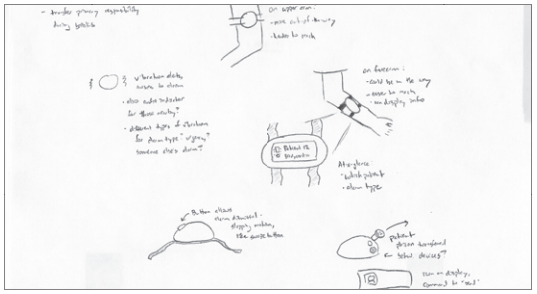
devices

From my system sketches I already had an idea of the devices that might be part of this system, and I did more sketching and ideation around those devices. I found that I could repurpose many of the devices already present in ICUs.

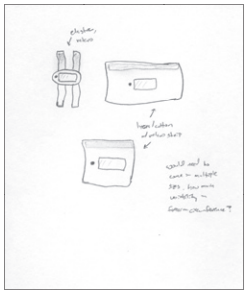




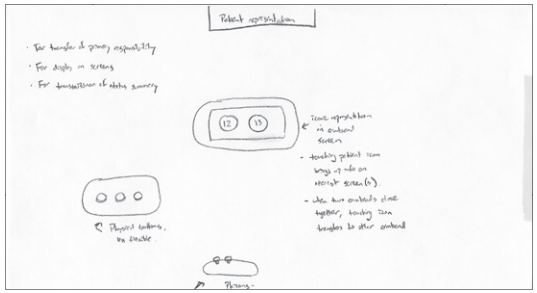
Sketches showing how multiple devices work together to notify nurses of alarms



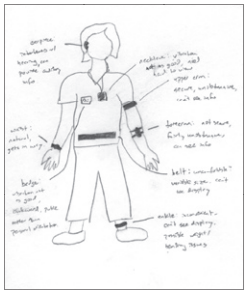
Form and interaction sketches for wearable device



Form sketches for wearable device



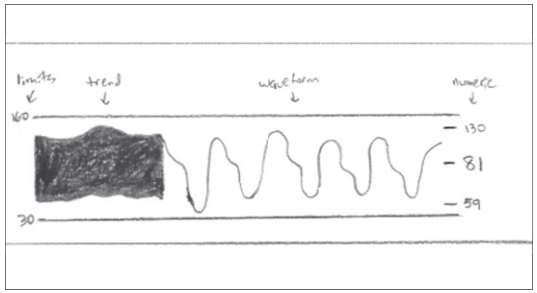
Interaction sketches for wearable device



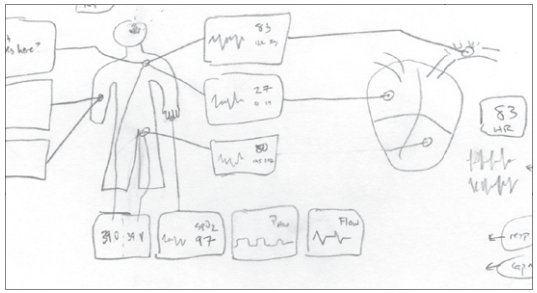
Sketch from exploration of possible wearable device placements on body

monitoring

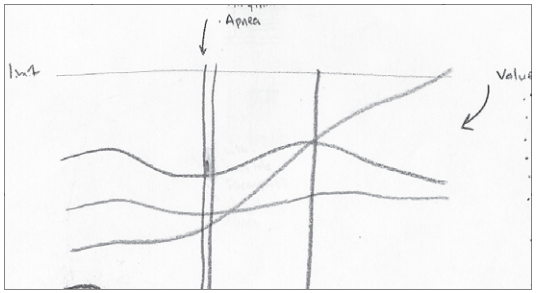
For the monitoring activity, information design played a key role. In particular, I focused on providing a quick summary view of patient status, something missing from current systems.



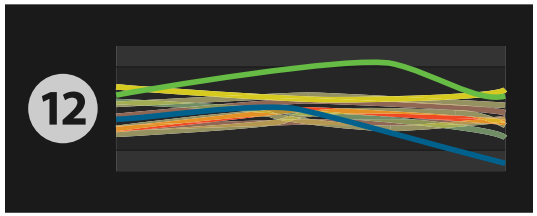
A sketch for an improved patient information display, integrating numerics, waveforms, trends, and alarm limits into one simplified view

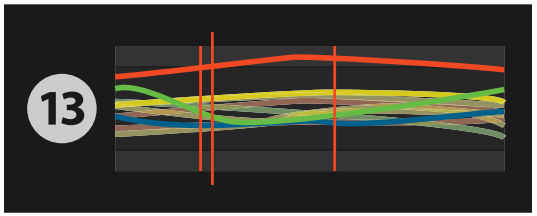


A preliminary sketch for moving patient information away from abstract representations and mapping it back to the patient's body



A preliminary sketch for the at-a-glance view, below

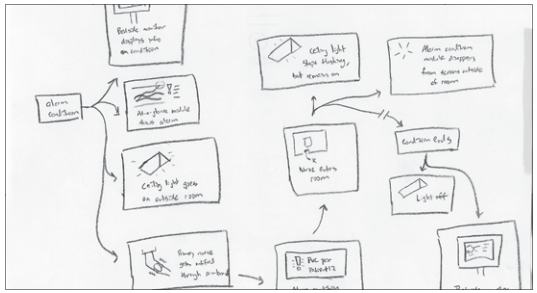




The final at-a-glance patient summary view, which scales a trendline of each numeric to its upper and lower alarm limits, allowing nurses to recognize problems before they trigger alarms

notification

For the alarm response activity I focused on communicating better information to nurses through alarm notifications. Rather than the current patchwork of idiosyncratic alarms I took a systematic approach, mapping information consistently across alarms.



A flow sketch of the alarm response process, including both nurse and device behavior

Alarm notifications

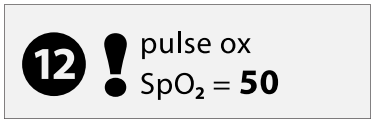
		Hall light	Displays	Wearable—primary nurse	Wearable—secondary nurse	Audible alarm
Primary nurse not in room	**Call**	• White, steady		• Audio tone		
	Low	• Colored, flashing slow	• Detailed info on monitor in room	• Audio tone		
	Medium	• Colored, flashing med	• Detailed info on monitor in room • Alarm summary on display(s) near primary nurse	• Audio tone • Vibration, med • Screen displays info	• Audio tone	
	High	• Colored, flashing med	• Detailed info on monitor in room • Alarm summary on display(s) near primary and secondary nurses	• Audio tone • Vibration, med • Screen displays info	• Audio tone • Vibration, med • Screen displays info	
	Emergency	• Colored, flashing fast	• Detailed info on monitor in room • Alarm summary on display(s) near primary and secondary nurses	• Audio tone • Vibration, fast • Screen displays info	• Audio tone • Vibration, fast • Screen displays info	• Audible alarm, fast
	Code	• Multicolored, flashing fast	• Code summary on display(s) near primary and secondary nurses	• Audio tone • Vibration, irregular • Screen displays info	• Audio tone • Vibration, irregular • Screen displays info	• Audible alarm, irregular
Primary nurse in room	**Call**					
	Low	• Colored	• Detailed info on monitor in room	• Audio tone		
	Medium	• Colored	• Detailed info on monitor in room	• Audio tone • Vibration, med • Screen displays info		
	High	• Colored	• Detailed info on monitor in room	• Audio tone • Vibration, med • Screen displays info		
	Emergency	• Colored	• Detailed info on monitor in room • Alarm summary on display(s) near primary and secondary nurses	• Audio tone • Vibration, fast • Screen displays info	• Audio tone • Screen displays info	• Audible alarm, fast
	Code	• Multicolored, flashing fast	• Code summary on display(s) near primary and secondary nurses	• Audio tone • Vibration, irregular • Screen displays info	• Audio tone • Vibration, irregular • Screen displays info	• Audible alarm, irregular

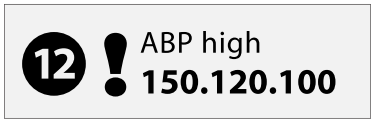
Descriptions of alarm notifications for each device organized by alarm priority

notification (continued)

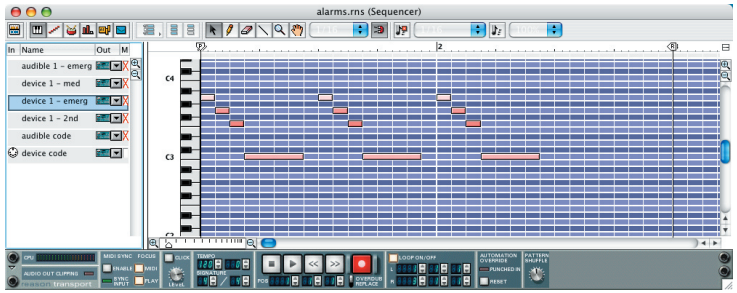
I explored visual and tactile alarm notifications in addition to audio, paying attention to which channels best conveyed different types of information. Because nurses' eyes and ears are often busy, a vibrating tactile alert had obvious advantages.

Alarm notification that appears on the networked displays, below the at-a-glance patient view





Alarm notifications that appear on the armband wearable device display



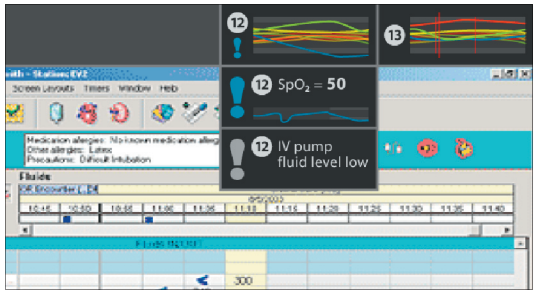
Screenshot from designing the audio notifications

prototypes

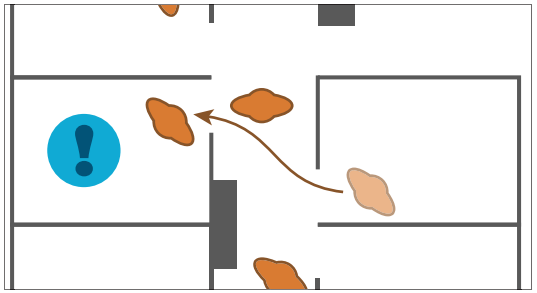
Prototypes helped make my ideas concrete and allowed me to explain them to others. I focused on prototyping the new elements of my system rather than the repurposed devices.

The “styrofoam and t-shirt” prototype demonstrates the general form of the wearable device and where it is worn on the body. It also serves as a paper prototype, with interchangeable screens, and hints at button interactions.

Using vibrating motors and a microprocessor, the vibrating prototype demonstrates all of the vibration patterns I designed as part of the alarm notification



A charting workstation prototype, showing the new at-a-glance patient view and alarm notifications on top of existing charting software



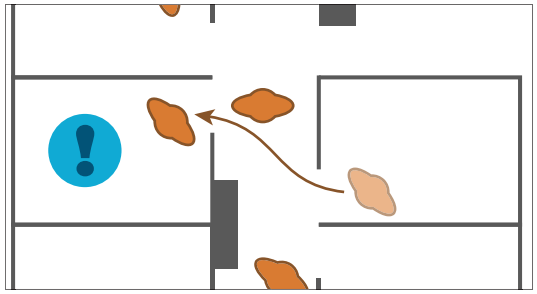
Scenarios prototype the more abstract aspects of the system’s behavior

EVALUATION

- Concept testing
- Notification testing

concept testing

Because I had neither a functional prototype of the entire system nor access to nurses for extended uninterrupted periods of time, I did concept testing with nurses, running through scenarios of using the system.



Scenarios and prototypes helped nurses understand the concept

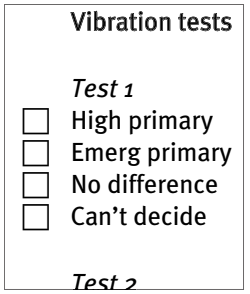
Summary of results

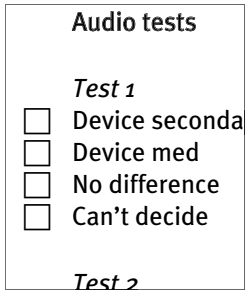
- Nurses were cautiously optimistic in general—intrigued by the concept, but would want to see how the details played out in practice before committing to such a big change.
- I underestimated the value of teamwork on my first iteration. Nurses complained that with targeted alarms they wouldn't know enough about what other nurses were doing. I revised the group interaction for my second iteration.
- Nurses were concerned with what would happen if the devices malfunctioned, leading me to include more redundancy in the second iteration.

notification testing

Alarm notification testing I could do with non-nurses. The tests focused on perceptions of urgency in audio and vibration notifications.

Participants were asked to rank vibrations and sounds in terms of perceived urgency





Detail of the data collection form, filled out by the tester based on verbal responses from participants

Summary of results

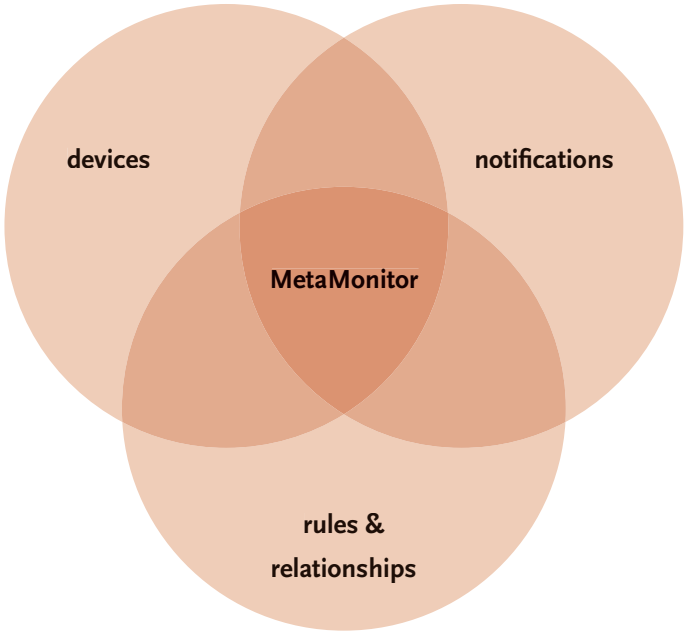
- In the first iteration, I used an on-off pattern of vibration with the rate mapped to urgency. Participants revealed that two conflicting variables were actually in play: speed of the pattern and length of each vibration. The second iteration standardized the length of the vibrations and only varied the length of the pauses.
- Participants found the musical tones of the audio notifications lighthearted and therefore less urgent. However, participants had no experience with musical alarm tones such as are used on many medical devices. I would need to check this finding with nurses.

FINAL CONCEPT

- Overview
- Devices
- Monitoring
- Notifications
- Rules & relationships
- Infrastructure
- Benefits
- Practicality

overview

My designs centered around three aspects of the system: the set of devices that support the monitoring and notification information, the design of the notifications themselves, and a set of rules and relationships that determine the system's behavior.

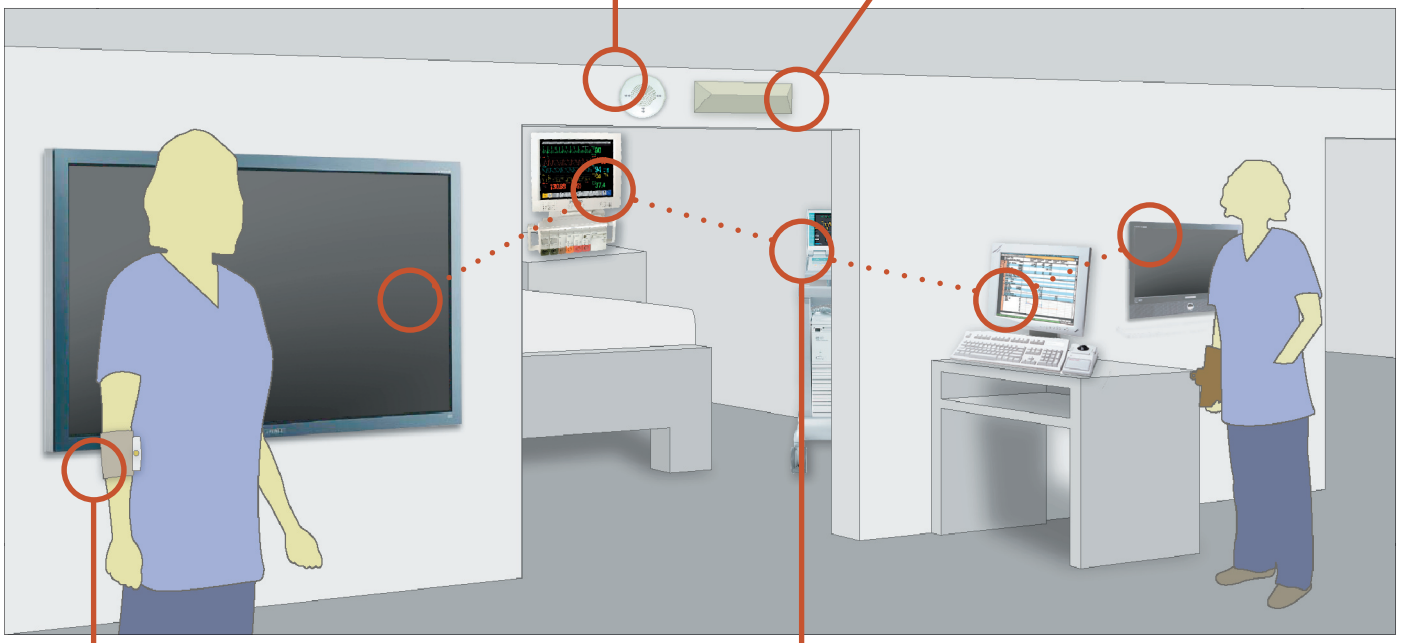


devices

Four devices are integral to MetaMonitor. The armband is the only entirely new device, the others are repurposed or redesigned devices already in the ICU environment.

single **speakers** outside each room replace audible alarms on individual devices

lights outside each room flash different colors for different alarms

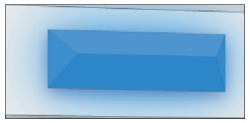


wearable **armband** devices provide individual alarm notification

networked **displays** can access any information anywhere in the unit

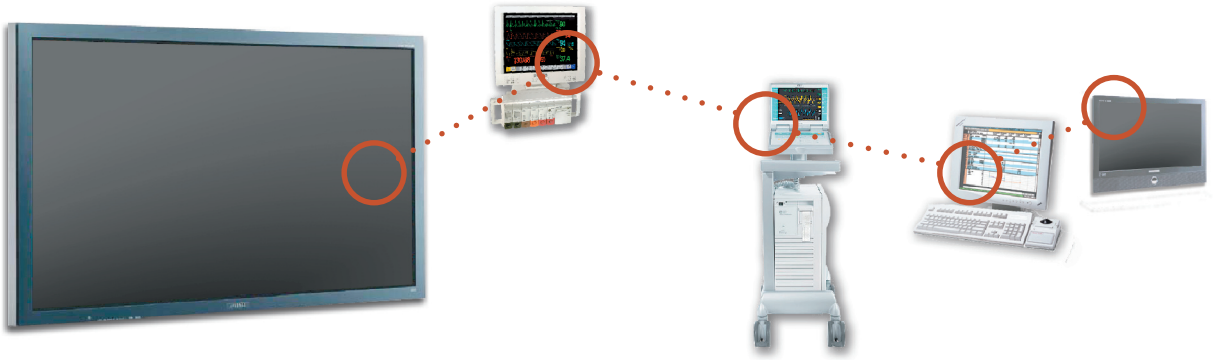
devices (continued)

With these three devices in combination, the entire space of the ICU becomes a monitoring and notification mechanism. In turn, the notifications are mapped back into the space of the ICU though the localization of lights and sounds.



Flashing hall **lights** help nurses locate which room has the alarm. The color indicates the category of alarm (eg, red for cardiac alarms) and the rate of flashing indicates the urgency.

A single **speaker** outside each room facilitates easier spatial location of alarm sounds, and evens out the difference in volume among different devices



The **networked displays** let nurses get patient information from anywhere in the unit. Since MetaMonitor knows where nurses are, it displays the at-a-glance patient view on the closest monitor at all times.

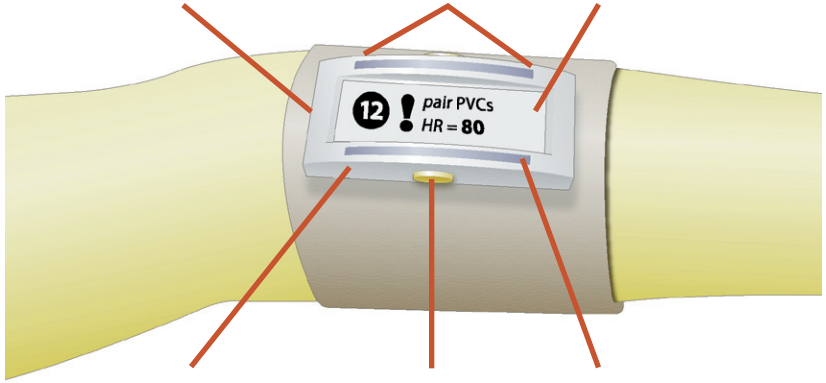
devices (continued)

The armband provides a personal compliment to the public nature of the other devices, allowing individual and targeted notifications.

A **speaker** allows the device to play patterns of tones

Two **vibrating motors** create tactile patterns

A touch-sensitive **LCD screen** displays information visually



Location tracking lets MetaMonitor know where nurses are

Dismissal buttons let nurses silence alarms

Escalation buttons let nurses indicate their inability to respond

In default view, the armband shows icons for each of the nurse's patients. The nurse can use these icons to bring up patient information on any of the networked displays, or transfer responsibility to another nurse when going on break.

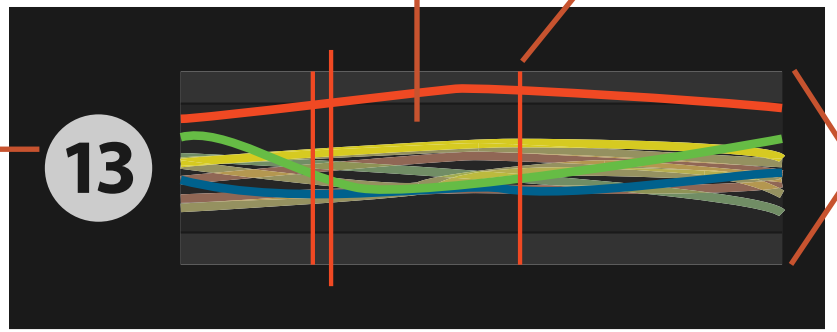
monitoring

The final at-a-glance patient summary view is a radical departure from the way patient information is currently displayed. Rather than giving a set of numbers it shows patterns over time, mapped to a meaningful and actionable scale.

The colored lines are **graphs** of the patient health numbers being monitored (eg, heart rate). Lines with more activity are in front.

Vertical bars represent discreet monitoring **events**, such as heart arrhythmias or apnea

The **patient** number is always prominent



The edge of the gray bars indicate the upper and lower **alarm limits** for each number being graphed

The at-a-glance summary view gives nurses a quick overview of patient status. Since the graph for each number is scaled to its alarm limits, any line that's too far toward the top or bottom indicates a problem. Using this view, nurses can spot problems before they trigger alarms. Because MetaMonitor knows where nurses are, the at-a-glance summary view follows them around the unit, always giving information about their patients on the nearest networked display.

notifications

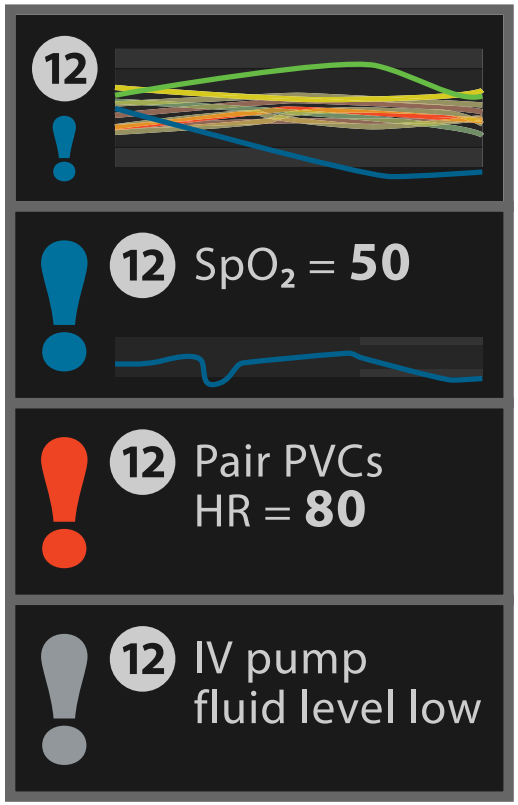
MetaMonitor's alarm notifications convey more information than current alarm systems, and in a more consistent manner. Information is presented consistently across channels when possible, such as the speed of the flashing light matching the speed of the sound and vibration.

Information	Mechanism	Coding
Alarm urgency	Hall light	• Rate of flashing
	Wearable device	• Rate of vibration pattern
	Audible alarm	• Rate of sound pattern
Alarm category	Hall light	• Light color
	Displays	• Alarm indication color
	Wearable device	• Audio tone
	Audible alarm	• Audio tone
Specific alarm condition	Displays	• Text description and numeric in alarm • Text description, numerics and detaile alarm detail
	Wearable device	• Text description and numeric on scree
Alarm condition context & decision-making info	Displays	• Trend line in alarm summary • Trends and detailed info in alarm deta
Which patient	Hall light	• Position in space of ICU
	Displays	• Room number in alarm summary
	Wearable device	• Room number on screen • Primary/secondary distinction made t vibration pattern
	Audible alarm	• Position in space of ICU
Presence of nurse in room	Hall light	• Flashing vs. steady
Nurse has responded	Hall light	• Steady
	Displays	• Alarm summary disappears
	Wearable device	• Vibration stops • Screen reverts to normal view
	Audible alarm	• Audible alarm ceases
Patient responsibility	Displays	• Primary nurse displayed on monitor in
	Wearable device	• Room numbers on screen

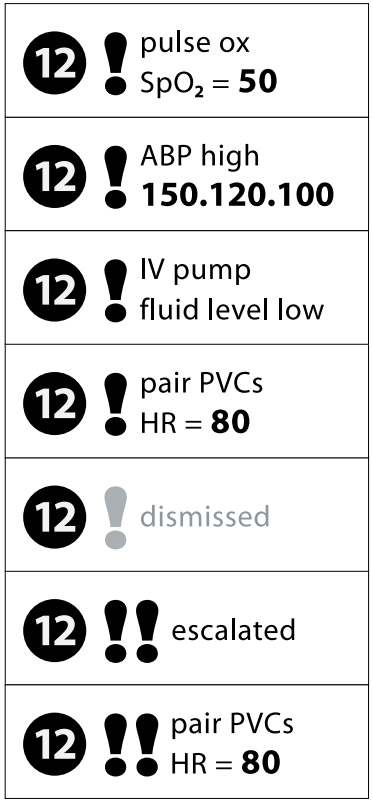
Detail of the information conveyed by alarm notifications, with the specific coding mechanism for each device

notifications

Visual notifications use a common visual language across alarms and across devices.



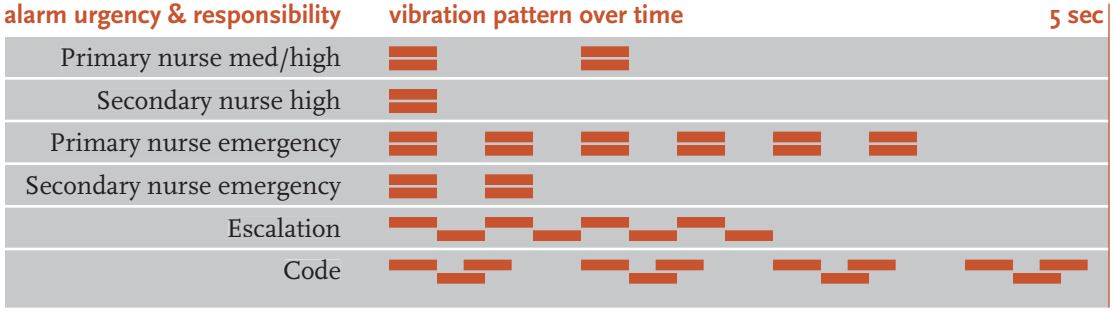
Alarm notifications as they appear on networked displays. The color coding matches the flashing hall lights to indicate the category of alarm.



Alarm notifications as they appear on the armband screen. Also shown are screens resulting from alarm dismissal and escalation.

notifications (continued)

Audio and tactile notifications use many of the same variables to map urgency and responsibility consistently across channels.



Visual representation of alarm notification vibration patterns on the armband by alarm urgency and patient responsibility. The two parallel bars represent the two vibrating motors over time.

To hear the **audio notifications**, please see the CD-ROM included with this book.

rules & relationships

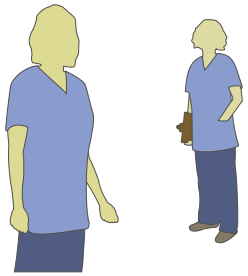
Devices and notifications represent only the visible part of MetaMonitor. Just as important are the rules and relationships that determine its behavior. The most important set of relationships is the hierarchy of alarm urgencies.

	Description	Examples	Notification
Low	Minor conditions that don't require immediate attention	• Bed deflated • IV pump running low	• Hall light • In-room info
Medium	Probably not serious, but should check	• Pulse oximeter	• Hall light • In-room info • Primary nurse notification
High	Potentially serious condition, needs prompt attention	• High arterial pressure	• Hall light • In-room info • Primary nurse notification • Secondary nurse notification
Emergency	Life threatening condition, requires immediate attention	• Ventricular tachycardia • Arterial line disconnect • Apnea	• Hall light • In-room info • Primary nurse notification • Secondary nurse notification • Audible alarm
Code	Extreme emergency, requires assistance from specialists. Must be called by nurses, not by monitoring equipment	• Asystole	• Hall light • General notification • Specialist notification • Audible alarm

Final alarm urgencies, including notification mechanisms for each level. The "low" urgency does not exist currently, but would allow unobtrusive notification of minor problems before they become major problems.

rules & relationships (continued)

Patient responsibility and location tracking also determine MetaMonitor's behavior.



Patient responsibility

MetaMonitor knows which nurse is responsible for which patient (the "primary" nurse) and which nurses happen to be nearby ("secondary" nurses). Different alarm notifications are given to each. Nurses can temporarily give responsibility to other nurses, if they're going on break for example.

Location tracking

MetaMonitor knows where nurses are within the unit by using an RFID-based real-time location system. This information is used to give different notifications when a nurse is already in the patient's room, to automatically silence alarms when nurses enter rooms, and to show relevant information on the networked display nearest to nurses.

infrastructure

MetaMonitor relies on several infrastructure elements that hospitals would need to put in place. Fortunately, all of them are starting to appear in hospitals, and all have other applications in addition to the proposed monitoring and alarm system.

Networking

In order to access any information anywhere, the displays have to be networked together and integrated with monitoring systems, as well as records, pharmaceutical, administrative, and other systems. Several vendors are already selling networked products.

Wireless communication

The armbands require wireless communication to notify nurses of alarms. Telemetry and other forms of wireless communication are increasingly used in intensive care units.

Device interoperability

In order for a system to collect and organize data from different monitoring devices, a standard protocol for exchanging information must be established. A few private standards exist, and a public standard is not inconceivable.

Location tracking

RFID tags are just starting to make real-time location systems (RTLS) feasible. Commercial versions are available, but have only been implemented in a few hospital environments.

benefits

MetaMonitor has many benefits over current monitoring and alarm systems. The benefits can be organized into a few categories.

Consistency

By unifying all alarms into a single framework with a consistent language, nurses would have less to learn and less to process. MetaMonitor conveys urgency, category, responsibility and location clearly and consistently across multiple notification channels.

Responsibility

MetaMonitor not only includes responsibility as part of the notification (by giving a different notification to primary and secondary nurses), but it also makes visible the fact that someone has responded to an alarm.

Targeting

By reserving general audio alarms for emergencies, MetaMonitor cuts down on the noise in the ICU, easing stress on patients.

Awareness

MetaMonitor provides a new summary view of patients, increasing nurses' monitoring capabilities. In addition, by pushing information out into the unit through distributed displays, the system makes patient information more accessible.

practicality

As well as being functional, MetaMonitor is designed to be practical within the financial realities of hospitals.

Works with existing equipment

MetaMonitor is not a replacement for existing monitoring equipment, but works with it. MetaMonitor can collect information from any type of monitoring device. Hospitals would not be required to buy new equipment or be locked into a proprietary system.

Modular design

MetaMonitor is designed to be flexible, working with many or few devices. In fact, any of the devices could be omitted altogether and the system would devolve gracefully. Without networked displays, for example, the armbands and lights would still work and would be an improvement over current systems.

APPENDIX A: BIBLIOGRAPHY

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APPENDIX B: SUMMARY OF FINDINGS FROM MEDICAL LITERATURE REVIEW

summary of findings: medical literature review

Activities

- 18% of alarms associated with patient interventions, 74% not associated. (Tsien and Fackler 1997)
- Most true alarms associated with interventions are clinically irrelevant, most not associated with interventions are relevant (Tsien and Fackler 1997).
- Most common reasons for alarms being silenced: procedures (drawing blood gases and suctioning) and patient movement (Tsien and Fackler 1997).

Environments

- Alarm noise cites as a leading cause of stress burnout in critical care nurses (Donchin and Seagull 2002).
- Patient sleep cycles disrupted by alarm sounds, leading to dementia ("ICU syndrome") (Donchin and Seagull 2002).

Interactions

- Average of one alarm every 37 minutes (Friesdorf, Buss, and Gobel 1999).
- 86% of alarms are false positive, 6% are clinically irrelevant, only 8% are clinically relevant (Tsien and Fackler 1997).
- In order to decrease the rates of false alarms, wider limits are set and alarms are disabled (Tsien and Fackler 1997).
- Priority and urgency of alarms is often poorly communicated (Meredith and Edworthy 1995; Mondor and Finley 2003; Solsona et al. 2001).
- Difficult to prioritize alarms in the ICU, because importance is heavily dependent on context (Donchin and Seagull 2002).
- Alarms focus on individual physiological measurements, not clinical big picture. No model for expected course of events. (Friesdorf, Buss, and Gobel 1999).
- Filters and other "intelligent alarm" approaches can reduce the number of false alarms (Becker et al. 1997; Chambrin 2001; Fried, Gather, and Imhoff 2001).

Objects

- At a minimum, patient is surrounded by respirator, monitor, and IV pool with 2-10 automatic infusion pumps (Donchin and Seagull 2002).
- Largest number of alarms and false alarms are from the pulse oximeter oxygen saturation signal. Arterial catheter mean blood pressure signal had lowest false alarm incidence, and highest clinical relevance. (Tsien and Fackler 1997).

Users

- The most junior nursing and medical staff manage the patients at the bedside where detailed physiological data is displayed on multichannel monitors. Lack of experience in pattern recognition and data overload lead to poor data discrimination and late diagnosis. (McIntosh 2002)
- More senior doctors are better at spotting and interpreting trends (McIntosh 2002).
- Technophiles tend to be drawn to the ICU (Clemmer 2003).

APPENDIX C: ICU OBSERVATION SHEETS

ICU observation sheets

Activities

Response to alarms

Device/alarm	Response	Information	Notes
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	

Activities

Procedures (diagnostics, routines, emergencies, etc.)

Procedure	People	Alarms	Notes

ICU observation sheets

Environment

Number of beds:

Staff/patient ratio:

Monitoring setup:

Central station:

Lighting:

Noise level:

Activity:

Interactions

ICU observation sheets

Objects

Bedside monitor	Data display	Alarms	Notes

Device	Data display	Alarms	Notes

Users

Person	Activities	Information	Notes
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	
		o Patient o Beside monitor o Other device o Chart o Other person	

APPENDIX D: ALARM TAXONOMY

alarm taxonomy

rm taxonomy.ooutline 11/18/03 2:17:3

Patient health			
• Temperature	Numeric	Hi, lo	Arterial, core, esophageal, rectal, skin, venous, nasopharyngeal
Cardiopulmonary			
Blood pressure	Waveform		Arterial, venous, atrial, ventricular, aortic, pulmonary arterial, umbilical arterial, umbilical venous, NBP
• Systolic	Numeric	Hi, lo	NBP, arterial line, Swan-Ganz catheter
• Diastolic	Numeric	Hi, lo	NBP, arterial line, Swan-Ganz catheter
• Mean	Numeric	Hi, lo	NBP, arterial line, Swan-Ganz catheter
• Disconnect	Boolean	Disconnect	Arterial line only
• Heart rate / pulse rate	Waveform (ECG/pressure), numeric	Hi, lo, extreme tachycardia, extreme bradycardia	NBP, arterial line, Swan-Ganz catheter, pulse oximeter, ECG
• Asystole	Boolean	Asystole	NBP, arterial line, Swan-Ganz catheter, pulse oximeter, ECG
• ST value	Waveform (ECG), numeric	Hi, lo	ECG
Arrythmia	Waveform (ECG), numeric, boolean		ECG
• Pacer	Waveform (ECG), boolean	Not capture, not paced	
• Irregular HR	Waveform (ECG), boolean	Irregular HR	
• Missed beat	Waveform (ECG), boolean	Missed beat	
• Pause	Waveform (ECG), boolean	Pause (time ≥ threshold)	
• Ventricular fibrillation/tachycardia	Waveform (ECG), boolean	Vent fib, V-tach	
• Non-sustained V-tach	Waveform (ECG), boolean	Non-sustained V-tach	
• Ventricular bigeminy, trigeminy	Waveform (ECG), boolean	Vent bigeminy, vent trigeminy	
• Ventricular rhythm	Waveform (ECG), boolean	Vent rhythm (adjacent Vs ≥ vent rhythm limit and vent HR ≤ Vtach HR limit)	
• Premature ventricular contractions	Waveform (ECG), boolean	Multi-form PVCs, pair of PVCs, run PVCs, R-on-T PVCs	
• Frequent PVCs	Waveform (ECG), numeric	Frequent PVCs (n ≥ limit)	
• Supraventricular beats	Waveform (ECG), boolean	Run SVTs (≥SVT limit)	
Blood gasses			
• SpO_2	Waveform, numeric	Hi, lo, desat limit	Pulse oximeter
• $Sv^{-}O_2$	???		Pulmonary artery catheter
• Trans-cutaneous CO_2	Numeric	Hi, lo	tcGas sensor

Pa

alarm taxonomy

• Trans-cutaneous O_2	Numeric	Hi, lo	tcGas sensor
▼ Cardiac output			Swan-Ganz catheter
• Continuous cardiac output		Hi, lo	
• CCI (based on CCO)	Numeric	Hi, lo	
• Blood temperature	Numeric	Hi, lo	
▼ Breathing			
• Respiratory rate	Waveform, numeric	Hi, lo, apnea (time ≥ limit)	ECG leads, capnography (mainstream airway, sidestream/microstream airway), anesthetic gas module
▼ Gases			
▼ Carbon dioxide	Waveform		Capnography (mainstream airway, sidestream/microstream airway), anesthetic gas module
• end tidal	Numeric	Hi, lo	
• inspired minimum	Numeric	Lo	
▼ Nitrous oxide, Oxygen	Waveform		anesthetic gas module
• end tidal	Numeric	Hi, lo	
• inspired	Numeric	Hi, lo	
▼ Anesthetic agents	Waveform		anesthetic gas module
• end tidal	Numeric	Hi, lo	
• inspired	Numeric	Hi, lo	
▼ Brain			
▼ Intracranial pressure	Waveform		ICP device
• Systolic	Numeric	Hi, lo	
• Diastolic	Numeric	Hi, lo	
• Mean	Numeric	Hi, lo	
• Cerebral perfusion (CPP)		Hi, lo	
• BIS		Hi, lo	BIS sensor
▶ **Devices**			

APPENDIX E: NURSE ACTIVITY TAXONOMY

activity taxonomy

Activity taxonomy: ICU nurses

	Activities	Observations	Opportunities & implications
Routine patient interaction	• Turning • Suctioning • Changing bedclothes • Physical therapy • Respiratory therapy • Medicating • Diagnostics (NBP)	• Many routine patient interactions have no reminder or alarm • Many activities involve either assisting or getting assistance from others • Recordkeeping not standardized for these activities • Patient intervention often causes clinically insignificant alarms	• Extend monitoring and alarming capability to include routine patient interactions not currently monitored (eg, turning, changing linens). But don't overdo it, too many alarms already • Improve, standardize, and/or automate recordkeeping • Reduce intervention-related alarms through context awareness
Non-routine patient interaction	• Admitting/discharging • Changing rooms • Surgery • Diagnostics (CO) • Adding/removing lines • Emergency/code	• Sometimes involves modifying alarm limits or setting up new alarms • Patient intervention often causes clinically insignificant alarms	• Reduce intervention-related alarms through context awareness
Recordkeeping	• Charting • Shift report	• Recordkeeping systems are often separate from monitoring systems, don't import data • Alarms don't appear on recordkeeping displays, only monitoring displays • The charting system is not available bedside, only monitoring information • Tacit knowledge (stories, explanations) aren't included in recordkeeping	• Integrate recordkeeping and monitoring systems • Make monitoring information more visible during recordkeeping activities • Formalize tacit knowledge into recordkeeping systems
Monitoring	• Listen for alarms • Check monitors • Observe patient	• Nurses have to look in many places for information • Often only find out about problems after the alarm sounds, not before • Numbers out of context have questionable utility • The patient is the primary source of information • Nurses develop stories to summarize and share patient status	• Consolidate and/or simplify information display • Display information to nurses in the locations where they most need it • Put numbers in context, allowing nurses to see problems before the alarm sounds • Map information to the patient's body • Formalize stories, possibly integrate them into recordkeeping systems

activity taxonomy

	Activities	Observations	Opportunities & implications
Alarm response	• Awareness, information, action (see model)	• Most alarms are clinically insignificant • Alarms are annoying, even to nurses • Many people hear alarms, few need to • Different categories of alarms are conveyed by different auditory signals, allowing nurses to quickly judge urgency • It's often difficult to locate the source of an alarm • The first action is often to silence the alarm, not tend to the patient • Many alarms go unanswered for extended periods of time • The charting system is not available bedside, only monitoring information • Numbers out of context have questionable utility • Silencing the alarm is often the only response, no patient intervention • Nuisance alarms lead nurses to silence alarms or adjust limits • Results of intervention sometimes have delayed effects, alarms continue to sound	• Improve predictive value of alarms • Make alarms less annoying • Target alarms to appropriate people • Need to preserve quick differentiation and categorization of alarms • Clearly convey location of alarm • Allow nurses to easily silence alarms • Improve alarm latching process, possibly combined with an escalationsystem • Integrate recordkeeping and monitoring systems • Put numbers in context, allowing nurses to see trends • Leverage context-awareness to improve alarm algorithms • Give nurses more control over alarm limits, changes over time
Interpersonal interaction	• Information exchange • Get advice/second opinion • Status reports • Logistics coordination • Assistance • Socializing	• Socializing serves important functions, including exchange of stories • Nurses cover for each other during breaks, need to know status and stories of patients • Visitors are more interested in stories than charts • Doctors are more interested in charts than stories • Structured knowledge (charts, etc.) rarely part of interpersonal information exchange	• Overhearing neighbors' alarms might serve an important role in keeping tabs on other nurses' patients • Facilitate interpersonal presentation of structured knowledge • Formalize tacit knowledge into recordkeeping systems

APPENDIX F: GENERATIVE SCENARIOS

generative scenarios

Scenarios

	Scenario	System requirements
routine monitoring	*Nurse at hall station* • Can see summary info for both patients, including trends • Gets status of / reminders for routine tasks • Quick access to detailed patient info: orders, charts, records, monitor data, pharmacy • Quick access to constellation contact info *Nurse in room* • Sees summary info for patient, including trends • Sees more detailed information for patient • Can see device information if desired • Gets status of / reminders for routine tasks • Quick access to detailed patient info: orders, charts, records, monitor data, pharmacy • Quick access to constellation contact info	• At-a-glance patient summary, easily visible from hall, charting workstation, or room • Routine task status/reminder system • Integrated record system • Contact mechanism • Detailed patient monitoring display • Patient records display • Device information display
alarms	*Nurse at hall station* • Alerted to alarm, patient, and alarm type • Sees summary info for patient, including trends • Sees more detailed information for alarm condition • Silences alarm • Quick access to detailed patient info: orders, charts, records, monitor data, pharmacy • Quick access to constellation contact info • When nurse enters room, alarm silenced, condition info remains	• Alarm system capable of alerting individual nurses • Indication of patient and alarm type • Alarm condition display, easily visible from hall, charting workstation, room, different room, and possibly elsewhere • Silencing mechanism • Location awareness • Public indication of alarms and response status

generative scenarios

	Scenario	System requirements
	Nurse in room • Alerted to alarm, patient, and alarm type • Sees summary info for patient, including trends • Sees more detailed information for patient • Sees more detailed information for alarm condition • Silences alarm • Can see device information if desired • Quick access to detailed patient info: orders, charts, records, monitor data, pharmacy • Quick access to constellation contact info • Response status conveyed to others *Nurse in different room* • Alerted to alarm, patient, and alarm type • Sees more detailed information for alarm condition • Silences alarm • Response status conveyed to others *Nurse elsewhere in unit* • Alerted to alarm, patient, and alarm type • Other nearby nurses alerted to alarm • Silences alarm • Response status conveyed to others *Nurse not in unit* • Other nearby nurses alerted to alarm • Silences alarm • Response status conveyed to others	
covering	• Departing nurse gives covering nurse summary of patient status, including orders, medications, status of routine tasks, and stories • Covering nurse has method of quickly contacting departing nurse • Covering nurse becomes primary nurse, gets info and alarms for patients • When departing nurse returns, covering nurse gives concise summary of events during departure	• Easily transferable patient status summary, with display mechanism • Patient responsibility transfer mechanism

generative scenarios

	Scenario	System requirements
shift change	• Departing nurse completes shift report • Departing nurse gives incoming nurse summary of patient status, including orders, medications, status of routine tasks, and stories • Incoming nurse has method of quickly contacting departing nurse • Incoming nurse becomes primary nurse, gets info and alarms for patients	• Integrated shift reporting
rounds	• Doctors see summary of patient status, including medications, status of routine tasks, and stories • Quick access to detailed patient info: orders, charts, records, monitor data, pharmacy • Quick access to constellation contact info • New orders conveyed to nurse	• Integrated order system
visitors	• Nurse gives visitors non-technical summary of patient status	• “Visitor view” of patient status

APPENDIX G: ALARM NOTIFICATION INFORMATION ENCODINGS

alarm notification information encodings

Information conveyed by notification mechanisms

Information	Mechanism	Coding
Alarm urgency	Hall light	• Rate of flashing
	Wearable device	• Rate of vibration pattern
	Audible alarm	• Rate of sound pattern
Alarm category	Hall light	• Light color
	Displays	• Alarm indication color
	Wearable device	• Audio tone
	Audible alarm	• Audio tone
Specific alarm condition	Displays	• Text description and numeric in alarm summary • Text description, numerics and detailed info in alarm detail
	Wearable device	• Text description and numeric on screen
Alarm condition context & decision-making info	Displays	• Trend line in alarm summary • Trends and detailed info in alarm detail
Which patient	Hall light	• Position in space of ICU
	Displays	• Room number in alarm summary
	Wearable device	• Room number on screen • Primary/secondary distinction made through vibration pattern
	Audible alarm	• Position in space of ICU
Presence of nurse in room	Hall light	• Flashing vs. steady
Nurse has responded	Hall light	• Steady
	Displays	• Alarm summary disappears
	Wearable device	• Vibration stops • Screen reverts to normal view
	Audible alarm	• Audible alarm ceases
Patient responsibility	Displays	• Primary nurse displayed on monitor in room
	Wearable device	• Room numbers on screen