in 2003 and included the reduction of harm stemming from clinical alarms in the National Patient Safety Goals of 2017. The lay press has also described in-hospital deaths associated with alarms. Further, inappropriate alarms negatively affect the patient’s experience of care. These noises raise concern when none is needed, create an impression of poor care when clinicians do not respond immediately, and disturb what is meant to be a healing environment.

Perhaps the impact to the patient is bigger than acoustic annoyance. What if excessive alarms negatively affect patients beyond the “hard” measures of patient safety? Prospective research in this area is scant, but there is a thread connecting the proliferation of inappropriate alarms, a noisy ICU environment disrupting rest and sleep, and increased risk of delirium with its attendant worsening of cognitive and psychological outcomes in survivors of critical illness.

A Proposed Link Between Alarms and Delirium

Much of the equipment used in the modern ICU has the capability to sound an alert if there is a perturbation from its “normal” operating state. Some alarms arise from critical disturbances in patient physiological parameters (cardiac rhythm, heart rate, pulse oximetry, respiratory rate, minute ventilation, peak inspiratory pressure, etc) while others are raised in response to a perceived disorder with the equipment itself. A patient room will contain several items capable of making sounds as alarms: physiological monitors, mechanical ventilators, IV infusion pumps, dialysis machines, enteral feeding pumps, sequential compression devices, vacuum pumps applied to wounds, and the bed itself. Specialized ICUs may have equipment that contributes a voice to the choir of alarms.

From the clinician’s perspective, alarms can be lifesaving, but the number and frequency of different sounds can reduce their importance and the urgency of the response. This phenomenon was noted 30 years ago, when an individual patient room contained fewer monitors than today. The problem is so pervasive that the Joint Commission highlighted alarm safety in 2003 and included the reduction of harm stemming from clinical alarms in the National Patient Safety Goals of 2017. The lay press has also described in-hospital deaths associated with alarms. Further, inappropriate alarms negatively affect the patient’s experience of care. These noises raise concern when none is needed, create an impression of poor care when clinicians do not respond immediately, and disturb what is meant to be a healing environment.

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Alarms: Proliferation and Lack of Specificity

The Development of Alarms in Critical Care

Critical care medicine grew out of a synthesis of new medical knowledge, specialized skill, and technology. Florence Nightingale, a British nurse, is credited with creating the first ICU as a specific area for treatment of the most seriously injured and ill during the Crimean War. The early 20th century saw growth of these units as a result of advances in surgery and increased volume of acute injury and disease. Modern mechanical ventilation and cardiac monitoring were some of the first specialized technologies brought into the ICU. One of the issues with the introduction of this technology was the lack of alarms. For example, in mechanically ventilated patients, endotracheal tubes could become disconnected from the ventilator without alerting the bedside staff. Adoption of continuous electrocardiography (ECG) on inpatient units began in the 1960s with the growth of cardiac
care units. Coincident with the deployment of cardiac monitors, implementation of computer-assisted ECG interpretation allowed for automated waveform interpretation and alarms for dysrhythmias.\textsuperscript{9,10} As technology and computing improved, alarms were added to life support and monitoring equipment.

The number of different alerts created by patient care equipment increased from 6 to more than 40 in just under 30 years.\textsuperscript{11} This occurred, in part, due to the progress of advanced physiological monitoring as well as an increase in the number of devices with alarms in proximity to the patient. Further, some pieces of equipment (such as monitors and ventilators) have different audible tones (high, medium, and low priority as well as technical alarms), which add to the number of different sounds experienced by the patient and staff.\textsuperscript{12}

**High Frequency of Nonactionable Alarms**

Despite their potential for saving lives, alarms are frequent harbingers of misinformation. A systematic review estimated that nonactionable alarms represented 78% to 99% of the alarm burden.\textsuperscript{13} A observational pediatric study noted an average of 21.3 alarms per patient hour. While nearly 50% of the alarms in the data were valid (they were alarming due to appropriate detection of a physiological disturbance), only 0.5% were found to be actionable.\textsuperscript{14} The cause of “false alarms” may be technical (a continuous ECG obtained during a sternal rub interpreted by the monitor as ventricular fibrillation), or the physiological value exceeding the alarm limits is expected and does not warrant intervention. The result of a high number of alarms infrequently representing an acute condition that requires action is a degradation in their perceived specificity. Physiological and technical alarms are vulnerable to this issue.

Continuous ECG monitoring is susceptible to artifact created by patient movement and poorly adherent electrode stickers. Consequently, the monitor’s interpretation of the ECG tracing may be inaccurate. Unfortunately, accurate interpretation of the ECG does not wholly guard against false alarms. In the critically ill population, intermittent cardiac rhythm disturbances or persistent conditions (such as tachycardia) may be detected despite not needing emergent intervention. The continuous ECG is interpreted appropriately in these cases, but the resulting alarm is not needed. Other physiological monitors are vulnerable to similar problems. Pulse oximetry, for example, is a significant cause of inappropriate alarms due to poor patient perfusion or transient changes in signal quality. Additionally, some illnesses produce a chronic state of hypoxia that is tolerated by the clinician. The default settings of the monitor may not take this tolerance into account.

**User Interface, Alarm Fatigue, and Clinician Experience**

From the perspective of the bedside clinician, volume and quality of the tones from devices do not have a clear relationship to the required urgency of response. Perhaps more worrisome is the finding that alarms associated with equipment issues are perceived as more urgent than alarms indicating changes in a patient’s condition.\textsuperscript{15} A malfunctioning sequential compression device may create a tone similar in volume and timbre as a cardiac monitor signaling asystole or ventricular fibrillation, but the needed speed of response is clearly different. This problem is one of user interface (the device alerting the operator to an issue outside the normal range of operation using an inappropriately shrill or loud tone) and psychology (the operator is taxed by different auditory signals, all of which sound urgent).

The combination of the increasing number of alarms and their lack of specificity is taking its toll on the bedside clinician. Multiple observational studies have associated increased, nonactionable alarms with longer response time to address the cause.\textsuperscript{13,16} Other factors identified in prolonging response time included length of time on duty, fewer years of experience, and increased patient to nurse ratios.\textsuperscript{14} In a survey examining the perceived effectiveness of bedside alarms, 78% of respondents noted that they intentionally disabled alarms.\textsuperscript{17} The safety issues in disabling or becoming desensitized to alarms
meant to indicate potentially life-threatening conditions are manifest.

Qualitative research regarding the impact of alarms on bedside clinicians, particularly nurses, has revealed multiple adverse effects on the ICU as a working environment. According to one study, “Nurses described the sounds by using a myriad of terms including ‘noxious,’ ‘unnerving,’ ‘ominous,’ and ‘strident.’” When discussing the quantity of false alarms and their impact, “nurses note that they ‘dissociate,’ ‘discount,’ and become ‘numb’ to alarms as a means of ‘self-preservation.’” The overlap between the language associated with the current state of alarms and the language associated with clinical burnout is striking.

The Soundscape of the ICU

The Volume

The days of a hushed inpatient ward are over. Since 1960, the average level of noise in a hospital during the daytime has more than doubled. The World Health Organization (WHO) recommends that inpatient hospital rooms have a measured background noise of 30 to 35 decibels (dB—a logarithmic scale measuring the intensity of sound). The WHO report notes, “For most spaces in hospitals, the critical effects [of noise] are sleep disturbance, annoyance, and communication interference, including warning signals.” Part of the justification for this recommended low level of background noise is that hospitalized patients have decreased reserve to cope with additional stressors such as a high level of background noise. Table 1 provides a comparison of indoor noises.

When noise is measured in the modern ICU, it soundly falls below the accepted standard. Average sound measurements across multiple ICUs have found that the baseline level of noise ranges between 54 and 59 dB—the equivalent of a constant conversation happening next to the patient. Sound measurements in multiple tertiary care ICUs showed that the WHO threshold is only met when all equipment is turned off in a controlled room. The addition of a mechanical ventilator raises the background sound by nearly 10 dB. When syringe pumps alarmed, the total noise level in the room rose to nearly

<table>
<thead>
<tr>
<th>Decibel Level, dB</th>
<th>Comparison Sound (dB)</th>
<th>Hospital Sound (dB)</th>
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<tbody>
<tr>
<td>100</td>
<td>Jackhammer at 10 m (100)</td>
<td>Portable radiograph machine (90)</td>
</tr>
<tr>
<td>90</td>
<td>Portable radiograph machine (90)</td>
<td>Patient monitor alarm, ventilator alarm, dialysis alarm (82-85)</td>
</tr>
<tr>
<td>80</td>
<td>Garbage disposal (80)</td>
<td>Connecting to gas or air supply (85)</td>
</tr>
<tr>
<td>70</td>
<td>Vacuum cleaner, hair dryer (70)</td>
<td>Measured bedside baseline ICU sound (55)</td>
</tr>
<tr>
<td>60</td>
<td>Ventilator (60)</td>
<td>WHO patient room recommendation (35)</td>
</tr>
<tr>
<td>50</td>
<td>Average conversation (50-65)</td>
<td>Sound of breathing 1 m (20)</td>
</tr>
<tr>
<td>40</td>
<td>“Noise of normal living,” background TV/radio</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Whisper (30)</td>
<td>Measured bedside baseline ICU sound (55)</td>
</tr>
<tr>
<td>20</td>
<td>Quiet forest (20)</td>
<td>WHO patient room recommendation (35)</td>
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<tr>
<td>10</td>
<td>Threshold of human hearing</td>
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<tr>
<td>0</td>
<td>Threshold of human hearing</td>
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</tbody>
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Data from Berglund et al, Tegnestedt et al, Stafford et al, National Institute on Deafness and Other Communication Disorders, and Tsiou et al.
60 dB. In fact, peaks greater than 60 dB occurred nearly every minute in patient rooms. When sound levels were trended in an actual patient room over 24 hours, times of high activity in the unit were associated with a greater burden of noise peaks. Spikes more than 85 dB (the level where hearing damage can occur, analogous to a lawnmower or blender being heard from 3 feet away) were seen at a rate of more than 25 per hour during the day and fewer than 10 per hour only during the earliest hours of the morning (1-4 AM). Peaks of greater than 100 dB (analogous to the noise from a cement mixer or garbage truck) were noted 1 to 3 times per hour.  

What is generating this sound? A significant amount comes from monitors, equipment, and alarms. Other major sources include staff and visitor conversations, televisions or radios, and telephones and pagers. A few efforts to quantify the fraction of each contribution have been undertaken. Simons and colleagues noted that equipment and alarms made up 43% of the sound events, while staff (speech and activity) created the remaining 57%. Tegnestedt and colleagues showed a similar distribution of sounds related to alarms (40%). Increased Acute Physiology and Chronic Health Evaluation II (APACHE II) scores have been associated with increased volumes in patient rooms.  

The Impact of Noise and Alarms  
Upon admission to an ICU, a patient and his or her family are introduced into an unfamiliar soundscape. Their expectation is that the patient is ensconced in a safe, healing environment. Alarms and unit noise disrupt that perception and adversely affect their experience of care, perception of care quality, and sleep. Patient and family testimonials show that frequent alarms raise concern. In one account about a mother seeing her daughter in a neonatal ICU, the author noted, “It seemed like every time her daughter moved an alarm would go off causing Afghah [the patient’s mother] to jump to her feet.” The Vanderbilt ICU Delirium and Cognitive Impairment Study Group has documented the stories of survivors of critical illness. One husband of a patient with acute respiratory distress syndrome recalls asking bedside nurses, “Is it okay if I reset the alarms? Because they would sometimes go on for 2 to 3 minutes. And they knew it was okay, but I didn’t.” The patient herself remembers a delusion of elevators next to her “constantly busy and constantly dinging.” She subsequently found out that her room was near the locked medication cabinet, a hub of ICU activity, and the devices supporting her would also alarm frequently, contributing to her delirium. The added anxiety and decreased rest resulting from unnecessary alarms and noise represent a clear target for improvement in the ICU. Unsurprisingly, excess noise has been associated with changes in physiological variables in critically ill patients. Future research on the impact of noise on patients is needed that goes beyond qualitative experience and examines objective outcomes.  

The burden of noise is also experienced by the ICU staff. A paucity of data are available regarding the association between noise and staff performance in the ICU. Certainly, qualitative research and the experience of alarms previously discussed demonstrate how excessive noise affects the perception of the ICU. Data from the operating room show that sound reduction interventions were associated with fewer surgical complications and a reduction in biometric measurements of surgeon stress. It would certainly appear that reducing the overall burden of noise in the ICU would humanize the care environment for patients, family, and staff.  

Sleep, Delirium, and Patient Outcome  
Sleep  
When sleep patterns of patients in the ICU have been measured, the results have consistently indicated poor quality and duration of sleep. Factors from the patient’s underlying pathophysiological condition as well as the critical care environment degrade patient sleep. Polysomnography in the ICU shows that sleep is frequently interrupted, is less deep, and only occurs in short bursts. The timing of sleep is also divorced from typical day-night,
wake-sleep cycles. Rapid eye movement (REM) sleep (the deepest part of the sleep cycle) accounts for 25% of sleep in healthy controls while it is measured as only 3% of sleep in intubated critically ill patients. The end result is a patient who, perhaps for weeks on end, does not have sufficient restorative sleep. When polysomnography was simultaneously recorded with sound levels, one sample showed that 17% of awakening from sleep was due to co-occurring noise. Noise is only one of many environmental factors disrupting sleep, but it is important, modifiable, and seen by patients as the leading sleep disruptor.

Patients’ perspectives on lack of sleep can be harrowing, including nightmares and a fear of sleep as they realize how critically ill they are. In a qualitative study, one patient noted, “I couldn’t sleep because the people around me were basically dying.” Participants in the same study continued to experience sleep derangement after surviving their critical illness. Survey data indicate that patients rated the quality of their sleep at home after their ICU course as worse compared with sleep at home prior to admission. Improving sleep for its own sake would be meritorious in terms of patient experience, and reducing the overall noise in the ICU setting would assist with that. However, evidence of a link between reduced noise exposure, improved sleep, and reduction in ICU-associated delirium may imply that improving sleep by protecting patients from excessive sound can have long-lasting effects.

**Noise, Sleep, and Delirium**

Delirium is characterized as an acute onset of cerebral dysfunction with an altered level of consciousness, inattention, and changes in cognition or disturbances of perception (such as hallucinations or delusions). Other associated symptoms include emotional lability and psychomotor agitation or slowing. The association of delirium with ICU treatment paralleled the growth of life-supporting technologies and our ability to treat the critically ill as well as perform increasingly complex surgeries. In the 1960s, heart surgery was frequently complicated by delirium, and it was said that patients in coronary care units “are subject to the ‘new madness of medical progress.’” Unfortunately, ICU delirium is still too common, affecting an estimated 74% of critically ill patients during their hospitalization. Patients who develop ICU delirium are at risk for longer ICU courses, longer inpatient stays, and worse post-ICU cognitive and psychological outcomes. Like derangements in the sleep patterns of critically ill patients, ICU delirium is a product of many factors. No publications to date have directly shown that a measured higher level of background noise is associated with increased delirium or worsened patient outcomes in the ICU. However, findings associating decreased noise exposure, increased sleep, and reduced delirium imply that a relationship may exist.

Earplugs have been used in ICU patients to reduce noise exposure and improve sleep. Earplugs have been shown to increase the proportion of REM sleep in simulated ICU environments and to improve patient-reported sleep quality. Further, critically ill patients randomized to use earplugs versus usual care showed a decreased incidence of delirium and confusion. Multimodal quality improvement targeting sleep, including the use of earplugs, demonstrated improved perception of excess noise as well objectively reduced incidence of delirium. Interestingly this study did not show better patient-reported sleep scores. This raises the possibility that the relationship between noise and delirium may be independent of sleep.

Excessive alarms and noise are multifactorial problems and represent significant safety and quality issues for intensive care clinicians and patients (see **Figure 1**). A relationship between increased noise and decreased sleep has been established. Patients lacking sleep are at higher risk for ICU delirium, which itself is a risk factor for poorer physical and psychological outcomes. Interventions to promote sleep by limiting a patient’s exposure to unneeded sound (through earplugs or unit noise reduction) have been effective in decreasing delirium. The
remaining link directly associating reduced noise and a decreased burden of delirium has not been found. Therefore, further research is required to establish a more direct relationship among alarms, noise, delirium, and ICU patient outcomes. Fortunately, recommendations related to alarms, delirium prevention, and sleep promotion can be used to improve care now.

**Improvement and Future Directions**

**Clinical Alarms**
The attention paid to issues surrounding clinical alarms has brought together stakeholders from clinical, patient safety, and bioengineering fields (such as the ECRI Institute and the Association for the Advancement of Medical Instrumentation). These partnerships have yielded recommendations to reduce noise, false alarms, and alarm fatigue and to improve the approach to alarms moving forward. Some practice changes address unit administration and quality improvement, while others focus on improved alarm parameters and signal fidelity.

- **Recognize the problem.** Healthcare administrators must realize that alarms can both promote and harm patient safety. Therefore, multidisciplinary teams should be formed to assess current alarm management, recommend and implement changes, and continue to monitor clinical alarm management.

- **Optimize alarm limits, tones, and delays.** When alarm parameters are tailored to meet the needs of the patients being monitored, fewer nonactionable alarms sound. The level of acuity assigned to each condition should be adjusted so the appropriate tone is heard for each circumstance. Using brief delays before alarms sound allow transient, self-correcting conditions (such as patient movement or pulse oximetry signal changes) to pass without an unactionable alert.

- **Implement practices to improve signal fidelity.** Single-use devices (such as ECG gel pads or oximetry probes) require optimal placement and appropriately timed changes to ensure optimal signal delivery. Additionally, cords and connections require careful routing and placement to not be disturbed and generate inappropriate alarms.

- **Mandate continued reporting and analysis.** Units should be held accountable for continuing to observe and address alarm use and make ongoing adjustments to alarms.

A full summary of these points is beyond the scope of this chapter, but further reading is available regarding improvement of alarm management.12,49,50
The immediate future of clinical alarms is focused on improving technology, developing better algorithms (to improve alarm specificity), and shifting the audible portion of the alarm from the bedside to the clinician. Further ahead on the horizon are adaptive alarms that can adjust to a patient’s “baseline” and thus automatically adjust physiological parameters that would trigger an alert. Similarly, monitors may be able to detect when displayed data are likely to be incorrect or false and thus trigger a different tone rather than a high-priority alert. Manufacturers have begun to integrate human factors into more holistic displays. Perhaps we are moving away from the several lines of discrete telemetry data and toward a “heads up” view of how the patient is faring. Finally, standardization of alarm tones and volume as well as inclusion of user feedback is vital. Once established, these standards must be incorporated into existing and future devices.

**Noise Reduction, Sleep Promotion, and Prevention and Mitigation of Delirium**

Noise reduction programs on a hospital and unit level have been successful in improving both patient and staff satisfaction with the clinical environment. These programs address the clinical space (using sound-absorbing ceiling tiles, reducing the number of overhead pages, isolating patients from noise-producing equipment, improving unit design and layout), unit culture (avoiding unnecessary phlebotomy after a specified hour at night to promote sleep, implementing quiet time), and clinician practice (coordinating patient care times with physicians and nurses, providing visual reminders of current conversation volume). While every ICU may not be amenable to installing new ceiling tile, it is important that unit leaders assess the acoustic environment and ask what changes can be made. Finally, external organizations should research and publish best practices to promote quiet critical care environments.

Often tied to noise reduction programs, sleep promotion programs exist to implement environmental and patient level changes. One successful intervention discussed previously is the use of earplugs. Face masks, music, and white noise have also been successfully used to promote sleep. In the ICU, checklists to optimize the critical care environment and promote day-night wake-sleep cycles have been implemented to good effect.

In the last several years, a concerted effort has been undertaken to reduce the incidence of delirium in survivors of critical illness. Leaders in this effort have included the Society of Critical Care Medicine and Vanderbilt’s ICU Delirium and Cognitive Impairment Study Group. One tool is termed “ABCDEF”: Assess, prevent, and manage pain; Both spontaneous awakening trials and spontaneous breathing trials; Choice of analgesia and sedation; Delirium—assess, prevent, and manage; Early mobility and Exercise; Family engagement and empowerment. Published society guidelines address elements of the bundle in detail. Implementation of these guidelines has been successful and resulted in decreases in delirium and increases in patient survival. Just as the causes of noise exposure, decreased sleep, and delirium are multifactorial, future efforts to prevent these problems will involve multiple solutions and disciplines. Some of the biggest changes will surround ICU unit and room design to optimize environmental factors that affect critical illness. Perhaps most important, patient input and the experience of ICU survivors will need to inform the interventions used to improve the critical care experience and survivorship.
REFERENCES


