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Combating Alarm Fatigue: The Quest for More Accurate and Safer Clinical Monitoring Equipment

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Additional information is available at the end of the chapter

Abstract

As the demand for health-care services continues to increase, clinically efficient and cost-effective patient monitoring takes on a critically important role. Key considerations inherent to this area of concern include patient safety, reliability, ease of use, and cost containment. Unfortunately, even the most modern patient monitoring systems carry significant drawbacks that limit their effectiveness and/or applicability. Major opportunities for improvement in both equipment design and monitor utilization have been identified, including the presence of excessive false and nuisance alarms. When poorly optimized, clinical alarm activity can affect patient safety and may have a negative impact on care providers, leading to inappropriate alarm response time due to the so-called alarm fatigue (AF). Ultimately, consequences of AF include missed alerts of clinical significance, with substantial risk for patient harm and potentially fatal outcomes. Targeted quality improvement initiatives and staff training, as well as the proactive incorporation of technological improvements, are the best approaches to address key barriers to the optimal utilization of clinical alarms, AF reduction, better patient care, and improved provider job satisfaction.

**Keywords:** alarm fatigue, clinical alarms, clinical monitoring, monitoring equipment, patient safety

1. Introduction

Highly reliable, precise, user-friendly, and cost-effective clinical alarm systems are critical to efficient functioning of health-care facilities [1–3]. Despite tremendous progress over the past few decades, the "perfect solution" remains elusive, with focus being placed primarily

on clinical indications and appropriateness of use for the existing equipment and monitoring frameworks [3–6]. Beyond the concept of "false alarm," suboptimal implementation of clinical monitoring systems can have much more profound and potentially dangerous consequences [7–9]. One such consequence, and the primary topic of this chapter, is the phenomenon of alarm fatigue (AF). It is defined as the decrease of clinician response caused by excessive alarms, sensory overload, and desensitization, in addition to other occupational and environmental variables [9–11]. Among contributing factors are also high staff workload, long shift hours, and work environments with high noise levels, all of which contribute to the "desensitization effect" associated with AF [10, 12].

Hospital patient care units tend to be high-paced and potentially unpredictable environments, with complex workflows. Multiple simultaneous interactions between patients, families, and health-care staff may create an added element of chaos [13, 14]. To help nurses and other staff cope with their many responsibilities, various audible and visual alerts have been implemented to prompt immediate response and clinical assessment of patients [15]. These alerts are relayed from patient monitoring devices, which provide continuous flow of vital sign data with a high degree of sensitivity. The advanced technology used in these surveillance systems has provided a significant amount of physiological data at low cost while being particularly helpful by facilitating the monitoring of critically ill patients to identify deviations of vital signs (e.g., heart rate, respiratory rate, blood pressure, and pulse oximetry) from normal ranges [16]. However, when various clinical alarm systems are superimposed on the need for constant vigilance in the setting of highly challenging and often chaotic environment of the typical clinical unit, the stage is set for the emergence of AF and other forms of cognitive lapses [17–19].

The prevalence of various monitoring modalities has increased significantly, with most health-care institutions utilizing some broadly defined combination of different alarm systems. As the use of these systems became more widespread, a major flaw became evident: the excessive amount of triggered alarms was contributing to unintended consequences, both in terms of patient outcomes and staff fatigue/dissatisfaction [8, 20, 21]. The high rate of nonactionable alarms, where immediate action is not required on the behalf of clinicians, was especially problematic [22]. In fact, the increasing frequency of "false alarms" has a significant desensitization effect on hospital staff, whereby some alarms may be erroneously "dismissed by assumption" as being "noncritical" [23]. This desensitization leads to both increased response times and decreased, or even lack of, clinician response. In the setting of a busy hospital, it is commonplace to hear constant chimes and beeps, each coming from different machines and indicating different "alarm conditions" (**Figure 1**). It should be more of an expectation that clinicians become desensitized to extraneous stimuli given the constant sensory bombardment coupled with the need for vigilance and differential interpretation of each alarm [25, 26]. When further compounded by heavy clinical workloads and long shifts, it becomes a matter of "statistical probability" before a critical alarm is missed [27–29]. Given the effect of this potentially dangerous phenomenon on both quality and safety of patient care, closer scrutiny of AF and related concepts is warranted. In this chapter, we will present a vignette-based discussion outlining fairly typical AF scenarios. Opportunities for improvement, including equipment, personnel, and systems-based considerations, will then be provided.
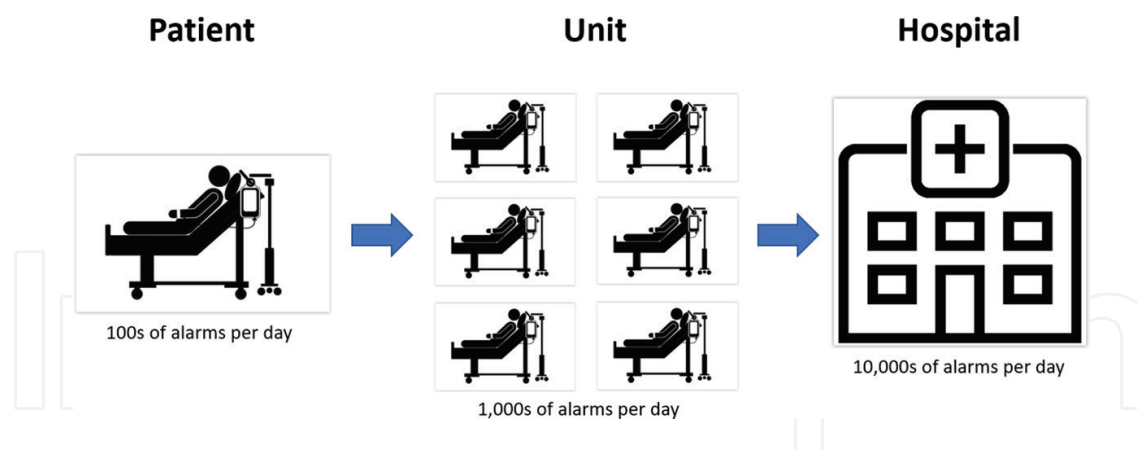
Figure 1. Conceptual model for daily observed alarms at a typical acute care hospital. Data shown in proportion to different scales, from individual patient to entire institution, showing the true magnitude of the problem (source: Ref. [24]).

2. Primary research methods

For the purposes of this chapter, the authors performed a thorough literature search using PubMed, Google Scholar™, and Bioline International. Primary search terms included "alarm fatigue," "health-care alarms," "patient monitoring," "provider burnout," as well as secondary terms consisting of various combinations of primary search terms. From over 47,000 unique search results, we distilled 73 most pertinent references immediately relevant to this document. Finally, additional sources that were cited across our primary search results were added, for a total of 101 references included in the final manuscript.

3. Patient monitoring: different types and modalities

A diverse number of patient monitors are widely used across various health-care settings [30–32]. When employed correctly, they provide potentially valuable, actionable, and real-time information about a patient's clinical status. Different monitoring devices are intended to measure different parameters, potentially allowing for rapid assessment of a patient. This is especially relevant in the context of the current discussion of AF and more specifically the domain of alarm trigger accuracy [32, 33]. As clinical monitoring becomes more sophisticated and better integrated, remote (off-site) implementations also become possible [34–36]. The subsequent discussion will outline major types of monitoring equipment and alarms, including ventilation/oxygenation, hemodynamic, and pressure point alert systems.

3.1. Ventilation/oxygenation alarms

In general, primary ventilation/oxygenation alarms (VOA) include capnography and pulse oximetry, respectively. More broadly, respiratory parameter monitoring indicates the patient's oxygen saturation, respiratory rate, and end-tidal carbon dioxide [33, 37]. The use of VOA has

been particularly important for critically ill patients who require mechanical ventilatory support. In such applications, the monitor is designed to be exquisitely sensitive to detect even the slightest changes in a patient's oxygenation or ventilation status [38]. As demonstrated in *Clinical Vignette #1* later in the chapter, an alarm may be triggered following the detection of a very small respiratory parameter "excursion," regardless of its clinical significance or magnitude of the observed change in the patient's actual clinical status. In this context, apnea and minute volume warnings are among the most common alarms triggered, with majority of such occurrences deemed clinically irrelevant upon further interrogation [39]. Moreover, many VOA triggers can be attributed to artifactual sources (e.g., patient movement, interruption of blood flow by inflating blood pressure cuff, and even atmospheric pressure variations) [37]. Thus, providers should be educated accordingly to ensure that the above considerations are appropriately factored into final clinical determinations and decisions.

3.2. Hemodynamic alarms

Hemodynamic alarms (HA) monitor a variety of parameters, of which the most common ones include heart rate, systolic/diastolic/mean blood pressure, and various other intravascular pressure measurements via both invasive and noninvasive approaches [37, 40]. Hemodynamic monitoring has become a useful tool for the bedside assessment of patients in a number of clinical scenarios, from routine telemetry applications to advanced intravascular catheter utilization. There is some degree of predictability based on measured parameters, especially when trend determination and volume responsiveness are being considered [41, 42]. Hemodynamic monitors are particularly important in the setting of an unstable (or potentially unstable) patient, similar to the one described in *Clinical Vignette #3* later in the chapter. In such capacity, HAs can help facilitate rapid intervention and prompt correction of emergent issues. Still, HAs are far from perfect, with significant shortcomings in their discriminatory capabilities. More specifically, HAs are unable to identify a patient as "stable" or "unstable," especially when physiologic compensatory processes mask any underlying instability or in the setting of rapid change in hemodynamic status [43]. Thus, when using any particular monitoring modality, there is no substitute for an astute clinician who is able to effectively correlate HA findings with the clinical reality [44–46].

3.3. Bed and chair pressure sensors

Bed and chair pressure sensor (BCPS) alarms are utilized across many hospitals and other health-care facilities to help reduce mechanical falls among patients who experience ambulatory or balance difficulties [47, 48]. Falls typically occur as patients attempt to mobilize and/or ambulate without the required assistance of trained health-care staff [49]. Consequently, the use of BCPS alarms serves to alert staff—typically by a pressure-sensitive mechanism—when a patient attempts to move from a bed or chair without assistance. However, the weight-sensitive pads are easily triggered by very slight patient movement, resulting in a significant number of false alarms [50, 51]. This challenge was readily apparent in *Clinical Vignette #3* later in the chapter, as the majority of BCPS alerts were likely due to the patient merely shifting slightly in the bed, and not by an actual attempt to independently mobilize and/or ambulate.

Unfortunately, the one true positive alarm became lost in "a sea of false negatives." The practicality of BCPS alarms is also diminished by the inability of staff members to immediately assess/respond to the triggered alarm. Instances have been noted in which the alarm signal is transmitted after the event already transpired, as patients tend to fall immediately upon leaving the bed or chair [52].

In summary, the above-referenced monitor/alarm types have become an important part of the modern health-care fabric. Despite their ubiquitous use and great potential for constructive and practical clinical application, each type of device carries inherent flaws that providers must be aware of. Detailed knowledge of the risk-benefit equation associated with each device and clinical alarm type is important not only for patient safety but also required to help improve the quality and accuracy of the next generation of monitoring devices.

4. Patient monitor alarm design

Patient monitors are designed to have high sensitivity to predefined changes in various measured parameters, including vital signs, respiratory/ventilator status, and patient movements. However, the major drawback associated with high alarm sensitivity is the poor specificity and inherently disproportionate number of nonactionable (or nonclinical) alarms triggered [22, 53, 54]. Depending on the specific alarm and clinical setting, the estimated in range of "false positives" may be as high as 80–99% of all triggered alarms [8]. Broadly speaking, nonactionable alarms can be categorized as false alarms, nuisance alarms, and technical alarms (**Figure 1**). To elaborate further, false alarms occur in the absence of an actual patient or system trigger and typically result from a measurement artifact [55]. Technical alarms mandate the provider to attend to some operational aspect of the monitoring system, such as when readjustment of monitor leads/sensors is required [21]. Nuisance alarms are defined as clinically insignificant alarms that may interfere with patient care [10]. In aggregate, these nonactionable alarms are a major cause of the overall desensitization of hospital staff that may ultimately result in AF (**Figure 2**).

Furthermore, to be effective, the alarms transmitted by monitoring systems must trigger some degree of cognitive response in health-care providers. This equates to introducing stress and the need for constant vigilance, both of which further heighten the risk of AF [56, 57]. When multiple clinical competing priorities collide, it becomes increasingly difficult for a provider to proactively address all ongoing problems, thus forcing them to resort to only partially addressing acute issues while at the same time disrupting other (parallel) activities due to multitasking [58–61]. Consequently, an ideal alarm should be perfectly audible and easily recognized by health-care providers working within the patient care unit [8], while at the same time minimizing the amount of stress imposed on the responding clinical staff.

The increasingly complex environment of modern health-care systems has led to several important considerations regarding the practical application of monitoring systems. For example, space-related issues deserve special mention, with overly crowded clinical units creating an abundance of alarm-related stimuli and geographically larger clinical units
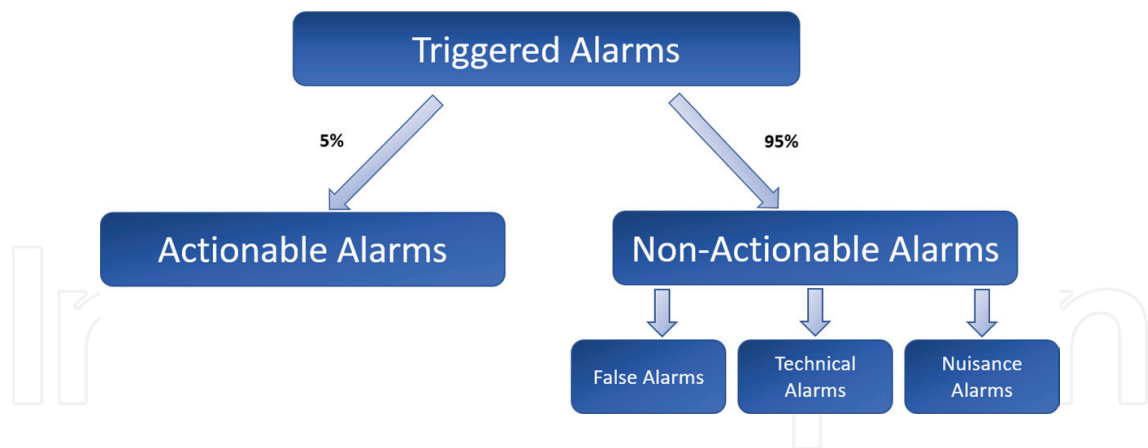
Figure 2. Schematic representation of the classification of alarm types triggered by various patient monitoring systems, including both actionable and nonactionable alerts (source: Ruskin [8]; Gorges [66]; and Tsien [67]).

presenting a barrier to prompt patient access. Elevated acuity and high patient throughput are also important considerations in this context [62].

Furthermore, technological advancements facilitated the development of increasingly sophisticated alarm systems, with novel features designed to decrease the nuisance factor of the alert mechanism while preserving the level of overall clinical vigilance [63, 64]. These are intended to provide a range of alarm tones that allow care providers to easily identify and prioritize alarms, typically as high, medium, or low priority. However, the implementation of such systems (e.g., IEC 60601-1-8 standard) has presented challenges in terms of recognizability of melodic alarm tones. More specifically, nurses found it difficult to accurately identify all of the melodic tones signifying high-priority alarms, in addition to the potential for confusion between certain alarm pairs [65]. An example of such phenomenon is presented in *Clinical Vignette #1* below, where two sets of tones were too difficult for the nurse to readily differentiate, rendering the alarm feature ineffective. Consequently, it is important for systems to have some degree of built-in learnability and flexible discriminative ability, with continued refinement, development, and testing of each clinical alarm, both alone and in tandem with other competing alarms [65]. Without exception, any observed deficits in patient monitor effectiveness and/or safety should prompt an immediate critical evaluation of both technical and clinical aspects of its implementation and function.

5. Clinical Vignettes

5.1. *Clinical Vignette #1*: 62-year-old female presenting with chronic obstructive pulmonary disease (COPD) exacerbation

A 62-year-old female was admitted to the local hospital 5 days ago due to chronic obstructive pulmonary disease (COPD) exacerbation. She was diagnosed with COPD several years prior and remained stable with no history of exacerbations until 1 week ago when she developed a progressively worsening cough. Soon after her symptoms worsened, she began to feel shortness of breath that was not relieved by rest. At this point, her family insisted she go to the

hospital for evaluation. Upon arriving in the emergency department, short-acting bronchodilators and oral corticosteroids were administered with only mild symptomatic improvement. Given the patient's dyspnea at rest, as well as decreased oxygen saturation of 86%, she was admitted to the pulmonology unit. Supplemental oxygen and intravenous corticosteroids were administered.

At admission, continuous pulse oximetry monitoring was started. The patient's hypoxemia seemed to improve slightly over the next 4 days, with oxygen saturation climbing to 88–90% range. Still, the patient's ventilatory monitor sent alarm signals to the hospital staff several times an hour due to high respiratory rate and episodic oxygen desaturations. Alarm signals were transmitted as either a single low tone (respiratory rate) or a double alarm (desaturations), alternating between low and medium tones. The difference of alarm tone indicated the range in which the patient's oxygen saturation was measured, but the assigned night-shift nurse found the tones to be too difficult to distinguish and would routinely just perform an in-person check of the saturation level upon entering the room. Throughout the first two nights, the same nurse responded to the alarms in a timely fashion, only to find the patient stable and with no signs of acute distress. Assuming that alarms are unlikely to represent any actionable clinical events, the same nurse then began to silence the sounds and began checking on the patient hourly. In the early morning hours of the fourth day, the nurse silenced the alarm once again, intending to assess the patient once the remainder of her rounding routine was completed. When the nurse finally came to the patient's room an hour later, she found the patient unresponsive and cyanotic. A rapid assessment showed an oxygen saturation of 79%. The patient was immediately intubated, transferred to intensive care unit, and mechanical ventilation was initiated.

5.2. *Clinical Vignette #2*: 65-year-old male transferred to inpatient unit following a total knee arthroplasty

A 65-year-old male with a history of osteoarthritis of the right knee and refractory pain underwent preoperative evaluation by an orthopedic surgeon. Given his adequate performance status and lack of comorbidities, the patient was determined to be a suitable candidate for total right knee arthroplasty. The surgical procedure was uneventful, with appropriate antibiotic and venous thrombosis prophylaxis administered perioperatively. Following a brief recovery in the postanesthesia care unit, the patient was transferred to the inpatient floor with expected discharge within 5 days postsurgery. Due to the nature of his surgery and apparent fall risk, the patient's room was fitted with weight-sensitive bed and chair alarms. During the first 3 days, he remained relatively sedated due to the frequent administration of pain medications. However, as the patient began to regain strength, his analgesia regimen was tapered. On day 4, the concurrent increase in patient's movement began to trigger his bed monitor to the point where the on-call nurse was receiving nearly constant alarm notifications. Multiple times, the nurse entered to assess the patient only to find him resting comfortably without apparent attempt to leave his bed. Later that night, after leaving the patient's room, the nurse was unexpectedly assigned to three additional patients due to an unplanned absence of a coworker. As the nurse hurried to assess the new patients, the bed monitor transmitted yet another alarm signal. Annoyed by the repeated negative alarms, the nurse disabled the alerts from the bed monitor,

intending to check in after tending to her newly assigned patients. When she finally returned to the patient's room, she found him sprawled on the floor and writhing in pain. The patient, emboldened by his rapid recovery, had attempted to ambulate to the bathroom without assistance and lost his balance in the process. The intense pain prevented him from reaching the call button on the hospital bed, so he was forced to lie on the floor in pain for approximately 1 h. A subsequent skeletal survey revealed a left hip fracture, which required additional surgery, prolonged hospital stay, and the need for inpatient rehabilitation stay due to temporary disability involving bilateral lower extremities (e.g., right knee arthroplasty and left hip injury).

5.3. *Clinical Vignette #3*: 71-year-old male with history of multiple myeloma admitted for right lower extremity swelling associated with minor pain

A 71-year-old male with a history of multiple myeloma was admitted to the urgent care center after noticing sudden onset of right lower extremity swelling associated with minor pain. The patient began induction therapy for multiple myeloma approximately 1 year prior, achieving adequate disease control. He was subsequently transitioned to maintenance treatment, which he continued for the past 6 months. Evaluation in the urgent care center with venous duplex studies revealed a deep venous thrombosis (DVT). Because of the patient's established history of malignancy, the triage clinician opted for hospital admission and therapeutic anticoagulation. While being transferred to the inpatient unit, unfractionated heparin anticoagulation was started. Per standard protocol, monitoring equipment was hastily fitted to the patient for noninvasive measurement of his blood pressure and heart rate. Overnight, the patient remained stable, with some resolution of lower extremity of pain despite persistent swelling. The on-call physician assessed the patient during morning rounds and ordered to repeat venous duplex for the afternoon to evaluate for resolution/progression of the DVT. Of note, throughout the night and into the morning hours, the patient's hemodynamic monitor had been sending intermittent alarm signals. With the first few alarms, the charge nurse promptly responded and quickly assessed the patient for any signs of instability or distress. However, as the shift progressed, the nurse increasingly dismissed repeated signals as "false alarms" due to a recurring pattern of mildly elevated blood pressure and heart rate secondary to episodic extremity pain. Because the inpatient unit continued to be understaffed during the morning shift, the charge nurse decided to disable the patient's repeated monitor alarms after the patient was assessed during morning rounds and found not to have any acute issues. It was hoped that this decision would eliminate the distraction of the nuisance alarms. However, during the patient's routine afternoon assessment, the rounding physician noted cold and diaphoretic extremities with markedly increased swelling. Interrogation of the monitor system revealed progressive bradycardia and hypotension over the past hour. An emergency CT angiogram showed a massive pulmonary embolism, prompting immediate thrombolytic therapy and patient transfer to intensive care. Despite aggressive management, the patient's shock became refractory, culminating in his death several hours later.

5.4. Summation of Clinical Vignettes: finding common threads

The three hypothetical clinical scenarios outlined above share a common theme: dedicated monitoring systems implemented to ensure early detection of clinical deterioration and thus

patient safety were utilized either ineffectively or incorrectly. In all three vignettes, a confluence of factors (environment, patient, medical personnel) subsequently led to AF and then adverse patient outcomes. In the following sections, we will further discuss the phenomenon of alarm fatigue, focusing on its impact on daily clinical practice.

6. Alarm fatigue

After the general introduction of AF earlier in the chapter, the authors will now discuss this important concept in greater detail. The phenomenon of AF is multifaceted and includes increased clinician response time with simultaneous decreased response rate that is mainly attributed to excessive stimuli from clinical alarms [8]. Depending on patient acuity and clinical monitoring requirements, typical bedside health-care personnel may be exposed to as many as 1000 alarms during a single shift, of which as many as 95% can be nonactionable and thus do not require immediate clinical determination [8, 66, 67]. Given the multitude of clinical alarms, a provider has to sort through during a typical hospital shift, there will be a natural tendency to potentially dismiss certain alarms as insignificant through rationalization. This phenomenon is described in the literature as the natural human behavioral reaction to "deprioritize signals" that have often been proven to be either false or misleading. Thus, staff may begin reflexively disabling or silencing alarm systems, which could effectively mask other alarms that may be clinically significant [68, 69]. To some extent, this behavioral pattern was seen in all three *Clinical Vignettes*, where the actionable alarm was masked by the vast number of nonactionable alarms that preceded it. Ultimately, the resulting delay in response or inadequate response puts patient safety at risk and may result in morbidity and/or mortality [70, 71]. Technologically advanced physiologic monitors bring a lot of promise, both in terms of earlier and more sensitive detection of patient deterioration (or other clinically significant event); however, the sensory overload and desensitization associated with AF will likely continue to present a major opportunity for improvement.

Certain other factors have been implicated in the increased incidence and severity of alarm fatigue, including greater staff workload, higher patient acuity, and the complexity of the modern health-care environment [10]. Nurses serve as key frontline staff in most clinical settings and play a pivotal role in overseeing patient care and monitoring. Moreover, nurses are subject to significant occupational stress that can be attributed to multiple causes, including heavy workloads [72]. This stress, as outlined in previous sections of this chapter, certainly influences AF by forcing nurses to instantaneously adjust their work activities (and priorities) according to perceived importance of near constant clinical alarm activity. Our *Clinical Vignette #2* illustrated the difficult task of ongoing patient triage, with the nurse having to prioritize between the three newly admitted patients and all of her other assigned patients. This constant need for clinical vigilance and prioritization is potentially disruptive to typical workflow, especially when high task complexity is involved. It can also contribute to the development of burnout [73]. Nurses have expressed the internal conflict between having to ignore the constant alarms simply to maintain sufficient focus to finish their routine tasks [74]. It is not surprising that increasing workload or task complexity has been associated with both suboptimal job performance and inconsistent alarm response [10]. Furthermore, the

Figure 3. The word cloud demonstrating the multifaceted phenomenon of alarm fatigue.

effort of acknowledging, evaluating, and responding to an alarm significantly increases the overall time commitment and workload of the nurses, which further perpetuates the trend of decreased alarm response and task performance [8].

Because multiple factors contribute to AF, many existing models struggle to fully account for (and address) clinician behavioral patterns seen with AF [75]. At the same time, it should be noted that AF is not unique to clinicians. In fact, a similar phenomenon has also been seen among human operators utilizing automated monitoring systems, such as aircraft pilots and nuclear power plant operators. The excessive number of alarm activations leads to the tendency of operators to ignore alerts, particularly when the monitoring system produces a high rate of false alarms or alerts [75]. For these operational environments, it has also been suggested that increased primary and secondary task workloads have a compounding effect on alarm response degradation that may occur in the setting of low alarm system reliability [76]. Similar to the clinical setting, AF can be associated with serious safety risks and represents a similar barrier to the practical application of automated monitoring systems in other fields (**Figure 3**).

7. Potential outcomes of alarm fatigue

Significant percentage of nonactionable alarms in the typical modern clinical environment can lead to the development (and subsequent habituation) of AF. As previously mentioned, AF can be characterized by alarm desensitization, mistrust of alert accuracy/utility, and delay of caregiver response (or even lack thereof). Commonly seen reactions to AF include the deactivation and silencing of systems or adjustment of alarm parameters to decrease the number of alarms. Such reactive behaviors have the potential to result in missed critical alarms, leading to patient morbidity or even mortality. In fact, patient safety considerations associated with AF are among the top items of Emergency Care Research (ECRI)

Institute's Health Technology Hazards list [77, 78]. The subject of AF has been extensively studied, primarily due to its high prevalence across essentially all health-care settings. The underreporting of alarm-related events has been recognized as a challenge, and it should be noted that recorded incidents likely reflect only a small proportion of actual events. Available records from the Joint Commission's Sentinel Event Database show 98 alarm-related occurrences between January 2009 and June 2012 (**Figure 4**). Of these reported events, several common alarm system issues (**Figure 5**) were directly connected to events leading to injury or death (**Table 1**) [79].
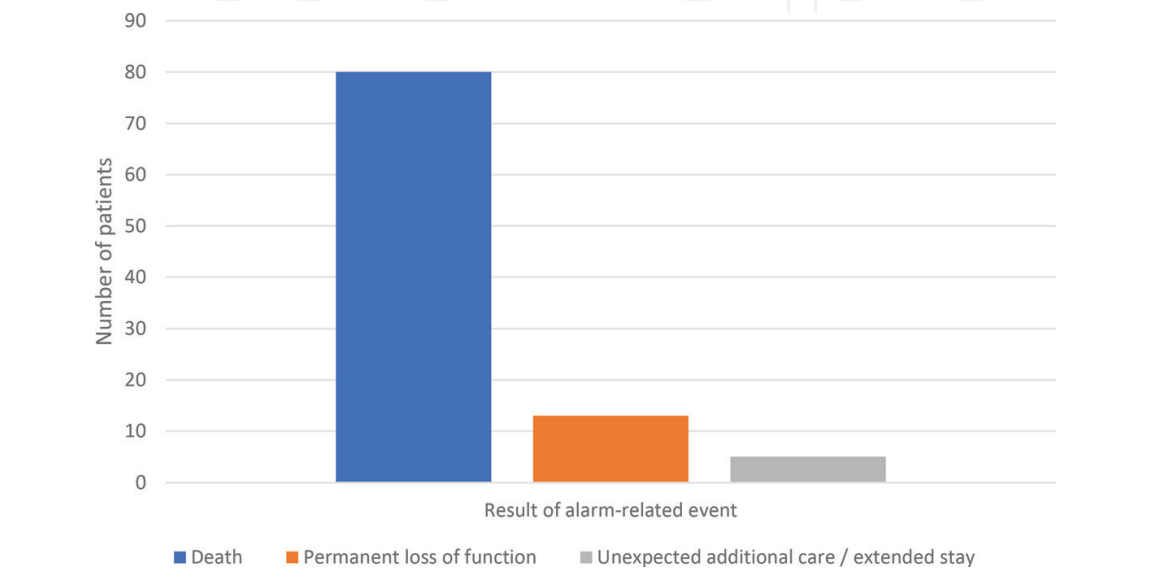
Figure 4. Alarm-related events and subsequent results from January 2009 to June 2012 (source: Joint Commission's Sentinel Event Database).
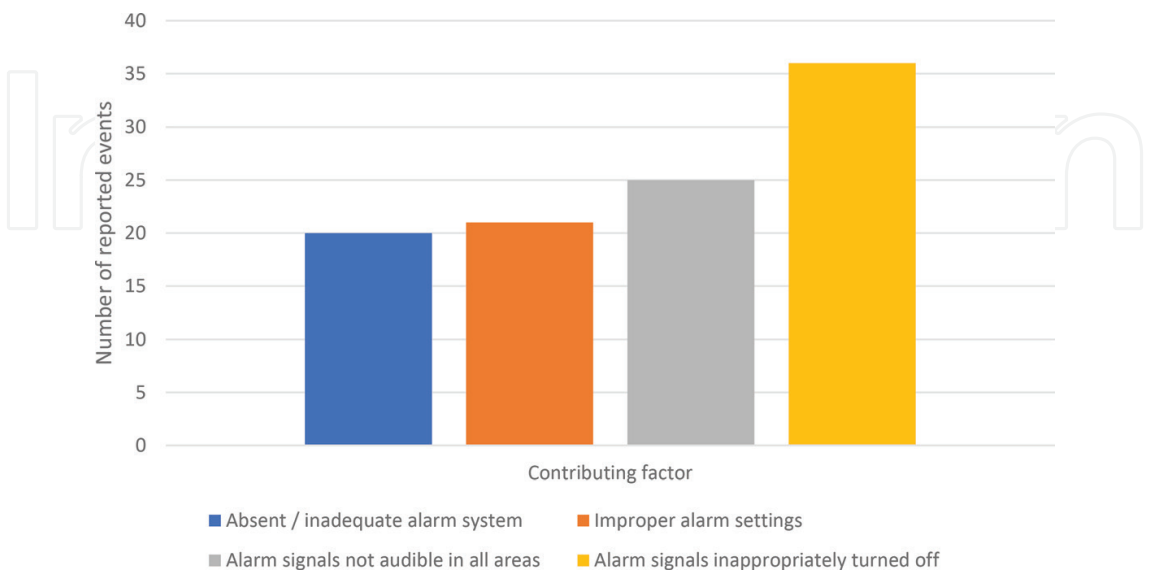
Figure 5. Major contributing factors of alarm-related events (source: Joint Commission's Sentinel Event Database).

| Event |
| --- |
| Falls |
| Delays in treatment |
| Delays in ventilator use |
| Medication errors |
| Source: Ref. [24]. |

Table 1. Common alarm-related events leading to injuries or deaths.

Additionally, the US Food and Drug Administration's Manufacturer and User Facility Device Experience (MAUDE) database has identified 566 alarm-related patient deaths between January 2005 and June 2010 [79]. Reports detailing alarm-related events have prompted thorough investigation into AF and possible strategies to address this important phenomenon in the clinical setting.

8. Quality improvement

Considering the potential for very serious clinical consequences of AF, quality improvement measures have been proposed to help reduce both nonactionable alarm occurrences and the incidence of AF. Successful quality improvement projects must address multiple facets of the overall problem, including root causes that lead to AF (**Figure 6**). For example, poor usability and lack of user-centered devices have the potential for elevating clinical personnel stress levels, creating unnecessary workload and interjecting workflow inefficiencies into an already tense environment [81].

Potential solutions for reducing the incidence of AF include multipronged approaches consisting of staff education, equipment (hardware and software) enhancements, and implementation of more efficient clinical protocols or guidelines [82–84]. From an educational perspective,
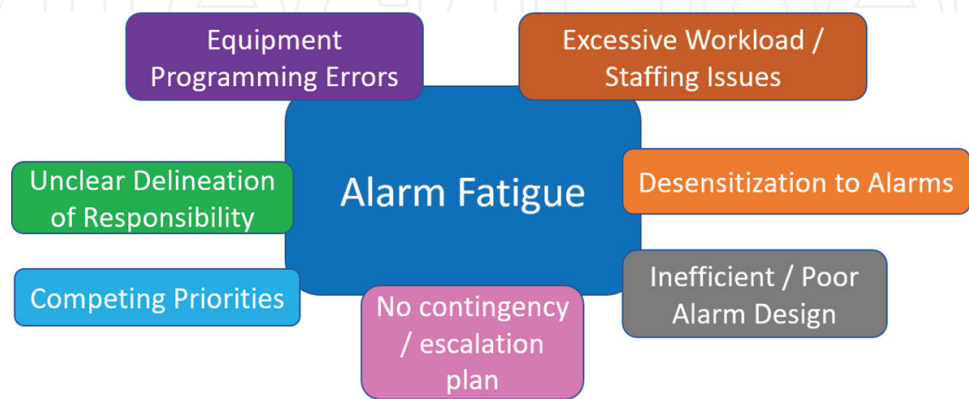
Figure 6. The different aspects of alarm fatigue that can be addressed through different quality improvement approaches (source: Ref. [80]).

it is important to ensure adequate staff education, equipment training, and closer team collaboration to improve patient safety within the existing framework [8, 85]. In addition to staff education, hospital policies have been developed and implemented to more clearly define which staff members are able to change alarm settings, as well as how such changes should be made and documented. Many of these polices have also delegated the responsibility of performing clinical alarm monitoring rounds to a staff member in order to allow for continued review of the application of patient monitoring systems [86–88].

To address the issues of staff workload, two potential approaches have been proposed. The first approach consists of secondary notification systems. The second option involves the use of dedicated staff to oversee alarms. A secondary notification system involves a specialized network interface that algorithmically facilitates the decision process regarding which alarms will be further communicated or escalated to pertinent downstream clinical staff. Further, this system would also enable the automatic escalation of an alert to another clinician, should the primary recipient fail to acknowledge the alarm within a designated timeframe. The use of staff to oversee alarms, while an expensive option, can give additional support to care providers in the form of dedicated personnel whose responsibility is to continuously monitor patient data trends and alarms from a central station [58].

No matter the solution, all the quality improvement processes require a multidisciplinary approach to address the causes and effects of AF. Only through collaborative efforts can substantial change be accomplished to reduce the number of alarm-related events in health care. In addition to the quality improvement measures taken by hospitals, technological advances have also led to more efficient and practical application of patient monitors in the clinical setting. These advances are directed at the reduction of nonactionable alarms with the goal of decreasing the alarm desensitization associated with AF. The importance of adequate information technology support, including better device designs, must be emphasized. As increasingly efficient and complex monitoring equipment is introduced into the clinical realm, certain phenomena, such as the emergence of "unpredictable code," may adversely affect computer performance (including the ability to effectively recognize important data patterns) and lead to clinical alerts being missed despite the fact that alert-specific data were clearly and provably present [89].

9. Technological advances in patient monitors

In general, clinical monitoring is based on a careful balance between sensitivity and specificity of alarm signal recognition, as well as the associated threshold setting required to trigger "alert condition" [90, 91]. Increasing monitor sensitivity helps ensure that truly significant events are not missed, primarily using single-parameter alarms and default thresholds [8]. However, as a trade-off this increases the incidence of nuisance alarms that are nonactionable. This issue may be remedied by the development of "smart alarm systems" that use algorithmic approaches to evaluate multiple parameters prior to determining whether the detected change is truly critical, and only then sending an alert to the operator [15]. This improvement in device specificity would result in significantly fewer false alarms and therefore reduce

System	Description	Application
Rule-based expert systems	Application of expert knowledge from a compiled database to new context and simulation of expert decisions	Development of a highly specific patient monitor system with electronic access to data available in a multichannel patient monitor and data management system to detect cardiac disturbances [37, 96]
Neural networks	Utilization of artificial neural networks to predict disease presence based on advanced information	Development of neuronal network used to detect myocardial infarction early on in patients admitted for chest pain [37, 97]
Fuzzy logic	Diffuse processing of exact data that does not indicate an explicit conclusion	Development of a monitor system able to diagnose simulated cardiac arrest via evaluation of EKG, capnography, and arterial blood pressure [37, 98]
Bayesian networks	System used for the estimation of event occurrence based on causal probabilistic networks	Application of system for decision support in cardiac event detection [37, 99]

Source: Schmid et al. [37].

Table 2. Applications of artificial intelligence in the development of intensive care monitoring.

AF. At the same time, the challenges of "unpredictable code" and "interrupted or corrupt data" have been noted and may represent an important safety issue due to the potential for missing data or data misinterpretation, especially when using memory-intensive applications on devices that are continually operating for prolonged periods of time [89, 92–95].

The ideal patient monitor would have high sensitivity, as well as high negative predictive value for life-threatening clinical scenarios. This would result in excellent "event detection rate" while reducing the number of false and nuisance alarms. Still, any improvement of sensitivity/negative predicative value for monitors must be accompanied by corresponding adjustment to specificity/positive predictive value, ensuring that clinically significant events are captured efficiently [33]. The accomplishment of the above goals may be possible using the application of artificial intelligence (AI) in monitoring systems, wherein AI would be incorporated into logic-based, decision-making systems. The ultimate goal would be the development of clinical monitoring capabilities that reflect and mirror human cognitive/decision-making processes [37]. In the context of this chapter's *Clinical Vignettes*, the application of such AI-based systems might be helpful in minimizing the number of nonactionable alarms, thus reducing the subsequent AF associated with adverse clinical events. So far, the utilization of AI has been explored in several different applications (**Table 2**).

10. Conclusion

Given the proliferation of advanced monitoring equipment, AF continues to be a major patient safety issue across modern health-care systems. While technological advances show great promise in improving patient care, significant barriers to more optimal implementations exist, including the ongoing struggle to balance the need for high sensitivity versus the excessive number nonactionable clinical alarms. The high frequency of clinical alerts, especially when

combined with heavy clinical workload, is known to have negative effects of hospital staff, including alarm desensitization and subsequent delay and/or lack of caregiver response. The resultant AF poses a serious risk to patient safety and has been associated with significant adverse events, including the need for additional or prolonged hospital care, excess attributable morbidity, and even mortality. Prevention of AF requires a multipronged approach consisting of quality improvement measures, staff training, better equipment management (e.g., monitor threshold adjustments) to reduce false alarms, and focus on optimizing staff workload.

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