Clinical paper

Understanding the "alarm problem" associated with continuous physiologic monitoring of general care patients

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Abstract

Study Aim: The aim of this study is to investigate the impact of alarm configuration tactics in general care settings.

Methods: Retrospective analysis of over 150,000 hours of medical/surgical unit continuous SpO2 and pulse rate data were used to estimate alarm rates and impact on individual nurses.

Results: Application of an SpO2 threshold of 80% vs 88% produced an 88% reduction in alarms. Addition of a 15 second annunciation delay reduced alarms by an additional 71% with an SpO2 threshold of 80%. Pulse rate alarms were reduced by 93% moving from a pulse rate high threshold of 120–140 bpm, and 95% by lowering the pulse rate low threshold from 60 to 50 bpm. A 15 second annunciation delay at thresholds of 140 bpm and 50 bpm resulted in additional reductions of 80% and 81%, respectively. Combined alarm frequency across all parameters for every 24 hours of actual monitored time yielded a rate of 4.2 alarms for the surveillance configuration, 83.0 alarms for critical care monitoring, and 320.6 alarms for condition monitoring. Total exposure time for an individual nurse during a single shift ranged from 3.6 min with surveillance monitoring, to 1.2 hours for critical care monitoring, and 5.3 hours for condition monitoring.

Conclusions: Continuous monitoring can eliminate unwitnessed/unmonitored arrests associated with significant increased mortality in the general care setting. The "alarm problem" associated with these systems is manageable using alarm settings that signify severely abnormal physiology to alert responsible clinicians of urgent situations.

Keywords: Clinical alarms, Failure to rescue, Alarm management, Surveillance monitoring, General care monitoring, Continuous monitoring

Introduction

Patients who have monitored and/or witnessed arrests are 2.4 times more likely to survive to discharge, although up to 27% of cardiopulmonary arrests go unwitnessed or unmonitored.[1] Continuous physiologic monitoring systems can be employed in the inpatient general care setting (i.e., medical/surgical units) to mitigate unwitnessed/unmonitored arrests by alerting clinicians to severe and sustained patient deterioration. Unfortunately, the so-called "alarm problem"[2] associated with continuous monitoring systems can make them ineffective, lead to distractions causing medical errors, and contribute to staff burnout.[3–7]

The Emergency Care Research Institute's Top Ten Health Technology Hazards list has included alarm hazards at or near the top since the list's inception in 2007. The Joint Commission,[8] the Association for the Advancement of Medical Instrumentation,[9] and the Anesthesia Patient Safety Foundation,[10] have advocated for and established alarm design and management guidelines,[7,11–17] focused predominantly on adoption of design and management concepts developed by other industries.[18] These approaches are based on well-founded cognitive science and human factors principles and decades of effective implementation.[11,14,19–23]

Alarm design and management are particularly challenging in general care where high patient to nurse ratios, increasing patient acuity, and workflow complexity place greater demand on clinician attention and capacity to respond. A surveillance approach to alarm configuration can be used to address these challenges. This approach is different from condition-specific monitoring commonly used in higher acuity care settings, where resources are more plen-

tiful and there is higher prevalence of patient deterioration events. Condition monitoring typically uses "tight" alarm thresholds, suitable for early detection of minor deviations from normal physiology in patients with known conditions or risk factors. In contrast, a surveillance model uses tactics such as "wide" parameter settings, alarm delays, and directed notification to reduce non-urgent alarms in populations with low or unidentified risk of deterioration, while still appropriately drawing attention to the bedside when life-threatening deterioration (i.e., cardiopulmonary arrest) occurs.[24]

Multiple studies demonstrate the benefits of alarm system design and surveillance monitoring principles.[25,26] Gross et al., for example, estimated a heart rate alarm load reduction of over 50% by changing the high heart rate alarm limit from 120 to 130 beats per minute (bpm). Similarly, changing the oxygen saturation limit from 90% to 85% and then to 80%, resulted in alarm load reductions of more than 36% and 65%, respectively.[27] Surveillance monitoring approaches also have higher adoption rates,[28] produce minimal non-urgent alarms,[13] are cost-effective, and yield positive patient safety impact.[15,29]

Despite this evidence, condition-specific monitoring alarm configurations are still common in the general care setting and alarm issues persist. While technology selection, performance measurement, and governance play pivotal roles in addressing the "alarm problem",[30] understanding principles of alarm system design and effects of alarm configuration are essential for long-term success of alarm-based devices.

This study supplements previous work by using continuous pulse oximetry monitoring data to compare alarm burden across a range of alarm settings. The study dataset constitutes the largest surveillance monitoring dataset described in the published literature, presenting a unique opportunity to estimate alarm rates within the range of the default surveillance alarm threshold settings (i.e., SpO2 above 80%, pulse rate (PR) greater than 50 and less than 140 bpm) with minimal confounders introduced by alarm-initiated interventions. The principal aim of this study is to investigate the impact of alarm configuration tactics in general care settings. This aim is accomplished by examining the effect of three key alarm features: activation thresholds, annunciation delays, and notification modes.

Methods

Setting

The study was carried out at a Level 1 trauma center in rural New England with over 1.6 million outpatient visits, nearly 28,000 discharges, and more that 23,000 procedures performed each year. Hospital patient acuity is in the top 5% in the United States.[31]

Pulse oximetry-based continuous monitoring is the standard of care in all 227 medical and surgical inpatient beds. Institutional policy requires patients to be monitored at all times, except when contraindicated (e.g., confused patients with risk of sensor cord entanglement) or when refused by the patient after a risk–benefit discussion. The monitoring system comprises bedside monitors with threshold-triggered alarms for SpO2 ≤ 80% and 50 ≤ PR ≤ 140), centralized data viewing stations, and nurse pager notification for alarm escalations (Masimo Root® and Radius® with Patient Safety Net®, Masimo Corp., Irvine, CA). Bedside monitor audible alarms are activated after 15 seconds for SpO2 and with no delay for PR. A message is sent to a nurse-worn pager if the audible alarm is active for 15 seconds and is escalated to multiple team pagers if the alarm condition persists for longer than 60 additional seconds. Re-escalation continues every 3 minutes as long as the alarm condition exists. Patient data collected at 1 Hz are archived to an institutionally maintained electronic medical record archive, including SpO2, pulse rate, alarm settings, and alarm status.

Study design and data set

This retrospective study was carried out with institutional review board approval. Matlab® (Mathworks®, Natick, MA, version 2020a) was used to perform all data analyses. SpO2, PR and alarm data were obtained from the data archive for 194 beds in 8 medical/surgical units over a 4-month period from November 2019–February 2020. Units were selected to provide a broad representation of patient physiology and conditions: two surgical units with predominant orthopedic, and thoracic/vascular populations; mixed medicine/-surgical units with ear, nose, and throat (ENT), neurology, hematology/oncology, and general populations; and three general medicine units. Admit/discharge information for the monitors was used to associate individual patients with bed-specific segments of surveillance data. Only patients with encounters classified as inpatient, observation, or same day overnight were included. Patients under 18 years old and those with incomplete data sets were excluded. Segments of surveillance data for patients moved from one bed to another during their hospital stay were analyzed separately. To ensure minimal impact on physiologic parameter values due to alarm-related interventions, individual parameter data in segments with alarm thresholds that were changed from the default for a parameter were eliminated from analysis. Patient characteristics including age, gender, and length of stay were obtained from the electronic medical record, and Charlson Comorbidity Index[32] (an independent predictor of 10-year survival) was calculated for each patient. Patient days were calculated as the number of days patients were present in each bed for any part of a calendar day. Actual monitored time was calculated as the total seconds data were recorded by the monitor. Descriptive statistics were used to compare distributions of parameter values, as well as patient age, gender, length of stay, and Charlson index.

Analysis of alarm frequency and duration

The impact of alarm thresholds and annunciation delays (i.e., a delay in activation of an alarm after trigger criteria are met) wasevaluated over a range of values bounded by surveillance monitoring settings using SpO2 and PR data. Audible alarm counts were estimated for SpO2 threshold values from 80% to 92% in 2% increments, 50–60 bpm in increments of 2 bpm for PR low, and 90–140 bpm in increments of 10 bpm for PR high. Annunciation delays from 0 to 15 seconds in increments of 5 seconds were used for all three parameters. Counts of initial pager notifications and escalations were calculated for each parameter separately using the standard offsets of 15 seconds from the audible alarm annunciation for the initial page, and 60 additional seconds for the escalation page.

Individual and combined parameter alarm characteristics were compared for three specific configurations: surveillance monitoring (SpO2 80%, PR low 50 bpm, PR high 140 bpm, 15 sec annunciation delay), critical care (SpO2 88%, PR low 50 bpm, PR high 140 bpm, no annunciation delay), and condition monitoring (SpO2 90%, PR low 60 bpm, PR high 120 bpm, no annunciation delay). Individual nurse alarm exposure was examined using mean unit size and typical values for nurse-to-patient ratio and shift length. Comparison

of performance with directed notification for escalation of alarms using paging vs unit-level alarm broadcast was also performed.

Results

There were 6172 monitor admission/discharge segments identified for the period of interest. One hundred ninety-nine (3.2%) segments were eliminated due to patient age <18 years, incomplete data/patient information, or encounter type. The remaining 5973 data segments represent 4744 separate patient encounters (hospitalizations) and 4108 unique patients. There were 1227 (25.9%) patient encounters with multiple surveillance segments, associated with patients admitted and discharged to the same device multiple times, or patients who changed location and were admitted to new devices during the encounter. The majority (98.91%) of segments contained surveillance data (i.e., the monitor collected patient data). Actual monitored time (days) was 6130.3 for SpO2, 9404.0 for PR low, and 10962.7 for PR high, whereas the number of patient days was 14,160 for SpO2, 17,520 for PR Low and 19,361 for PR high.

Mean patient age was 62.5 years (SD 16.5), 49% were females, mean Charlson score was 10.9 (SD 12.9); and mean length of stay was 3.4 days (SD 5.1). Seventy percent (3305) of SpO2 data segments, 95% (4495) of PR high data segments, and 84% (3974) of PR low data segments from the original dataset had default alarm settings set and were used in subsequent analysis. Distributions of SpO2, PR high and PR low for study data are shown in Fig. 1. SpO2 mean was 94.6% (SD 2.9), PR low mean was 82.0 bpm (SD 15.0), and PR high mean was 78.9 bpm (SD 15.0). Relatively small proportions of patient data were outside of surveillance settings: 0.04% for PR high; 0.07% for PR low; and 0.15% for SpO2. Proportions of data above/below condition monitoring threshold settings were significantly larger: 12.3% for SpO2, 3.22% for PR low, and 21.2% for PR high.

Fig. 2 shows the count of audible alarms, pager notifications, and escalations for SpO2, PR high, and PR low estimated with various thresholds and annunciation delays. In this example, alarm counts are normalized using actual monitored time to provide the most accurate estimation with respect to available parameter data. Significant reduction in alarm counts can be seen moving from application of typical critical care level thresholds towards a surveillance configuration with wider thresholds and increased annunciation delays. For instance, there is an 88% decrease in alarm rate between an SpO2 value of 80% and 88% with a 0 second annunciation delay. Adding a 15 second delay at SpO2 threshold of 88% further reduces the alarm rate by 71%. Similar differences are seen for PR high, with a 93% decrease moving from 120 to 140 bpm and a 95% reduction moving from 60 to 50 bpm. A 15 second annunciation delay at 140 bpm and 50 bpm results in an alarm rate difference of 80% and 81%, respectively. Less significant differences in alarm rates are seen at higher annunciation delays, as a substantial proportion of SpO2 (59–65%) and PR (low 61–73%; high 43–67%) alarms are less than 15 seconds in duration across all thresholds applied.

Table 1 summarizes alarm characteristics for the model surveillance, critical care, and condition monitoring configurations. SpO2 alarms account for the greatest proportion of alarms across all configurations, followed by PR low and PR high. Total alarm frequency combining all parameters yields a rate of 4.2 alarms for every 24 hours of actual monitored time for the surveillance configuration. In contrast, alarm frequency is an order of magnitude higher for critical care monitoring (83.0 alarms/day of monitored time) and two orders of magnitude higher for condition monitoring (320.6 alarms/day of monitored time). Similar patterns are observed for initial pages and escalation pages.

Table 1 also summarizes characteristics of alarm duration distributions for each configuration. Alarm annunciation delays are intended to reduce rates of short alarms often produced by brief changes in patient physiology. This effect can be seen in the higher mean durations for PR low and PR high for surveillance monitoring
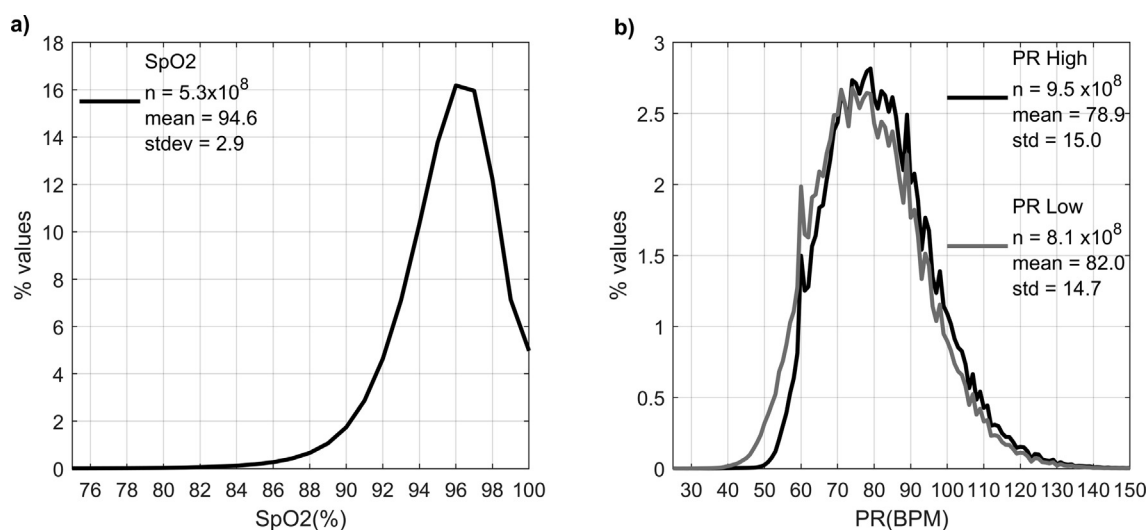

Fig. 1 – Parameter value distributions. Distributions of parameter values for segments when the parameter thresholds were at default settings are shown for (a) SpO2 and (b) PR low and high. Distributions for PR low and high are shown separately since thresholds for each parameter can be changed independently and only segments with the default settings in place for that parameter were included in calculations.
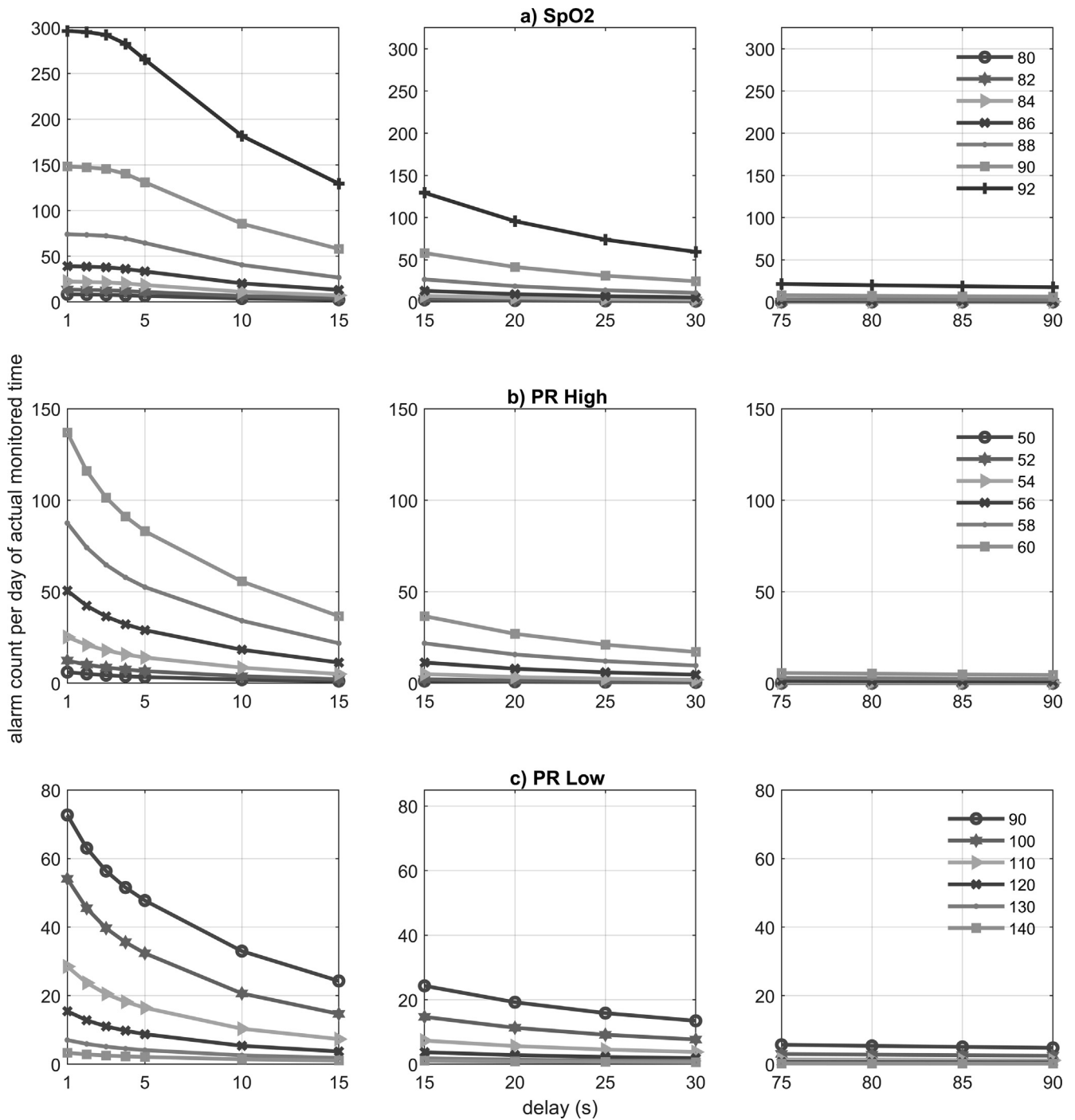
Fig. 2 – Alarm frequency across configuration parameters. Counts of estimated audible alarms for threshold and annunciation delay combinations normalized by days of actual monitored time are shown for (a) SpO2 (b) PR high (c) PR low. Total alarm time is reduced in each instance by the alarm delay applied. The figure is separated into panels to distinguish between rates of audible alarms (left panel) that would generate pager notifications (center panel) and pager escalation notifications (right panel) 15 seconds and 75 seconds after alarms are annunciated.

vs critical care monitoring. The thresholds for each configuration are the same, but the delay applied for surveillance eliminates a large proportion of alarms, shifting the mean upwards. PR low alarms have shorter mean duration than either SpO2 or PR high alarms for all configurations. Alarm duration and variation is highest for PR high using surveillance monitoring (mean 51.17 (SD 166.26)). Mean SpO2 duration is similar across configurations, although variation

increases moving from surveillance to condition monitoring. In terms of total alarm duration per 24 hours of actual monitored time, surveillance monitoring produces much less alarm sound (90.3 seconds) vs critical care (31.7 minutes) or condition monitoring (2.2 hours).

Cumulative alarm duration is represented as a proportion of actual monitored time in Fig. 3. Curves for each parameter illustrate how surveillance monitoring settings result in lower overall alarm

Table 1 – Summary alarm frequency and duration characteristics by configuration.

Alarm characteristics	Surveillance monitoring				Critical Care monitoring				Condition monitoring			
	SpO2	PR low	PR high	Total	SpO2	PR low	PR high	Total	SpO2	PR low	PR high	Total
Alarm frequency												
Audible Alarms	2.5	1.2	0.5	4.2	74.1	6.2	2.6	83.0	148.3	137.0	35.4	320.6
Pages	1.0	0.4	0.2	1.7	26.8	1.2	0.5	28.5	58.0	36.7	7.8	102.5
Escalation pages	0.1	0.0	0.0	0.2	3.2	0.1	0.1	3.3	8.0	5.6	1.4	15.0
Alarm duration												
Mean ± CI	20.7 ± 0.6	18.3 ± 0.47	51.2 ± 3.0		24.3 ± 0.2	11.1 ± 0.1	25.1 ± 0.2		29.0 ± 0.24	21.3 ± 0.15	23.6 ± 0.8	
Standard deviation	37.95	25.1	166.3		82.7	15.8	97.8		115.1	87.2	161.1	
Median/Mode	11/3	12/1	12/1		12/7	6/2	8/2		12/7	8/2	7/2	
Min-Max	1–1580	1–391	1–4917		1–8350	1–406	1–4932		1–12026	1–9147	1–19029	
IQR	20	19	37		14	10	17		15	14	12	
Total alarm duration (days)	3.7	2.4	6.9	13	127.6	7.5	10.7	145.8	304.6	316.9	46.3	667.8
Total duration/day of actual monitored time	52.0	21.6	16.7	90.3	30 min	68.7	35.1	31.7 min	71.6 min	48.5 min	11.6 min	131.7 min

Total alarm counts, pages, and escalation pages are shown for each configuration. Alarm counts are normalized by days of actual monitored time. Total alarm duration is normalized by day and by days of actual monitored time. Mean alarm duration and other distribution characteristics are also shown. Alarm duration metrics are in seconds, unless otherwise noted.
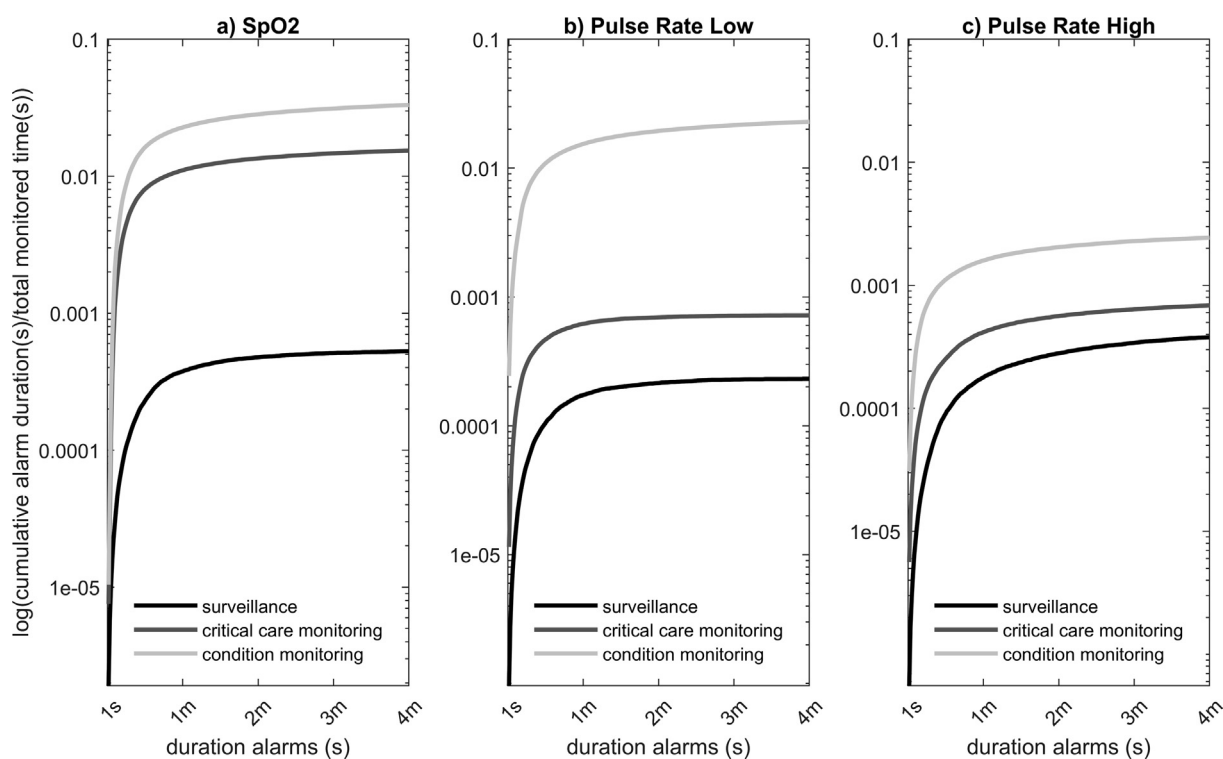

Fig. 3 – Cumulative clinical alarm duration. Proportion of cumulative alarm durations normalized by actual monitored time up to four minutes of alarm duration is shown using a log scale for surveillance, critical care, and condition monitoring configurations.

duration, with orders of magnitude difference observed in the proportion of monitored time that alarms are active between surveillance, critical care, and condition monitoring. Short duration alarms contribute to the majority of total SpO2 and PR low alarm time, e.g., with 65.4% and 72.8% of total alarm time coming from alarms of one minute or less with surveillance settings. PR high alarms have a higher proportion of longer alarms with only 28.7% of total alarm time coming from alarms up to 1 minute in length. Similar patterns are seen for critical care and condition monitoring.

Table 2 illustrates the effect of using directed alarm notification and alarm exposure for an individual nurse. In this analysis, alarm counts and duration are normalized by patient days adjusted by unit

Table 2 – Impact of directed notification on nurse alarm exposure.

Exposure metrics for 1 nurse during a shift			Surveillance monitoring	Critical Care monitoring	Condition monitoring
Alarm Counts	Directed notification	Audible alarms	10.1	184.6	788.7
		Pages	2.0	31.3	123.1
		Escalation pages	0.4	7.2	36.2
	Broadcast notification	Audible alarms	25.2	461.4	1971.7
Alarm Duration	Directed notification	Duration	3.6 min	1.2 h	5.3 h
		Duration after page	59.5 s	18.8 min	1.6 h
		Duration after escalation	32.9 s	17.3 min	1.7
	Broadcast	Alarm duration	9.1 min	2.9 h	13.2 h

Patient to nurse ratio of 5:1, 12-hr nurse shift, and unit size of 25 beds were used to estimate alarm burden for an individual nurse. For directed notification, it was assumed that each nurse would hear alarms from 10 patients including 5 assigned beds and 5 other neighboring beds. They would receive pages for 5 patients, and escalations would be received from 10 patients. For broadcast alarms, all 25 beds would produce alarms heard by each nurse.

size and nurse to patient ratio to appreciate the experience of the bedside nurse during an entire shift. With directed notification, nurse exposure ratios were 18:1 for SpO2, 16:1 for PR low, and 18:1 for PR high using critical care vs surveillance monitoring settings while a change from surveillance to condition monitoring increases nurse exposure to 78:1 for SpO2, 62:1 and 90:1 for PR low and high, respectively. The total duration of alarms increases from seconds to minutes to hours moving from surveillance to critical care to condition monitoring. There are 2.5 times more audible alarms using a broadcast approach to notification vs directed notification.

Discussion

This study demonstrates that alarm behavior calculated using various combinations of alarm activation thresholds, annunciation delays, and notification modes revealed profound differences in alarm rates reaching unit staff, individual nurses, and patients. Remarkably, the study shows that when broadcast (community audible) alarms with condition monitoring settings are used, a nurse on a 25-bed unit will be exposed to 1971 alarms during a 12-hour shift. This equates to 2.74 alarms being initiated each minute of their busy shift, all while managing medications, providing usual care, and responding to acute problems for their patients. Clearly, most of the patients whose SpO2 and PR values would have generated these alarms did not require immediate assistance at the bedside. Furthermore, the cognitive overload created by constant alarm noise reduces clinicians' ability to recognize actionable alarms, and increases risk of the effects of the widely studied[5–7,11] and publicized[3,4] "alarm problem". In contrast, surveillance settings with directed notification reduce nurse exposure nearly 80-fold to 10 audible alarms and 60-fold to only two pages per 12-hour shift.

The surveillance approach to alarm configuration shifts the clinical objective from notification of minor physiologic abnormalities (e.g., condition monitoring approach) to focus on severe and sustained abnormalities that truly need immediate investigation, with sufficient time to mitigate patient harm or death.[33] Each of the three alarm configuration tactics considered in this analysis contributes to this goal: alarm trigger thresholds that signify severely abnormal physiology; annunciation delays that eliminate alarms from transient phenomena due to signal noise or self-correcting conditions; and directed notification to alert only responsible clinicians about urgent situations.

This work represents the largest and most comprehensive general care setting alarm study to date, with analysis of over 150,000 hours of pulse oximetry-based continuous monitoring data from 4744 general care inpatient encounters. The study is also distinctive in comparison to other alarm studies given that it: provides a unique opportunity for analysis with minimal alarm/intervention interference due to application of surveillance settings during data collection; includes all adult (≥18 years) inpatients in the study units with no exclusions for diagnosis, comorbidities, or other variables; uses a comprehensive range of values for alarm features to illustrate alarm burden; and demonstrates the individual and combined impact of configuration settings on alarm burden, alarm escalations, and nurse exposure.

This study has several limitations and reveals opportunity for additional work. The study data used in the analysis was acquired from a single, high acuity tertiary care center, whose population may not be representative of other organizations. The exclusion of data from patients for whom alarm settings were changed from the surveillance default minimizes, but does not eliminate, the effects of alarm-associated interventions, environmental conditions, or variation in nursing practice within or across units. No attempt was made to relate these data to the level of actionability or response to alarms (i.e., clinical interventions, alarm silencing) or patient outcomes. Specifically, the study does not quantify the effect of earlier rescue prompted by appropriately configured alarm settings in reducing progression to severe levels of deterioration. However, other studies have documented the effects of surveillance monitoring and suggest positive long-term impact on patient outcomes.[13,33] We also acknowledge that there are other alarm system features not considered in this analysis and indeed other system-level tactics, such as patient state scores and remote assessment, that can help address the alarm problem. This study evaluates only clinical alarm characteristics and the effect of simultaneous alarms generated from multiple patients or concurrent alarms triggered by multiple parameters in the same patient were not assessed. Analysis is focused on monitoring for detection of severe deterioration events such as cardiopulmonary arrest, and does not address the management of all alarming devices that "load" the care team at the bedside. However, all hospitals have learned to differentiate urgent/emergent systems such as a code blue paging system, from standard pages used for routine communication of non-critical information.

Conclusion

Unrecognized/unwitnessed cardiopulmonary arrest is associated with significantly increased morbidity and mortality due to delays in initiating resuscitative care.[34] This study illustrating the impact of alarm configuration on alarm rates and duration demonstrates that the "alarm problem" should not be a barrier to implementing continuous monitoring using a surveillance configuration to address this important patient safety issue.[35–37]

Conflict of Interest Statement

Authors McGovern and Perreard declare no competing interests. Author McGrath declares a consulting relationship with Masimo, Inc. to provide educational talks about surveillance monitoring. Author Blike declares a relationship with the I-PASS Institute and The Family Heart Foundation, unrelated to this work.

CRediT authorship contribution statement

Susan P. McGrath: Conceptualization, Writing – original draft, Methodology, Formal analysis, Visualization, Funding acquisition, Project administration, Supervision. **Irina M. Perreard:** Writing – original draft, Software, Formal analysis, Conceptualization, Methodology, Visualization. **Krystal M. McGovern:** Conceptualization, Writing – original draft, Methodology, Formal analysis. **George T. Blike:** Conceptualization, Writing – original draft, Methodology, Formal analysis.

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