

## REVIEWS

# Systematic Review of Physiologic Monitor Alarm Characteristics and Pragmatic Interventions to Reduce Alarm Frequency

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**BACKGROUND:** Alarm fatigue from frequent nonactionable physiologic monitor alarms is frequently named as a threat to patient safety.

**PURPOSE:** To critically examine the available literature relevant to alarm fatigue.

**DATA SOURCES:** Articles published in English, Spanish, or French between January 1980 and April 2015 indexed in PubMed, Cumulative Index to Nursing and Allied Health Literature, Scopus, Cochrane Library, Google Scholar, and ClinicalTrials.gov.

**STUDY SELECTION:** Articles focused on hospital physiologic monitor alarms addressing any of the following: (1) the proportion of alarms that are actionable, (2) the relationship between alarm exposure and nurse response time, and (3) the effectiveness of interventions in reducing alarm frequency.

**DATA EXTRACTION:** We extracted data on setting, collection methods, proportion of alarms determined to be actionable, nurse response time, and associations between interventions and alarm rates.

**DATA SYNTHESIS:** Our search produced 24 observational studies focused on alarm characteristics and response time and 8 studies evaluating interventions. Actionable alarm proportion ranged from <1% to 36% across a range of hospital settings. Two studies showed relationships between high alarm exposure and longer nurse response time. Most intervention studies included multiple components implemented simultaneously. Although studies varied widely, and many had high risk of bias, promising but still unproven interventions include widening alarm parameters, instituting alarm delays, and using disposable electrocardiographic wires or frequently changed electrocardiographic electrodes.

**CONCLUSIONS:** Physiologic monitor alarms are commonly nonactionable, and evidence supporting the concept of alarm fatigue is emerging. Several interventions have the potential to reduce alarms safely, but more rigorously designed studies with attention to possible unintended consequences are needed. *Journal of Hospital Medicine* 2016;11:136–144. © 2015 Society of Hospital Medicine

Clinical alarm safety has become a recent target for improvement in many hospitals. In 2013, The Joint Commission released a National Patient Safety Goal prompting accredited hospitals to establish alarm safety as a hospital priority, identify the most important alarm signals to manage, and, by 2016, develop policies and procedures that address alarm management.<sup>1</sup> In addition, the Emergency Care Research Institute has named alarm hazards the top health technology hazard each year since 2012.<sup>2</sup>

The primary arguments supporting the elevation of alarm management to a national hospital priority in the United States include the following: (1) clinicians rely on alarms to notify them of important physiologic changes, (2) alarms occur frequently and usually do not warrant clinical intervention, and (3) alarm overload renders clinicians unable to respond to all alarms, resulting in alarm fatigue: responding more slowly or ignoring alarms that may represent actual clinical deterioration.<sup>3,4</sup> These arguments are built largely on anecdotal data, reported safety event databases, and small studies that have not previously been systematically analyzed.

Despite the national focus on alarms, we still know very little about fundamental questions key to improving alarm safety. In this systematic review, we aimed to answer 3 key questions about physiologic monitor alarms: (1) What proportion of alarms warrant attention or clinical intervention (ie, “actionable” alarms), and how does this proportion vary between adult and

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pediatric populations and between intensive care unit (ICU) and ward settings? (2) What is the relationship between alarm exposure and clinician response time? (3) What interventions are effective in reducing the frequency of alarms?

We limited our scope to monitor alarms because few studies have evaluated the characteristics of alarms from other medical devices, and because missing relevant monitor alarms could adversely impact patient safety.

## METHODS

We performed a systematic review of the literature in accordance with the Meta-Analysis of Observational Studies in Epidemiology guidelines<sup>5</sup> and developed this manuscript using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.<sup>6</sup>

### Eligibility Criteria

With help from an experienced biomedical librarian (C.D.S.), we searched PubMed, the Cumulative Index to Nursing and Allied Health Literature, Scopus, Cochrane Library, ClinicalTrials.gov, and Google Scholar from January 1980 through April 2015 (see Supporting Information in the online version of this article for the search terms and queries). We hand searched the reference lists of included articles and reviewed our personal libraries to identify additional relevant studies.

We included peer-reviewed, original research studies published in English, Spanish, or French that addressed the questions outlined above. Eligible patient populations were children and adults admitted to hospital inpatient units and emergency departments (EDs). We excluded alarms in procedural suites or operating rooms (typically responded to by anesthesiologists already with the patient) because of the differences in environment of care, staff-to-patient ratio, and equipment. We included observational studies reporting the actionability of physiologic monitor alarms (ie, alarms warranting special attention or clinical intervention), as well as nurse responses to these alarms. We excluded studies focused on the effects of alarms unrelated to patient safety, such as families' and patients' stress, noise, or sleep disturbance. We included only intervention studies evaluating pragmatic interventions ready for clinical implementation (ie, not experimental devices or software algorithms).

### Selection Process and Data Extraction

First, 2 authors screened the titles and abstracts of articles for eligibility. To maximize sensitivity, if at least 1 author considered the article relevant, the article proceeded to full-text review. Second, the full texts of articles screened were independently reviewed by 2 authors in an unblinded fashion to determine their eligibility. Any disagreements concerning eligibility were

resolved by team consensus. To assure consistency in eligibility determinations across the team, a core group of the authors (C.W.P, C.P.B., E.E., and V.V.G.) held a series of meetings to review and discuss each potentially eligible article and reach consensus on the final list of included articles. Two authors independently extracted the following characteristics from included studies: alarm review methods, analytic design, fidelity measurement, consideration of unintended adverse safety consequences, and key results. Reviewers were not blinded to journal, authors, or affiliations.

### Synthesis of Results and Risk Assessment

Given the high degree of heterogeneity in methodology, we were unable to generate summary proportions of the observational studies or perform a meta-analysis of the intervention studies. Thus, we organized the studies into clinically relevant categories and presented key aspects in tables. Due to the heterogeneity of the studies and the controversy surrounding quality scores,<sup>5</sup> we did not generate summary scores of study quality. Instead, we evaluated and reported key design elements that had the potential to bias the results. To recognize the more comprehensive studies in the field, we developed by consensus a set of characteristics that distinguished studies with lower risk of bias. These characteristics are shown and defined in Table 1.

For the purposes of this review, we defined nonactionable alarms as including both invalid ("false") alarms that do not accurately represent the physiologic status of the patient and alarms that are valid but do not warrant special attention or clinical intervention ("nuisance" alarms). We did not separate out invalid alarms due to the tremendous variation between studies in how validity was measured.

## RESULTS

### Study Selection

Search results produced 4629 articles (see the flow diagram in the Supporting Information in the online version of this article), of which 32 articles were eligible: 24 observational studies describing alarm characteristics and 8 studies describing interventions to reduce alarm frequency.

### Observational Study Characteristics

Characteristics of included studies are shown in Table 1. Of the 24 observational studies,<sup>7–30</sup> 15 included adult patients,<sup>7–21</sup> 7 included pediatric patients,<sup>22–28</sup> and 2 included both adult and pediatric patients.<sup>29,30</sup> All were single-hospital studies, except for 1 study by Chambrin and colleagues<sup>10</sup> that included 5 sites. The number of patient-hours examined in each study ranged from 60 to 113,880.<sup>7–11,13–16,18–27,29,30</sup> Hospital settings included ICUs (n = 16),<sup>9–11,13,14,16–19,22–27,29</sup> general wards (n = 5),<sup>12,15,20,22,28</sup> EDs (n = 2),<sup>7,21</sup> postanesthesia care unit

**TABLE 1. General Characteristics of Included Studies**

| First Author and Publication Year       | Alarm Review Method |                    |                       |                   | Indicators of Potential Bias for Observational Studies |                         |                                  |                           |  | Indicators of Potential Bias for Intervention Studies |   |                 |                                       |                   |                 |                    |
|---|---------------------|--------------------|-----------------------|-------------------|--|-------------------------|----------------------------------|---------------------------|--|---|---|-----------------|---------------------------------------|-------------------|-----------------|--------------------|
|   | Monitor System      | Direct Observation | Medical Record Review | Rhythm Annotation | Video Observation                                      | Remote Monitoring Staff | Medical Device Industry Involved | Two Independent Reviewers | At Least 1 Reviewer Is a Clinical Expert | Reviewer Not Simultaneously in Patient Care           | Clear Definition of Alarm Actionability | Census Included | Statistical Testing or QI SPC Methods | Fidelity Assessed | Safety Assessed | Lower Risk of Bias |
|   |                     |                    |                       |                   |  |                         |                                  |                           |  |   |   |                 |                                       |                   |                 |                    |
| Adult Observational                     |                     |                    |                       |                   |  |                         |                                  |                           |  |   |   |                 |                                       |                   |                 |                    |
| Atzema 2006 <sup>7</sup>                | ✓*                  |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Billinghurst 2003 <sup>8</sup>          | ✓                   |                    |                       |                   |  |                         | ✓                                | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Biot 2000 <sup>9</sup>                  | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Chambrin 1999 <sup>10</sup>             | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Drew 2014 <sup>11</sup>                 | ✓                   |                    |                       | ✓                 |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 | ✓                  |
| Gazzarian 2014 <sup>12</sup>            | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Görges 2009 <sup>13</sup>               | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Gross 2011 <sup>15</sup>                | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 | ✓                  |
| Inokuchi 2013 <sup>14</sup>             | ✓                   |                    |                       |                   | ✓  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 | ✓                  |
| Koski 1990 <sup>16</sup>                | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Morales Sánchez 2014 <sup>17</sup>      | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Pergher 2014 <sup>18</sup>              | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Siebig 2010 <sup>19</sup>               | ✓                   |                    | ✓                     |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Voepel-Lewis 2013 <sup>20</sup>         | ✓                   |                    |                       |                   | ✓  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Way 2014 <sup>21</sup>                  | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Pediatric Observational                 |                     |                    |                       |                   |  |                         |                                  |                           |  |   |   |                 |                                       |                   |                 |                    |
| Bonafide 2015 <sup>22</sup>             | ✓                   |                    |                       |                   | ✓  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 | ✓                  |
| Lawless 1994 <sup>23</sup>              | ✓†                  |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Rosman 2013 <sup>24</sup>               | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Talley 2011 <sup>25</sup>               | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Tsien 1997 <sup>26</sup>                | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| van Pul 2015 <sup>27</sup>              | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Varpio 2012 <sup>28</sup>               | ✓†                  |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Mixed Adult and Pediatric Observational |                     |                    |                       |                   |  |                         |                                  |                           |  |   |   |                 |                                       |                   |                 |                    |
| O'Carroll 1986 <sup>29</sup>            | ✓†                  |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Wiklund 1994 <sup>30</sup>              | ✓                   |                    |                       |                   |  |                         |                                  | ✓                         |  | ✓   |   |                 |                                       |                   |                 |                    |
| Adult Intervention                      |                     |                    |                       |                   |  |                         |                                  |                           |  |   |   |                 |                                       |                   |                 |                    |
| Albert 2015 <sup>32</sup>               |                     |                    |                       |                   |  | ✓                       |                                  |                           |  |   | ✓                                       |                 |                                       | ✓                 |                 | ✓                  |
| Ciech 2013 <sup>33</sup>                | ✓                   |                    |                       |                   |  |                         |                                  |                           |  |   | ✓                                       |                 |                                       |                   |                 |                    |
| Ciech 2014 <sup>34</sup>                | ✓                   |                    |                       |                   |  |                         |                                  |                           |  |   | ✓                                       |                 |                                       |                   |                 |                    |
| Graham 2010 <sup>35</sup>               | ✓                   |                    |                       |                   |  |                         |                                  |                           |  |   | ✓                                       |                 |                                       | ✓                 |                 | ✓                  |
| Rheinck-Leyssius 1997 <sup>36</sup>     | ✓                   |                    |                       |                   |  |                         |                                  |                           |  |   | ✓                                       |                 |                                       | ✓                 |                 | ✓                  |
| Taenzer 2010 <sup>31</sup>              | ✓                   |                    |                       |                   |  |                         |                                  |                           |  |   | ✓                                       |                 |                                       | ✓                 |                 | ✓                  |
| Whalen 2014 <sup>37</sup>               | ✓                   |                    |                       |                   |  |                         |                                  |                           |  |   | ✓                                       |                 |                                       | ✓                 |                 | ✓                  |
| Pediatric Intervention                  |                     |                    |                       |                   |  |                         |                                  |                           |  |   |   |                 |                                       |                   |                 |                    |
| Dandoy 2014 <sup>38</sup>               | ✓                   |                    |                       |                   |  |                         |                                  |                           |  |   | ✓                                       |                 | ✓                                     | ✓                 |                 | ✓                  |

NOTE: †Lower risk of bias\* for observational studies required all of the following characteristics be reported: (1) two independent reviewers of alarms, (2) at least 1 clinical expert reviewer (ie, physician or nurse), (3) the reviewer was not simultaneously involved in clinical care, and (4) there was a clear definition of alarm actionability provided in the article. These indicators assess detection bias, observer bias, analytical bias, and reporting bias and were derived from the Meta-analysis of Observational Studies in Epidemiology checklist.<sup>39</sup> ‡Lower risk of bias\* for intervention studies required all of the following characteristics be reported: (1) patient census accounted for in analysis, (2) formal statistical testing of effect or statistical process control methods used to evaluate effect, (3) intervention fidelity measured and reported (defined broadly as some measurement of whether the intervention was delivered as intended), and (4) relevant patient safety outcomes measured and reported (eg, the rate of code blue events before and after the intervention was implemented). These indicators assess reporting bias and internal validity bias and were derived from the Downs and Black checklist.<sup>42</sup> §Monitor system: alarm data were electronically collected directly from the physiologic monitors and saved on a computer device through software such as BedMasterEx. Direct observation: an in-person observer, such as a research assistant or a nurse, takes note of the alarm data and/or responses to alarms. Medical record review: data on alarms and/or responses to alarms were extracted from the patient medical records. Rhythm annotation: data on waveforms from cardiac monitors were collected and saved on a computer device through software such as BedMasterEx. Video observation: video cameras were set up in the patient's room and recorded data on alarms and/or responses to alarms. Remote monitor staff: clinicians situated at a remote location observe the patient via video camera and may be able to communicate with the patient or the patient's assigned nurse. Abbreviations: QI, quality improvement; RN, registered nurse; SPC, statistical process control. \*Monitor system + RN interrogation. ‡Assigned nurse making observations. §Monitor from central station. □Alarm outcome reported using run chart, and fidelity outcomes presented using statistical process control charts.

(PACU) ( $n = 1$ ),<sup>30</sup> and cardiac care unit (CCU) ( $n = 1$ ).<sup>8</sup> Studies varied in the type of physiologic signals recorded and data collection methods, ranging from direct observation by a nurse who was simultaneously caring for patients<sup>29</sup> to video recording with expert review.<sup>14,19,22</sup> Four observational studies met the criteria for lower risk of bias.<sup>11,14,15,22</sup>

### Intervention Study Characteristics

Of the 8 intervention studies, 7 included adult patients,<sup>31–37</sup> and 1 included pediatric patients.<sup>38</sup> All were single-hospital studies; 6 were quasi-experimental<sup>31,33–35,37,38</sup> and 2 were experimental.<sup>32,36</sup> Settings included progressive care units ( $n = 3$ ),<sup>33–35</sup> CCUs ( $n = 3$ ),<sup>32,33,37</sup> wards ( $n = 2$ ),<sup>31,38</sup> PACU ( $n = 1$ ),<sup>36</sup> and a step-down unit ( $n = 1$ ).<sup>32</sup> All except 1 study<sup>32</sup> used the monitoring system to record alarm data. Several studies evaluated multicomponent interventions that included combinations of the following: widening alarm parameters,<sup>31,35–38</sup> instituting alarm delays,<sup>31,34,36,38</sup> reconfiguring alarm acuity,<sup>35,37</sup> use of secondary notifications,<sup>34</sup> daily change of electrocardiographic electrodes or use of disposable electrocardiographic wires,<sup>32,33,38</sup> universal monitoring in high-risk populations,<sup>31</sup> and timely discontinuation of monitoring in low-risk populations.<sup>38</sup> Four intervention studies met our prespecified lower risk of bias criteria.<sup>31,32,36,38</sup>

### Proportion of Alarms Considered Actionable

Results of the observational studies are provided in Table 2. The proportion of alarms that were actionable was <1% to 26% in adult ICU settings,<sup>9–11,13,14,16,17,19</sup> 20% to 36% in adult ward settings,<sup>12,15,20</sup> 17% in a mixed adult and pediatric PACU setting,<sup>30</sup> 3% to 13% in pediatric ICU settings,<sup>22–26</sup> and 1% in a pediatric ward setting.<sup>22</sup>

### Relationship Between Alarm Exposure and Response Time

Whereas 9 studies addressed response time,<sup>8,12,17,18,20–22,27,28</sup> only 2 evaluated the relationship between alarm burden and nurse response time.<sup>20,22</sup> Voepel-Lewis and colleagues found that nurse responses were slower to patients with the highest quartile of alarms (57.6 seconds) compared to those with the lowest (45.4 seconds) or medium (42.3 seconds) quartiles of alarms on an adult ward ( $P = 0.046$ ). They did not find an association between false alarm exposure and response time.<sup>20</sup> Bonafide and colleagues found incremental increases in response time as the number of nonactionable alarms in the preceding 120 minutes increased ( $P < 0.001$  in the pediatric ICU,  $P = 0.009$  on the pediatric ward).<sup>22</sup>

### Interventions Effective in Reducing Alarms

Results of the 8 intervention studies are provided in Table 3. Three studies evaluated single interventions;<sup>32,33,36</sup> the remainder of the studies tested inter-

ventions with multiple components such that it was impossible to separate the effect of each component. Below, we have summarized study results, arranged by component. Because only 1 study focused on pediatric patients,<sup>38</sup> results from pediatric and adult settings are combined.

Widening alarm parameter default settings was evaluated in 5 studies:<sup>31,35–38</sup> 1 single intervention randomized controlled trial (RCT),<sup>36</sup> and 4 multiple-intervention, quasi-experimental studies.<sup>31,35,37,38</sup> In the RCT, using a lower SpO<sub>2</sub> limit of 85% instead of the standard 90% resulted in 61% fewer alarms. In the 4 multiple intervention studies, 1 study reported significant reductions in alarm rates ( $P < 0.001$ ),<sup>37</sup> 1 study did not report preintervention alarm rates but reported a postintervention alarm rate of 4 alarms per patient-day,<sup>31</sup> and 2 studies reported reductions in alarm rates but did not report any statistical testing.<sup>35,38</sup> Of the 3 studies examining patient safety, 1 study with universal monitoring reported fewer rescue events and transfers to the ICU postimplementation,<sup>31</sup> 1 study reported no missed acute decompensations,<sup>38</sup> and 1 study (the RCT) reported significantly more true hypoxemia events ( $P = 0.001$ ).<sup>36</sup>

Alarm delays were evaluated in 4 studies:<sup>31,34,36,38</sup> 3 multiple-intervention, quasi-experimental studies<sup>31,34,38</sup> and 1 retrospective analysis of data from an RCT.<sup>36</sup> One study combined alarm delays with widening defaults in a universal monitoring strategy and reported a postintervention alarm rate of 4 alarms per patient.<sup>31</sup> Another study evaluated delays as part of a secondary notification pager system and found a negatively sloping regression line that suggested a decreasing alarm rate, but did not report statistical testing.<sup>34</sup> The third study reported a reduction in alarm rates but did not report statistical testing.<sup>38</sup> The RCT compared the impact of a hypothetical 15-second alarm delay to that of a lower SpO<sub>2</sub> limit reduction and reported a similar reduction in alarms.<sup>36</sup> Of the 4 studies examining patient safety, 1 study with universal monitoring reported improvements,<sup>31</sup> 2 studies reported no adverse outcomes,<sup>35,38</sup> and the retrospective analysis of data from the RCT reported the theoretical adverse outcome of delayed detection of sudden, severe desaturations.<sup>36</sup>

Reconfiguring alarm acuity was evaluated in 2 studies, both of which were multiple-intervention quasi-experimental studies.<sup>35,37</sup> Both showed reductions in alarm rates: 1 was significant without increasing adverse events ( $P < 0.001$ ),<sup>37</sup> and the other did not report statistical testing or safety outcomes.<sup>35</sup>

Secondary notification of nurses using pagers was the main intervention component of 1 study incorporating delays between the alarms and the alarm pages.<sup>34</sup> As mentioned above, a negatively sloping regression line was displayed, but no statistical testing or safety outcomes were reported.



**TABLE 2. Results of Included Observational Studies**

| First Author and Publication Year  | Setting    | Monitored Patient-Hours | Signals Included |                |                 |                | Total Alarms                              | Actionable Alarms <sup>†</sup>   | Alarm Response   | Lower Risk of Bias |
|------------------------------------|------------|-------------------------|------------------|----------------|-----------------|----------------|---|--|--|--------------------|
|                                    |            |                         | SpO <sub>2</sub> | ECG Arrhythmia | ECG Parameters* | Blood Pressure |   |  |  |                    |
| Atzema 2006 <sup>7</sup>           | ED         | 371                     | ✓                | ✓              |                 | 1,762          | 0.20%                                     | Nurses with higher acuity patients and smaller % of valid <sup>‡</sup> ; alarms had slower response rates                | ✓  |                    |
| Billinghurst 2003 <sup>8</sup>     | CCU        | 420                     | ✓                | ✓              |                 | 751            | Not reported; 17% were valid <sup>‡</sup> |  |  |                    |
| Biot 2000 <sup>9</sup>             | ICU        | 250                     | ✓                | ✓              | ✓               | 3,665          | 3%  | Response to 47% of alarms  | ✓  |                    |
| Chambrin 1999 <sup>10</sup>        | ICU        | 1,971                   | ✓                | ✓              | ✓               | 3,188          | 26%                                       |  |  |                    |
| Drew 2014 <sup>11</sup>            | ICU        | 48,173                  | ✓                | ✓              | ✓               | 2,558,760      | 0.3% of 3,861 VT alarms                   | Response to 93% of alarms, of which 50% were within 10 seconds   | ✓  |                    |
| Gazarian 2014 <sup>12</sup>        | Ward       | 54 nurse-hours          | ✓                | ✓              | ✓               | 205            | 22%                                       |  |  |                    |
| Gorges 2009 <sup>13</sup>          | ICU        | 200                     | ✓                | ✓              | ✓               | 1,214          | 5%  | Response to 93% of alarms, of which 50% were within 10 seconds   | ✓  |                    |
| Gross 2011 <sup>15</sup>           | Ward       | 530                     | ✓                | ✓              | ✓               | 4,393          | 20%                                       |  |  |                    |
| Inokuchi 2013 <sup>14</sup>        | ICU        | 2,697                   | ✓                | ✓              | ✓               | 11,591         | 6%  | 72% of alarms stopped before nurse response or had > 10 minutes response time  | ✓  |                    |
| Koski 1990 <sup>16</sup>           | ICU        | 400                     | ✓                | ✓              | ✓               | 2,322          | 12%                                       |  |  |                    |
| Morales Sanchez 2014 <sup>17</sup> | ICU        | 434 sessions            | ✓                | ✓              | ✓               | 215            | 25%                                       | Response time was longer for patients in highest quartile of total alarms <sup>‡</sup>                                   | ✓  |                    |
| Pergher 2014 <sup>18</sup>         | ICU        | 60                      | ✓                | ✓              | ✓               | 76             | Not reported                              |  |  |                    |
| Siebig 2010 <sup>19</sup>          | ICU        | 982                     | ✓                | ✓              | ✓               | 5,934          | 15%                                       | Nurses responded to more alarms in resuscitation room vs acute care area, but response time was longer                   | ✓  |                    |
| Voepel-Lewis 2013 <sup>20</sup>    | Ward       | 1,616                   | ✓                | ✓              | ✓               | 710            | 36%                                       |  |  |                    |
| Way 2014 <sup>21</sup>             | ED         | 93                      | ✓                | ✓              | ✓               | 572            | Not reported; 75% were valid <sup>‡</sup> | Incremental increases in response time as number of nonactionable alarms in preceding 120 minutes increased <sup>‡</sup> | ✓  |                    |
| Bonafide 2015 <sup>22</sup>        | Ward + ICU | 210                     | ✓                | ✓              | ✓               | 5,070          | 13% PICU, 1% ward                         |  |  |                    |
| Lawless 1994 <sup>23</sup>         | ICU        | 928                     | ✓                | ✓              | ✓               | 2,176          | 6%  | Assigned nurse did not respond to 6% of alarms within 45 seconds   | 70% of all alarms and 41% of crisis alarms were not responded to within 1 minute |                    |
| Rosman 2013 <sup>24</sup>          | ICU        | 8,232                   | ✓                | ✓              | ✓               | 54,656         | 4% of rhythm alarms "true critical"       |  |  |                    |
| Talley 2011 <sup>25</sup>          | ICU        | 1,470 <sup>  </sup>     | ✓                | ✓              | ✓               | 2,245          | 3%  | Assigned nurse did not respond to 6% of alarms within 45 seconds   | 70% of all alarms and 41% of crisis alarms were not responded to within 1 minute |                    |
| Tsien 1997 <sup>26</sup>           | ICU        | 298                     | ✓                | ✓              | ✓               | 2,942          | 8%  |  |  |                    |
| van Pul 2015 <sup>27</sup>         | ICU        | 113,880 <sup>  </sup>   | ✓                | ✓              | ✓               | 222,751        | Not reported                              | Assigned nurse did not respond to 6% of alarms within 45 seconds   | 70% of all alarms and 41% of crisis alarms were not responded to within 1 minute |                    |
| Varpio 2012 <sup>28</sup>          | Ward       | 49 unit-hours           | ✓                | ✓              | ✓               | 446            | Not reported                              |  |  |                    |
| O'Carroll 1986 <sup>29</sup>       | ICU        | 2,258 <sup>  </sup>     | ✓                | ✓              | ✓               | 284            | 2%  | Both   | ✓  |                    |
| Wiklund 1994 <sup>30</sup>         | PACU       | 207                     | ✓                | ✓              | ✓               | 1,891          | 17%                                       |  |  |                    |

NOTE: <sup>||</sup>Lower risk of bias<sup>†</sup> for observational studies required all of the following characteristics be reported: (1) two independent reviewers of alarms, (2) at least 1 clinical expert reviewer (i.e. physician or nurse), (3) the reviewer was not simultaneously involved in clinical care, and (4) there was a clear definition of alarm actionability provided in the article. Abbreviations: CCU, cardiac/telemetry care unit; ECG, electrocardiogram; ED, emergency department; ICU, intensive care unit; PACU, postanesthesia care unit; SpO<sub>2</sub>, oxygen saturation; VT, ventricular tachycardia.  
<sup>†</sup>Includes respiratory rate measured via ECG leads. <sup>‡</sup>Actionable is defined as alarms warranting special attention or clinical intervention. <sup>||</sup>Valid is defined as the alarm accurately representing the physiologic status of the patient. <sup>||</sup>Directly addresses relationship between alarm exposure and response time. <sup>||</sup>Not provided directly; estimated from description of data collection methods.

**TABLE 3. Results of Included Intervention Studies**

| First Author and Publication Year     | Design   | Setting     | Main Intervention Components |              |                          |                        |  |   | Key Results | Results Statistically Significant? | Lower Risk of Bias |
|---------------------------------------|--|-------------|------------------------------|--------------|--------------------------|------------------------|--|---|-------------|------------------------------------|--------------------|
|                                       |  |             | Widen Default Settings       | Alarm Delays | Reconfigure Alarm Acuity | Secondary Notification | ECG Changes  | Other/ Comments   |             |                                    |                    |
| Albert 2015 <sup>32</sup>             | Experimental (cluster-randomized)                              | CCU         |                              |              |                          | Adult                  | ✓  | Disposable leads had 29% fewer no-telemetry, leads-fail, and leads-off alarms and similar artifact alarms   | ✓           | ✓                                  |                    |
| Czech 2013 <sup>33</sup>              | Quasi-experimental (before and after)                          | CCU and PCU |                              | ✓*           |                          |                        | ✓  | 46% fewer alarms/bed/day  |             |                                    |                    |
| Czech 2014 <sup>34</sup>              | Quasi-experimental (ITS)                                       | PCU         |                              |              |                          |                        |  | Slope of regression line suggests decrease of 0.75 alarms/bed/day   |             |                                    |                    |
| Graham 2010 <sup>35</sup>             | Quasi-experimental (before and after)                          | PCU         | ✓                            |              | ✓                        |                        |  | 43% fewer crisis, warning, and system warning alarms on unit  |             |                                    |                    |
| Rheinbeck-Leyssius 1997 <sup>36</sup> | Experimental (RCT)   | PACU        | ✓                            | ✓†           |                          |                        |  | Alarm limit of 85% had fewer alarms/patient but higher incidence of true hypoxemia for > 1 minute (6% vs 2%)  | ✓           | ✓                                  |                    |
| Taenzer 2010 <sup>31</sup>            | Quasi-experimental (before and after with concurrent controls) | Ward        | ✓                            | ✓            |                          |                        | Universal SpO <sub>2</sub> monitoring                          | Rescue events decreased from 3.4 to 1.2 per 1,000 discharges; transfers to ICU decreased from 5.6 to 2.9 per 1,000 patient-days, only 4 alarms/patient-day‡ | ✓           | ✓                                  |                    |
| Whalen 2014 <sup>27</sup>             | Quasi-experimental (before and after)                          | CCU         | ✓                            | ✓            | ✓                        | Pediatric              |  | 89% fewer audible alarms on unit  | ✓           |                                    |                    |
| Dandoy 2014 <sup>38</sup>             | Quasi-experimental (ITS)                                       | Ward        | ✓                            | ✓            |                          |                        | Timely monitor discontinuation; daily change of ECG electrodes | Decrease in alarms/patient-days from 180 to 40  |             | ✓                                  |                    |

NOTE: \*Lower risk of bias† for intervention studies required all of the following characteristics be reported: (1) patient census accounted for in analysis, (2) formal statistical testing of effect or statistical process control methods used to evaluate effect, (3) intervention fidelity measured and reported (defined broadly as some measurement of whether the intervention was delivered as intended), and (4) relevant patient safety outcomes measured and reported (eg, the rate of code blue events before and after the intervention was implemented). Abbreviations: CCU, cardiac telemetry care unit; ECG, electrocardiogram; ICU, intensive care unit; ITS, interrupted time series; PACU, postanesthesia care unit; PCU, progressive care unit; SpO<sub>2</sub>, oxygen saturation. †Delays were part of secondary notification system only. ‡Delays explored retrospectively only; not part of prospective evaluation. §Preimplementation count not reported.

Disposable electrocardiographic lead wires or daily electrode changes were evaluated in 3 studies:<sup>32,33,38</sup> 1 single intervention cluster-randomized trial<sup>32</sup> and 2 quasi-experimental studies.<sup>33,38</sup> In the cluster-randomized trial, disposable lead wires were compared to reusable lead wires, with disposable lead wires having significantly fewer technical alarms for lead signal failures ( $P = 0.03$ ) but a similar number of monitoring artifact alarms ( $P = 0.44$ ).<sup>32</sup> In a single-intervention, quasi-experimental study, daily electrode change showed a reduction in alarms, but no statistical testing was reported.<sup>33</sup> One multiple-intervention, quasi-experimental study incorporating daily electrode change showed fewer alarms without statistical testing.<sup>38</sup> Of the 2 studies examining patient safety, both reported no adverse outcomes.<sup>32,38</sup>

## DISCUSSION

This systematic review of physiologic monitor alarms in the hospital yielded the following main findings: (1) between 74% and 99% of physiologic monitor alarms were not actionable, (2) a significant relationship between alarm exposure and nurse response time was demonstrated in 2 small observational studies, and (3) although interventions were most often studied in combination, results from the studies with lower risk of bias suggest that widening alarm parameters, implementing alarm delays, and using disposable electrocardiographic lead wires and/or changing electrodes daily are the most promising interventions for reducing alarms. Only 5 of 8 intervention studies measured intervention safety and found that widening alarm parameters and implementing alarm delays had mixed safety outcomes, whereas disposable electrocardiographic lead wires and daily electrode changes had no adverse safety outcomes.<sup>29,30,34–36</sup> Safety measures are crucial to ensuring the highest level of patient safety is met; interventions are rendered useless without ensuring actionable alarms are not disabled. The variation in results across studies likely reflects the wide range of care settings as well as differences in design and quality.

This field is still in its infancy, with 18 of the 32 articles published in the past 5 years. We anticipate improvements in quality and rigor as the field matures, as well as clinically tested interventions that incorporate smart alarms. Smart alarms integrate data from multiple physiologic signals and the patient's history to better detect physiologic changes in the patient and improve the positive predictive value of alarms. Academic–industry partnerships will be required to implement and rigorously test smart alarms and other emerging technologies in the hospital.

To our knowledge, this is the first systematic review focused on monitor alarms with specific review questions relevant to alarm fatigue. Cvach recently published an integrative review of alarm fatigue using research published through 2011.<sup>39</sup> Our review builds

upon her work by contributing a more extensive and systematic search strategy with databases spanning nursing, medicine, and engineering, including additional languages, and including newer studies published through April 2015. In addition, we included multiple cross-team checks in our eligibility review to ensure high sensitivity and specificity of the resulting set of studies.

Although we focused on interventions aiming to reduce alarms, there has also been important recent work focused on reducing telemetry utilization in adult hospital populations as well as work focused on reducing pulse oximetry utilization in children admitted with respiratory conditions. Dressler and colleagues reported an immediate and sustained reduction in telemetry utilization in hospitalized adults upon redesign of cardiac telemetry order sets to include the clinical indication, which defaulted to the American Heart Association guideline-recommended telemetry duration.<sup>40</sup> Instructions for bedside nurses were also included in the order set to facilitate appropriate telemetry discontinuation. Schondelmeyer and colleagues reported reductions in continuous pulse oximetry utilization in hospitalized children with asthma and bronchiolitis upon introduction of a multifaceted quality improvement program that included provider education, a nurse handoff checklist, and discontinuation criteria incorporated into order sets.<sup>41</sup>

## Limitations of This Review and the Underlying Body of Work

There are limitations to this systematic review and its underlying body of work. With respect to our approach to this systematic review, we focused only on monitor alarms. Numerous other medical devices generate alarms in the patient-care environment that also can contribute to alarm fatigue and deserve equally rigorous evaluation. With respect to the underlying body of work, the quality of individual studies was generally low. For example, determinations of alarm actionability were often made by a single rater without evaluation of the reliability or validity of these determinations, and statistical testing was often missing. There were also limitations specific to intervention studies, including evaluation of nongeneralizable patient populations, failure to measure the fidelity of the interventions, inadequate measures of intervention safety, and failure to statistically evaluate alarm reductions. Finally, though not necessarily a limitation, several studies were conducted by authors involved in or funded by the medical device industry.<sup>11,15,19,31,32</sup> This has the potential to introduce bias, although we have no indication that the quality of the science was adversely impacted.

Moving forward, the research agenda for physiologic monitor alarms should include the following: (1) more intensive focus on evaluating the relationship between alarm exposure and response time with

analysis of important mediating factors that may promote or prevent alarm fatigue, (2) emphasis on studying interventions aimed at improving alarm management using rigorous designs such as cluster-randomized trials and trials randomized by individual participant, (3) monitoring and reporting clinically meaningful balancing measures that represent unintended consequences of disabling or delaying potentially important alarms and possibly reducing the clinicians' ability to detect true patient deterioration and intervene in a timely manner, and (4) support for transparent academic–industry partnerships to evaluate new alarm technology in real-world settings. As evidence-based interventions emerge, there will be new opportunities to study different implementation strategies of these interventions to optimize effectiveness.

## CONCLUSIONS

The body of literature relevant to physiologic monitor alarm characteristics and alarm fatigue is limited but growing rapidly. Although we know that most alarms are not actionable and that there appears to be a relationship between alarm exposure and response time that could be caused by alarm fatigue, we cannot yet say with certainty that we know which interventions are most effective in safely reducing unnecessary alarms. Interventions that appear most promising and should be prioritized for intensive evaluation include widening alarm parameters, implementing alarm delays, and using disposable electrocardiographic lead wires and changing electrodes daily. Careful evaluation of these interventions must include systematically examining adverse patient safety consequences.

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