Video Analysis of Factors Associated With Response Time to Physiologic Monitor Alarms in a Children’s Hospital

Christopher P. Bonafide, MD, MSCE; A. Russell Localio, PhD; John H. Holmes, PhD; Vinay M. Nadkarni, MD, MS; Shannon Stemler, BA; Matthew MacMurchy, BA; Miriam Zander, BA; Kathryn E. Roberts, RN, MSN; Richard Lin, MD; Ron Keren, MD, MPH

IMPORTANCE Bedside monitor alarms alert nurses to life-threatening physiologic changes among patients, but the response times of nurses are slow.

OBJECTIVE To identify factors associated with physiologic monitor alarm response time.

DESIGN, SETTING, AND PARTICIPANTS This prospective cohort study used 551 hours of video-recorded care administered by 38 nurses to 100 children in a children’s hospital medical unit between July 22, 2014, and November 11, 2015.

EXPOSURES Patient, nurse, and alarm-level factors hypothesized to predict response time.

MAIN OUTCOMES AND MEASURES We used multivariable accelerated failure-time models stratified by each nurse and adjusted for clustering within patients to evaluate associations between exposures and response time to alarms that occurred while the nurse was outside the room.

RESULTS The study participants included 38 nurses, 100% (n = 38) of whom were white and 92% (n = 35) of whom were female, and 100 children, 51% (n = 51) of whom were male. The race/ethnicity of the child participants was 45% (n = 45) black or African American, 33% (n = 33) white, 4% (n = 4) Asian, and 18% (n = 18) other. Of 11 745 alarms among 100 children, 50 (0.5%) were actionable. The adjusted median response time among nurses was 10.4 minutes (95% CI, 5.0-15.8) and varied based on the following variables: if the patient was on complex care service (5.3 minutes [95% CI, 1.4-9.3] vs 11.1 minutes [95% CI, 5.6-16.6] among general pediatrics patients), whether family members were absent from the patient’s bedside (6.3 minutes [95% CI, 2.2-10.4] vs 11.7 minutes [95% CI, 5.9-17.4] when family present), whether a nurse had less than 1 year of experience (4.4 minutes [95% CI, 3.4-5.5] vs 8.8 minutes [95% CI, 7.2-10.5] for nurses with 1 or more years of experience), if there was a 1 to 1 nursing assignment (3.5 minutes [95% CI, 1.3-5.7] vs 10.6 minutes [95% CI, 5.3-16.0] for nurses caring for 2 or more patients), if there were prior alarms requiring intervention (5.5 minutes [95% CI, 1.5-9.5] vs 10.7 minutes [5.2-16.2] for patients without intervention), and if there was a lethal arrhythmia alarm (1.2 minutes [95% CI, −0.6 to 2.9] vs 10.4 minutes [95% CI, 5.1-15.8] for alarms for other conditions). Each hour that elapsed during a nurse’s shift was associated with a 15% longer response time (6.1 minutes [95% CI, 2.8-9.3] in hour 2 vs 14.1 minutes [95% CI, 6.4-21.7] in hour 8). The number of nonactionable alarms to which the nurse was exposed in the preceding 120 minutes was not associated with response time.

CONCLUSIONS AND RELEVANCE Response time was associated with factors that likely represent the heuristics nurses use to assess whether an alarm represents a life-threatening condition. The nurse to patient ratio and physical and mental fatigue (measured by the number of hours into a shift) represent modifiable factors associated with response time. Chronic alarm fatigue resulting from long-term exposure to nonactionable alarms may be a more important determinant of response time than short-term exposure.

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Factors Associated With Response Time to Physiologic Monitor Alarms

Original Investigation Research

Physiologic monitors are intended to help clinicians detect clinical emergencies by alarming when vital signs exceed preset thresholds or when cardiac arrhythmias occur. For alarms to be effective, they should activate only for serious physiologic changes and be considered important by staff members. Unfortunately, most current physiologic monitors generate high rates of alarms that are rarely actionable. In 6 studies of pediatric wards and intensive care settings, monitor alarm rates ranged from 1.5 to 24 alarms per monitored patient-hour. In pediatric intensive care settings, 5 studies found that 3% to 13% of physiologic monitor alarms warranted action, and 1 study performed on a pediatric ward found that only 1% warranted action. Perhaps as a result, the response times of nurses to alarms were slow. A delayed response to a patient whose alarm represents impending cardiac arrest could be catastrophic.

National surveys of health care staff members performed in 2005 and 2011 ranked “frequent false alarms, which lead to reduced attention or response to alarms when they occur” as the most important alarm issue to address. More than 75% of respondents agreed or strongly agreed that nuisance alarms reduce trust in alarms and cause caregivers to inappropriately turn alarms off. As a result, nurses likely develop the expectation that most physiologic monitor alarms are not important and prioritize other routine care tasks above responding to alarms when they are busy unless there are specific concerning features of the patient or the alarm.

Video recording provides an opportunity to thoroughly evaluate and improve the quality of care delivered in hospitals. In a previous pilot study using video, we identified an association between increased nonactionable physiologic monitor alarm exposure (a proxy for acute alarm fatigue) and delayed nurse response time. In this study, we examined a broader set of exposure variables and evaluated the associations of patient-, nurse-, and alarm-level factors with the response time of nurses to physiologic monitor alarms.

Methods

Study definitions are provided in the Box. We conducted this prospective cohort study on 1 inpatient unit admitting patients to the general pediatrics and medically complex services at The Children’s Hospital of Philadelphia between July 22, 2014, and November 11, 2015. The medically complex service admits patients with a wide range of comorbidities and technology dependence. Examples include patients with intestinal failure, complications of extreme prematurity, genetic syndromes, and other diagnoses that result in a population that is medically fragile and often requires intensive care during hospital admissions. Patients on this unit undergoing continuous cardiorespiratory and/or pulse oximetry monitoring were eligible. To gain the analytic benefits of contrasting the effects of different exposures within individual nurses over time, we invited the nurses of eligible patients to participate in multiple sessions.

This study was approved by the institutional review board of The Children’s Hospital of Philadelphia. We obtained written in-person consent from each patient’s parent and nurse. We obtained a Certificate of Confidentiality from the National Institutes of Health to reassure and protect hospital employees if the research video was subpoenaed. We could then use the Certificate to legally refuse to disclose any video recordings or associated data.

Monitoring Equipment and Secondary Notification

All bed spaces included General Electric Dash 3000 (General Electric) monitors that were used if ordered by the physician. Physicians specified alarm parameters using an electronic clinical alarm that correctly identifies the physiologic status of the patient. Validity was based on waveform quality, signal strength indicators, and artifact conditions, referencing the monitor’s operator’s manual.

Actionable alarm: A valid clinical alarm that either (1) leads to an observed clinical intervention (such as initiating supplemental oxygen) or (2) leads to an observed consultation with another clinician (such as discussing the patient’s tachycardia with a resident) at the bedside or (3) warrants intervention or consultation for a clinical condition (such as a prolonged desaturation) but the condition was unwitnessed: occurring while no clinicians are present and resolving before any clinicians entered the room or visualized the central monitoring station.

Nonactionable alarm: An alarm that does not meet the actionable definition above, including invalid alarms such as those caused by motion artifact, alarms that are valid but nonactionable, and technical alarms.

Technical alarm: An alarm for a problem with the physiologic monitor device or associated sensors.

Key Points

Question: What factors are associated with response time to hospital physiologic monitor alarms?

Findings: In this cohort study, alarms for patients on a complex care service or without family members present received faster responses. Nurses who responded faster included those who were earlier in their shifts, had less than 1 year of experience, previously responded to an alarm requiring intervention, were caring for only 1 patient, and were responding to an alarm for lethal arrhythmia.

Meaning: Response time was associated with factors that likely contribute to heuristics that nurses use to assess the probability that a patient’s condition is life threatening.

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health record order set with age-based defaults. Changing parameters required new orders. A central monitoring station with a display of all the waveforms of all of the unit’s monitored patients was at the nurses’ station, but there were no staff members assigned to review alarms centrally.17

On the unit we studied, approximately 40% of patients were continuously monitored. In addition to alarming at the bedside, alarms for asystole, ventricular tachycardia, ventricular fibrillation, apnea, heart rate, respiratory rate, oxygen saturation by pulse oximeter, pulse oximeter probe off, and leads fail also automatically sent text messages to the bedside nurse (Table 1).

Table 1. Characteristics of the 11710 Evaluable Clinical Alarms

<table>
<thead>
<tr>
<th>Alarm Label</th>
<th>Alarm Condition</th>
<th>Text to Nurse Phone</th>
<th>Total No.</th>
<th>No. (%)</th>
<th>Valid</th>
<th>Actionable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical arrhythmias</td>
<td>Asystole Asystole Yes 44 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>V Tach ≥6 Beats of ventricular tachycardia Yes 18 0 0</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>VFib/VTac Ventricular fibrillation Yes 2 0 0</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Noncritical arrhythmias</td>
<td>PVC Premature ventricular contraction No 1220 10 (0.8) 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>PVC HI Threshold for No. of premature ventricular contractions exceeded No 106 0 0</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>Irregular Irregular rhythm No 135 36 (26.7) 0</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Couplet Couplet No 159 1 (0.6) 0</td>
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<tr>
<td></td>
<td>Bigeminy Bigeminy No 3 0 0</td>
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<tr>
<td></td>
<td>Trigeminy Trigeminy No 3 0 0</td>
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<tr>
<td></td>
<td>R on T Ventricular contraction near T-wave peak No 28 0 0</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Pause RR interval exceeds set duration No 26 0 0</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>VT &gt; 2 3-5 Rapid ventricular contractions No 30 0 0</td>
<td></td>
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</tr>
<tr>
<td>Pulse oximetry</td>
<td>SpO2 LO Low oxygen saturation Yes 3265 608 (18.6) 43 (1.3)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Heart rateb</td>
<td>Tachy Tachycardia using ECG arrhythmia algorithm No 1531 1512 (98.8) 0 (0.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HR HI Tachycardia using ECG rate algorithm Yes 1328 1291 (97.2) 1 (0.1)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rate HI Tachycardia using SpO2 pulse rate algorithm No 251 245 (97.6) 0</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Brady Bradycardia using ECG arrhythmia algorithm No 346 221 (63.9) 2 (0.6)</td>
<td></td>
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<tr>
<td></td>
<td>HR LO Bradycardia using ECG rate algorithm Yes 95 62 (65.3) 1 (1.1)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>Rate LO Bradycardia using SpO2 pulse rate algorithm No 1 1 (100.0) 0</td>
<td></td>
<td></td>
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<tr>
<td>Respiratory rate</td>
<td>RSP HI Respiratory rate, high Yes* 574 431 (75.1) 1 (0.2)</td>
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<td></td>
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<tr>
<td></td>
<td>RSP LO Respiratory rate, low Yes* 312 202 (64.7) 0 (0.0)</td>
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<tr>
<td></td>
<td>Apnea No breath detected in 15 seconds (infant) or 20 seconds (child/adult) Yes 13 9 (69.2) 2 (15.4)</td>
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<tr>
<td>Blood pressure</td>
<td>NBP S HI Systolic blood pressure, high No 21 12 (57.1) 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NBP M HI Mean blood pressure, high No 8 8 (100.0) 0</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>NBP D HI Diastolic blood pressure, high No 27 18 (66.7) 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST segment</td>
<td>ST-I HI ST segment elevation in lead I No 1 0 0</td>
<td></td>
<td></td>
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<tr>
<td>Overall</td>
<td>9547 4667 (48.9) 50 (0.5)</td>
<td></td>
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</tr>
</tbody>
</table>

Abbreviations:
ECG, electrocardiogram; RR, respiratory rate; SpO2, oxygen saturation.

* All alarms generated immediate audible alerts at the bedside and at the central monitoring station. Only a subset of the alarms generated automatic text messages and sent them to the bedside nurse’s phone, as shown in the Table.

b Tachy and Brady heart rate alarms are generated using a different algorithm than HR HI and HR LO; all 4 are generated using the ECG leads. Rate LO and Rate HI alarms are generated using the SpO2 probe.

* Respiratory rate high and low alarms are sent to the nurse's phone 15 seconds after they occur at the bedside. If the condition resolves during the 15 seconds, a text message is not sent. All other text messages are sent without a delay as soon as alarms occur at the bedside.

Data Collection
We combined video recordings with time-stamped alarm data from BedMasterEx software (Excel Medical Electronics) running on a server connected to the monitor network. Our recording and annotation methods have been described.
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previously, and the acceptability, feasibility, and costs of performing this study have been reported. We temporarily mounted up to 6 small video cameras in the rooms of patients and 1 camera on the central monitoring station and recorded for approximately 6 hours per session. The camera on the central monitoring station captured any responses that occurred when nurses visualized monitors remotely.

**Video Review**
We trained a research assistant to review the video recordings and determine the validity and actionability of clinical alarms. During the training period, the research assistant reviewed 4675 clinical alarms (every clinical alarm that required interpretation from the first 42 patients) with oversight from an expert in physiologic monitoring (Bonafide).

We then determined if the research assistant could accurately review alarms independently. The research assistant and expert separately reviewed every clinical alarm that required interpretation from 10 additional patients (n = 883 alarms). The research assistant and expert agreed on the validity determination for 99.3% of the 883 alarms. Using the expert as the gold standard, the research assistant’s sensitivity (she assessed an alarm as valid when the physician also did) was 99.4% (95% CI, 97.9%-99.9%) and her specificity (she assessed an alarm as invalid when the physician also did) was 99.3% (95% CI, 98.1%-99.8%). The research assistant and expert agreed on the actionability determination for 99.7% of the 883 alarms. The research assistant’s sensitivity was 100% (1-sided 97.5% CI, 99.8%-100%) and her specificity was 99.9% (95% CI 99.0%-99.9%). Based on these results, for the remaining 48 patients the expert performed a secondary review of only the clinical alarms that the research assistant determined to be valid.

**Response Time Outcome**
Our analysis examined response time, measured as the number of seconds elapsing between the start time of each audible alarm on the bedside monitor and the time a clinical staff member either entered the patient’s room or viewed the central monitoring station. Since all patients on the unit had their waveforms displayed on the central monitoring station, we conservatively assumed that any viewing of the central monitoring station included viewing the vital signs of the patient under study and counted as a response. Responses by other clinical staff members were censored at the time of their response.

We limited our analyses of response time to “out-of-room” alarms that (1) occurred while no clinicians were in the patient’s room or were viewing the central monitoring station, and (2) sent an automatic text message to the bedside nurse (Box). We focused on these alarms because we wanted to identify the factors influencing the decision nurses must make when they receive an alarm notification, whether that is to interrupt their current patient care task and respond immediately or whether to delay responding until their current task is complete.

**Exposures of Interest**
In planning the exposure variables to measure and include in the analysis, we developed a theoretical framework linking constructs such as a “nurse’s concern that patient is at increased risk of a life-threatening event” with specific variables and response time (eFigure in the Supplement). Since our previous pilot study identified an association between the number of nonactionable alarms to which a nurse was exposed for the same patient in the preceding 120 minutes and response time, we also evaluated nonactionable alarm exposure groups as exposure variables. We divided the nonactionable alarm counts into quartiles of increasing alarm frequency exposure in our primary analysis. To explore the stability of our findings, we also examined nonactionable alarm count exposure divided into tertiles and the categories we previously used in our pilot.

**Statistical Analysis**
We first analyzed the data without the nonactionable alarm exposure variables. We visually examined the relationships between each exposure variable and nurse response time with unadjusted Kaplan-Meier failure plots. We then constructed a multivariable accelerated failure-time model based on the Weibull distribution stratified by each nurse with clustering by patient. This stratified model evaluated the within-nurse effects of different exposures. Accelerated failure-time models are comparable with Cox models but emphasize the time to an event rather than hazards. We included all of the variables in the multivariable model regardless of significance level to describe the adjusted contribution of each. We reported the adjusted median response times and 95% confidence intervals for each variable subgroup as estimated in the model and the P values contrasting pairs of subgroups, adjusted for multiple comparisons using the Bonferroni method whenever more than 1 comparison was made. Statistical significance was set at P = .05. Since nurse experience does not vary within nurses, it could not be estimated directly from the stratified model. We obtained this estimate adjusted for all of the variables included in the stratified model from a separate model that allowed for the estimation of nurse-level factors and accounted for nurse clustering.

We then restricted the data set to alarms occurring after the first 120 minutes of video recording to estimate the association between nonactionable alarm exposure in the preceding rolling 120-minute window and the response time of nurses. We analyzed the relationship between nonactionable alarm exposure groups and response time and adjusted for all of the other variables in the theoretical framework in the same multivariable accelerated failure-time model stratified by nurse with clustering by patient.

For further details on our model building and evaluation, please refer to the eMethods in the Supplement. We used REDCap (Vanderbilt) for our data entry and management and Stata/SE version 14.1 (StataCorp) for our statistical analysis.

**Results**
We performed 100 video recordings among 100 patients and 38 nurses over 551 hours. Each nurse participated in a median of 3 (range, 1-6) video recordings. Nurses were female (100%) and predominantly white (92%). They had a median of 2 years
of experience (range, 2 months-20 years). Most (79%) worked 36 or more hours per week, usually in 8- to 12-hour shifts.

Most patients (82%) were admitted to the general pediatric service, with 18% on the medically complex service. Consistent with the population of the unit, patients were young, with 75% younger than 6 months. Fifty-one percent were male.

The race distribution was 45% black or African American, 33% white, 4% Asian, and 18% other.

We captured 11,745 alarms on video (9,582 clinical and 2,163 technical), averaging 21.3 alarms per monitored patient-hour. Alarms per patient ranged from 0 to 484 (median, 90; interquartile range, 59-163). We excluded 35 alarms (0.3%) for which a response could not be determined because of camera obstruction. Overall, 48.9% of the clinical alarms were valid and 0.5% (50 alarms among 19 patients) were actionable. Further details about actionable alarms are in the eTable in the Supplement. There were no instances of missed alarms that required emergency assistance in the form of a rapid response or code blue team call. Details by alarm type are in Table 1. The data flow diagram is in the Figure.

We found that with each successive hour that passed in a nurse’s shift, response time was slower. Nurses with less than 1 year of experience and those in a 1 to 1 nurse to patient assignment responded more quickly than nurses with more experience and those caring for more than 1 patient, respectively. Patients without family members present at the bedside and those on the complex care service had their alarms responded to more quickly than those with parents present and those on the general pediatrics service, respectively. Patients with prior alarms during the nurse’s shift that required interventions were responded to more quickly than those without prior interventions. Lethal arrhythmia alarms received the fastest responses. Patient age, central venous catheters, and nasogastric/nasojugal tubes were not associated with response time.

In evaluating the association between nonactionable alarm exposure quartiles and response time, we found that the middle quartiles had significantly slower response times than the lowest quartile, possibly consistent with acute alarm fatigue, but there was no evidence of a dose-response relationship between increasing nonactionable alarm exposure and slowing of response time (Table 3). We examined nonactionable alarm count exposure divided into tertiles and the groupings we previously used in our pilot and the results were similar (data not shown).
Abbreviations: NG, nasogastric; NJ, nasojejunal.

without those characteristics; (2) nurses responded faster if they
the bedside received faster responses than alarms for patients
complex care service and patients without family members at
This study’s main findings were (1) alarms for patients on the
Discussion

A Adjusted for 3 comparisons using the Bonferroni method.

b Evaluated as a continuous variable in model; hours 2 and 8 are presented as

clustering.

allowed for the estimation of nurse-level factors and accounted for nurse
adjusted estimate reported here was obtained from a separate model that
response time could not be estimated directly from the stratified model. The
representative examples. Time ratio 1.15 (95% CI, 1.04-1.28; P=.001).

Between Groups

<table>
<thead>
<tr>
<th>Value of Contrast</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartile 1: 0-17 alarms vs Quartile 2: 18-31 alarms</td>
<td>.46</td>
</tr>
<tr>
<td>Quartile 2: 18-31 alarms vs Quartile 3: 32-52 alarms</td>
<td>.97</td>
</tr>
<tr>
<td>Quartile 3: 32-52 alarms vs Quartile 4: ≥53 alarms</td>
<td>&gt;.97</td>
</tr>
</tbody>
</table>

had less than 1 year of experience, if they were in a 1 to 1 assignment,
or if they had previously responded to an actionable alarm for the
same patient that required intervention; (3) lethal arrhythmia alarms received the fastest responses among all of the
variables we measured; (4) each hour that passed in a nurse’s shift was associated with longer response times; and (5) the
number of nonactionable alarms to which the nurse was exposed in the preceding 120 minutes was not associated with a
dose-dependent slowing of response time.

It is well established that nurses use intuition and heuristics in clinical decision making.23 We theorize that the decision
whether to respond immediately to an alarm is based on heuristics, to which many of the factors described earlier contribute. These heuristics are used to make intuitive judgments about the probability that the alarm represents a life-threatening condition that warrants an immediate response to prevent patient harm. The finding of faster responses among the least experienced nurses could be explained by a lack of chronic alarm fatigue, although alternative explanations (eg, the least experienced nurses were more nervous or less skilled at triaging important vs unimportant alarms) are also possible. Slower response times with each hour of work likely represents physical and mental fatigue.

Compared with the pilot study we previously published using the same video recording methods on the same unit,4
response time in this study was faster overall (7.0 vs 9.8 minutes) and we did not find a dose-dependent slowing of re-
response time with increasing nonactionable alarm exposure. There are several possible explanations for this. The first is that this is a larger study with over 5-fold more alarms in the same setting, and the association seen in the pilot study could have been incidental. Another possibility is that nursing practices surrounding alarm management have changed. Since this pi-
lot study was completed, there have been initiatives including a communication campaign focused on spreading awareness of the 2014 Joint Commission National Patient Safety Goal that was focused on improving the safety of clinical alarm systems24 and hospital-wide mandatory education on hospital alarm policy and practice. These could have blunted some of the acute alarm fatigue effects seen previously. An additional difference is that there was nursing turnover on this unit between studies, with recent nursing school graduates replacing older, more experienced nurses. In the pilot study, nurses from this unit had a median of 9.8 years of experience with a range of 2 to 28 years. In this study, nurses had a median of 2

Discussion

This study’s main findings were (1) alarms for patients on the
complex care service and patients without family members at
the bedside received faster responses than alarms for patients
without those characteristics; (2) nurses responded faster if they

<table>
<thead>
<tr>
<th>Variable</th>
<th>Adjusted Response Time, Median (95% CI), min</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall response time</td>
<td>10.4 (5.0-15.8)</td>
<td></td>
</tr>
<tr>
<td>Nurse experience, ya</td>
<td>4.4 (3.4-5.5)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>&lt;1</td>
<td>8.8 (7.2-10.5)</td>
<td></td>
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<tr>
<td>&gt;1</td>
<td>3.5 (1.3-5.7)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Nurse to patient ratio</td>
<td>10.6 (3.3-16.0)</td>
<td></td>
</tr>
<tr>
<td>1:1</td>
<td>6.1 (2.8-9.3)</td>
<td>.03</td>
</tr>
<tr>
<td>1:2 or more</td>
<td>14.1 (6.4-21.7)</td>
<td></td>
</tr>
<tr>
<td>Patient had prior alarm requiring intervention</td>
<td>5.5 (1.5-9.5)</td>
<td>.049</td>
</tr>
<tr>
<td>Yes</td>
<td>10.7 (5.2-16.2)</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>8.2 (1.0-15.3)</td>
<td>.46</td>
</tr>
<tr>
<td>Central venous catheter</td>
<td>10.4 (5.1-15.8)</td>
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<tr>
<td>Present</td>
<td>10.3 (3.0-17.6)</td>
<td>.97</td>
</tr>
<tr>
<td>Absent</td>
<td>10.4 (5.0-15.9)</td>
<td></td>
</tr>
<tr>
<td>NG or NJ tube</td>
<td>12.5 (3.4-21.5)</td>
<td></td>
</tr>
<tr>
<td>Present</td>
<td>13.1 (4.1-22.1)</td>
<td>&gt;.97</td>
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<tr>
<td>Absent</td>
<td>8.8 (4.9-12.7)</td>
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</tr>
<tr>
<td>Patient age, mo</td>
<td>12.2 (5.4-21.5)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>&lt;2</td>
<td>13.1 (4.1-22.1)</td>
<td>&gt;.97</td>
</tr>
<tr>
<td>2-&lt;6</td>
<td>12.2 (5.4-21.5)</td>
<td></td>
</tr>
<tr>
<td>≥6</td>
<td>12.5 (3.4-21.5)</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: NG, nasogastric; NJ, nasojejunal.

A. Since nurse experience does not vary within nurses, its association with response time could not be estimated directly from the stratified model. The adjusted estimate reported here was obtained from a separate model that allowed for the estimation of nurse-level factors and accounted for nurse clustering.

B. Evaluated as a continuous variable in model; hours 2 and 8 are presented as representative examples. Time ratio 1.15 (95% CI, 1.04-1.28; P=.008).

C. Adjusted for 3 comparisons using the Bonferroni method.
years of experience with a range of 2 months to 20 years. Since nurses with less experience respond to alarms more quickly, this might have contributed to the observed differences.

To our knowledge, few other studies have examined factors that affect response time to alarms. Voepel-Lewis and colleagues evaluated response times to pulse oximetry alarms in a higher-risk setting, a postoperative orthopedic unit where one-third of alarms were actionable and the median response time was under 1 minute. They found a longer response time for patients in the highest quartile of alarms compared with those in lower quartiles, which they attributed to possible alarm fatigue. In an adult intensive care unit study, Deb and Claudia found that alarm responses were driven by the personality characteristics of nurses (extraversion, agreeableness, and neuroticism), mental workload, apathy, noise level, the elapsed time since the start of the nurse’s shift, and the nurse to patient ratio.

**Limitations**

This study has several limitations. First, it was performed on just 1 inpatient unit. We did this intentionally to take advantage of the natural experiment that occurs when 1 nurse is observed across multiple patients and many alarms. Despite the statistical advantages offered by the repeated measures within nurses, the generalizability is limited. Multicenter studies would allow us to determine if these findings are externally valid. Second, while we showed that response time was dependent on several variables, we did not directly measure the effect of an intervention on response time. As we strive to improve response time so that any alarm that is potentially life-threatening occurs while a nurse is outside the room gets an immediate response, we need to know not only the individual factors that predict response time but also the interventions that are effective in improving it. The next steps in this line of research could include evaluating the effect of interventions such as shorter shifts and higher nurse to patient ratios on response time. Additionally, to begin reducing non-actionable alarms, researchers should develop guidelines establishing which children should be monitored (including metrics for over- and under-monitoring), what vital signs should be continuously measured, what settings optimize the detection of actionable events, and when monitoring should be discontinued.

**Conclusions**

We identified a set of patient-, nurse-, and alarm-level factors that were associated with faster responses to physiologic monitor alarms. We theorize that many of these factors contribute to the heuristics nurses use to rapidly make intuitive judgments about the probability that the alarm represents a life-threatening condition that warrants an immediate response to prevent patient harm. Changing the baseline assumption of nurses that most alarms do not represent life-threatening conditions will likely require hospitals to critically evaluate their alarm management practices and commit to reducing low priority alarms that are unlikely to represent life-threatening conditions. Nurse to patient ratio and physical/mental fatigue (measured by hours into a shift) represent additional modifiable factors associated with response time that should be included in intervention studies. Chronic alarm fatigue, the result of long term exposure to nonactionable alarms during a nurse’s career, may be a more important predictor of response time than short term exposure to nonactionalable alarms.

**Author Contributions:** Dr Bonafide had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Concept and design: Bonafide, Localio, Nadkarni, MacMurchy, Zander, Roberts, Lin, Keren. Acquisition, analysis, or interpretation of data: All authors. Drafting of the manuscript: Bonafide, Holmes, Nadkarni, Stemler, MacMurchy, Zander, Roberts. Critical revision of the manuscript for important intellectual content: Bonafide, Localio, Holmes, Nadkarni, Roberts, Lin, Keren. Statistical analysis: Bonafide, Localio. Obtained funding: Bonafide, Nadkarni. Administrative, technical, or material support: Holmes, Nadkarni, Stemler, MacMurchy, Zander. Supervision: Holmes, Nadkarni, Keren. No additional contributions: Roberts, Lin.

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**REFERENCES**


