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REVIEW PAPER

What's all that noise—Improving the hospital soundscape

Anthony J. Oleksy[1] · **Joseph J. Schlesinger**[1]

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Abstract
Hospital noise levels regularly exceed those recommended by the World Health Organization (WHO). It is uncertain whether high noise levels have adverse effects on patient health. High levels of noise increase patient sleep loss, anxiety levels, length of hospital stay, and morbidity rates. Staff conversation and auditory medical alarms are amongst the leading noise producing stimuli, with combinations of stimuli accounting for much of the high noise levels. The Hospital Consumer Assessment of Healthcare Providers and Systems survey shows a slight improvement in overall hospital noise levels in the United States, indicating a minor reduction in noise levels. Alarm ambiguity, alarm masking and inefficient alarm design contributes to a large portion of sounds that exceed the environmental noise level in the hospital. Improving the hospital soundscape can begin by training staff in noise reduction, enforcing noise reduction programs, reworking alarm design and encouraging research to evaluate the relative effects of noise producing stimuli on the hospital soundscape.

Keywords Alarms · Noise · Conversation · Reduction · Design · Stimuli

1 Background

Noise levels in hospitals across the world well exceed the 30–40 dB recommendation by the World Health Organization (WHO) [1]. It is uncertain whether overall Intensive Care Unit (ICU) noise is a significant contributor to patient sleep deprivation and sleep arousals [2–4]. This contradicting literature shows that overall noise levels in the ICU have both a major and minor role in affecting patient sleep and overall disturbances [2–4]. Comparing the findings of these opposing viewpoints helps to identify the noise sources that are most responsible for the adverse noise levels and helps focus noise reduction efforts on the main contributors. In a meta-analysis done to compile the findings from 11 different studies, five found noise to be the most significant cause of patient sleep deprivation [2]. Multiple noise sources are likely the reason for the controversy surrounding the negative impact of ICU noise. Individual noise sources are additive in effect and are cumulatively more disturbing than each individual source alone [2]. The Hospital Consumer Assessment of Healthcare Providers and Systems Survey (HCAHPS) has data showing a slight improvement in the overall hospital quietness in the United States, yet other studies find data supporting large noise producing sources in the hospital environment which contradicts the HCAHPS survey results.

1.1 The negative effects of noise

Excessive noise levels have many negative effects on patients, hospital staff and visitors. Noise results in noise-induced hearing impairment, interferes with speech interpretation, disturbs patient rest and sleep, negatively impacts psychophysiological and mental health, diminishes overall performance and interferes with intended activities [1, 3, 4]. Patient sleep arousals are significantly correlated with patient health, with the resulting lack of sleep significantly increasing patient recovery times [4, 5]. The types of sounds that are most commonly associated with these harmful effects are characterized by sharp, sudden noises that surpass auditory arousal thresholds and often times induce autonomic reactions which increase heart rate [4, 5]. These noises act as stressors and cause constant activation of the

✉ Anthony J. Oleksy
anthony.j.oleksy@vanderbilt.edu

Joseph J. Schlesinger
joseph.j.schlesinger@vanderbilt.edu
http://www.vandydreamteam.com

[1] Division of Critical Care Medicine, Department of Anesthesiology, Vanderbilt University Medical Center, 1211 21st Avenue South Suite 526, Nashville, TN 37212, USA

sympathetic nervous system which additionally increases heart rate [3, 4, 6, 7]. Determining and eliminating sources of noise in patient care areas is critical to improving patient health in the ICU and other hospital areas.

1.2 Noise producing sources

Several studies have identified many sources that either contribute significantly to the overall noise levels in the ICU or have significant peak noise levels [8–12]. Staff communication, medical equipment and medical alarms are most commonly reported as major sources of ICU noise [2]. A study by Grossman et al. found that patients reported staff conversations (15% of patients), medical alarms (25% of patients), and general ICU noise (26% of patients) as being the most disruptive to sleep [4]. The next sections serve to focus on the relative contributions of staff noise and alarms and different noise reduction strategies, as well as analyze the effects of staff noise and alarms on patient health.

2 Sleep

Stanchina et al. found that white noise may have reduced the number of arousals by decreasing the difference between sound peaks and baseline noise levels [12]. In a control situation with baseline noise levels, subjects showed between 10 and 20 arousals per hour of sleep [12]. When a recorded ICU noise environment was played during the night, arousals spiked to 20–65 arousals per hour of sleep [12]. In the third condition, where white noise was played in conjunction with the recorded ICU noise, the arousals per hour of sleep counts resembled those of the baseline conditions, with 10–26 arousals [12]. Raising the threshold noise level through the implementation of white noise resulted in the suppression of minor noise peaks, since they were unable to break past the elevated threshold and cause an arousal.

2.1 Auditory thresholds

The threshold is the level at which the difference between baseline and peak is great enough to evoke these negative responses [12]. Therefore, reducing the noise difference between baseline noise levels and peak noise levels is speculated to reduce the number of arousals [12]. It is important to reduce the overall threshold level in the hospital setting and understand its relationship with alarm levels. Waye et al. utilized a recorded ICU noise environment to demonstrate that peak noise levels contributed most to patient sleep arousals [5]. By removing other hospital stimuli and elevating both the ambient noise level and peak noise levels played through the speakers, this study isolated the threshold variable and showed that these peaks significantly hindered patient sleep and satisfaction [5]. Patient sleep deprivation increases patient healing times, thereby increasing the length of hospital stay. Tilz et al. documented the specific noise contributions of alarms and found ambient medical alarm noise to be mostly below 70 dB(A) with occasional peaks over 80 dB(A) [13]. The term dB(A) refers to a mathematically weighted curve that accounts for the difference between the sound in its actual decibel level and the decibel level that the human ear perceives [13].

2.2 Medical equipment contributions

These short peaks explain why the overall contribution to environmental noise levels of medical equipment is low. It is important to understand, however, that these short, high decibel peaks are those that supersede the ambient noise threshold level and contribute to significant patient sleep arousals and increased anxiety [5, 8–12]. The larger the difference between the sound peaks and baseline noise levels, the greater the probability that the sound will have adverse effects on humans. While not contributing as often to the overall ICU noise levels, alarms are responsible for a large amount of noise peaks beyond this threshold and are directly correlated with the negative effects of noise [8–12].

3 Anxiety

Patients often report medical equipment noise as being scary because they are often unsure of the severity of the alarm [9]. With one alarm sounding like another, alarm ambiguity leads to patient and staff confusion and results in induced anxiety [9, 14, 15]. Anxiety acts as a state of constant stress and promotes activation of the sympathetic nervous system [9]. It is common to find that as the duration of the patient's stay increases, their familiarity with the alarms increases, and patients show reduced levels of anxiety [9]. While anxiety resulting from the unknown meaning of the alarm may fade, anxiety from the sudden onset of the alarm itself persists [9]. While alarms are usually loud and irritating, tones that are low and rhythmic tend to be drowned out in the noisy environment but can help drown out other surrounding noises. These sounds seem to have a soothing effect on patients and staff and are not as disturbing as one may expect, but lack the attention acquiring aspect of alarms that is vital to their proper functioning and makes these sounds unfit for alarm design [10, 12]. The sudden, loud noises that are common with many alarm systems break past the ambient threshold noise levels [1, 5, 7]. These are the sounds that patients find most disturbing and are most responsible for the negative effects associated with excessive noise [10, 12]. Because of the design of the alarm itself, many studies show alarms amongst the most disturbing noise producing

sources because of their large divergences from threshold noise levels [1, 5, 8–12].

4 Staff noise

Research and hospital improvements have been focused on reducing the negative contribution that talking has on the noise environment and patient well-being. Two different studies showed that patients reported background staff noise (talking) as being comforting in certain situations [9, 16]. Conversations between staff members where the patient was unsure of who was being talked about, loud or distinguishable speech, as well as conversations with other patients, were perceived as scary [9, 16]. One of the most popular movements has been the implementation of "Quiet Hours" in the regular ICU schedule.

4.1 Quiet hours

This effort focuses on reducing light levels and the intensity of alarms and discourages talking in the ICU [6, 17]. Doors to patient's rooms are shut and conversations near patient rooms are discouraged [7]. One limitation with this strategy is that the efforts are not precisely monitored and enforced. In studies analyzing the relative effects of "Quiet Hours" on the ICU environment, there are disagreements whether or not "Quiet Hours" have a significant effect on improving ICU conditions [6, 7, 17]. It is, however, agreed upon that both patients and staff appreciate the "Quiet Hours", and patients are more likely to be found asleep during these time periods [7, 17]. The contradiction between statistical significance and patient and staff appreciation, questions the overall effectiveness of "Quiet Hours".

4.2 Effectiveness

While studies may have found an apparent contradiction between statistical significance and patient and staff responses, this may be due to experimental error or inconsistent measurements [6, 7, 17]. While statistical significance is important, patient and staff opinions are more representative of the actual environmental setting. This contradiction between statistical significance and patient and staff responses may suggest a more complex situation than is immediately apparent. Data from HCAHPS shows a very slight improvement (two points) in overall hospital quietness within the past 5 years, but a seven-point increase over the past 10 years (Fig. 1) [18–20]. Since the survey is administered to hospital patients and staff, these findings both contradict and support the previously reported patient and staff satisfaction. While initial efforts at reducing the staff noise contributions may have improved scores over a 10-year period, these efforts seem to peak within the past 5 years, indicating a lack of improvement for staff noise.

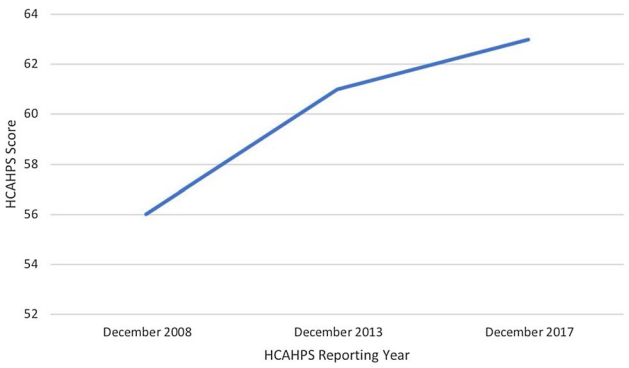

Fig. 1 HCAHPS U.S. quietness of hospital environment. Reporting period from December 2008 to December 2017 (data from summary of HCAHPS survey results. December 2008, December 2013, and December 2017). Created using Microsoft Word 2018

4.3 Interpretation

Interpreting this data suggests that other factors in the hospital environment, such as alarms, may play a larger part in overall hospital noise levels. The lack of success in reducing overall hospital noise levels may be due to sources not specifically targeted by "Quiet Hours". They emphasize reduction in the staff noise category with a minor focus on reduction in medical equipment intensity. Many alarms come with pre-set volume settings that cannot be adjusted [8]. Therefore, while "Quiet Hours" may recommend a reduction in the noise contributions of medical equipment, it may in fact have a lesser than expected effect.

5 Auditory medical alarms

The fact that most medical alarms have pre-set volume levels supports the idea that alarms have a greater than expected effect on the hospital soundscape. The US Food and Drug Administration's (FDA) Manufacturer and User Facility Device Experience (MAUDE) data-base has data showing a significant number of patient deaths as a result of the tendency of clinicians to silence pre-set volume levels. This data would imply that pre-set volume levels indirectly contribute to many patient deaths. Behavioral modification programs for hospital staff members have been implemented to reduce the contributions of alarms that are a result of improperly trained staff [21, 22]. These programs showed a decrease in the overall contribution of medical alarms to the ICU noise environment [22]. These behavioral modifications focus on reducing alarm fatigue in hospital staff and decrease staff response time to triggered alarms [21, 22].

5.1 Alarm fatigue

It is not solely the effect of one source or the other, but the interaction between staff and alarms that is a significant contributing source to overall hospital noise. The colloquial definition of alarm fatigue is the desensitization to medical alarms resulting from an overabundance of false alarms in the hospital setting [23]. This leads to alarms that surpass the ambient noise level sounding for extensive periods of time, resulting in a large contribution to the overall hospital noise environment [8–12]. Alarms may have a greater than reported effect on the overall soundscape, and their effects may be influenced by staff behaviors.

5.2 False alarms and smart alarm systems

Combined with their tones, the issue of false alarms adds to the many problems associated with medical alarm systems that are found in the typical hospital setting [14, 24]. Alarm trigger ranges are designed to be largely inclusive and general. This extreme level of sensitivity is the result of a "just-in-case" mentality [14, 15]. The problem with this mentality is that the alarms sound so often as to render themselves useless to those that rely on them for patient safety [14]. Less sensitive alarms that have a high positive predictive value (PPV) are more likely to trigger appropriate responses that can be understood by staff and minimize the number of false alarms [25]. Higher PPV scores indicate an alarm that is more likely to be meaningful when it sounds [25]. Smart alarm systems are an improvement to medical alarms that serve to reduce the number of false alarms by the device, and additionally reduce the overall noise contribution of alarms. Smart alarms work as an intelligent algorithm system which uses complex algorithms to distinguish a meaningful stimulus from normal stimuli to eliminate many false alarms [26]. These systems integrate information from multiple monitored variables and allow fluctuation within a calculated "normal" range to distinguish meaningful situations from random ones [26]. An interpretation as to why these systems have not been implemented is because alarm fatigue may be remedied by reducing the number of meaningless alarms and not necessarily the overall general number of alarms. While this type of system reduces the overall effect that alarms have on the soundscape, it still does not alter the design of the alarms and the negative effects those sounds have on patients and staff.

6 Alarm masking

Alarm design that favors easily distinguishable, yet highly similar sounds across a variety of medical alarms brings up the issue of alarm masking. This is a situation in which some alarm sounds become drowned out amongst the regular hospital environmental noise and other auditory alarms [27]. Increasing the level of sound for certain alarms eliminates the issue of alarm masking but generates the high-decibel sound peaks that lead to the negative effects mentioned before. When multiple machines are designed with this mentality, the result is a collection of high-decibel producing noise sources that negatively impact the hospital environment. Staff then have difficulty identifying the proper alarm they are looking to respond to, which leads to multiple alarms sounding for longer than is necessary to alert [15, 28]. Many modern alarms have no implied association with the meaning of their alarm [29]. Having many ambiguous alarms sounding at one time leads to confusion in the ICU across staff and patients.

6.1 Eliminating alarm masking

Hasanain et al. developed a mol which allows alarm systems to compute a proper frequency for the alarm to be audibly different than surrounding hospital noise [27]

$$abs_{maskee} = 3.64 \times \left(\frac{f_{maskee}}{1000}\right)^{-0.8} - 6.5 \times e^{-0.6\left(\frac{f_{maskee}}{1000} - 3.3\right)^2} + 10^{-3} \times \left(\frac{f_{maskee}}{1000}\right)^{4}.$$

This equation developed by Hasanain et al. [27], represents the calculation of the absolute threshold of hearing (abs_{maskee}) in dB, based on the maskee's frequency (f_{maskee}) in hertz. It is a small part of the complete model developed by Hasanain et al. This model has proven effective at reducing alarm masking by having a dynamic alarm system which increases the efficiency of many alarms in the hospital environment. While there are efforts being made in alarm design to reduce the effects of alarm masking and ambiguity, much of the medical equipment currently in use is plagued by these inefficient alarms. Efforts to promote more advanced systems would increase auditory alarm effectiveness and reduce the noise contributions of these devices.

7 Summary

7.1 Auditory medical alarm design

In designing alarms, it is critical to consider the patient and staff perspectives in addition to practicality and efficiency. While some types of alarms may show superb effectiveness in alarm response times and a reduction in alarm fatigue, the effects on patients may outweigh the apparent benefits. With more high-tech medical equipment being developed, the number of alarms in the hospital environment is increasing at an accelerating pace [23]. Modifying the tone of alarms

has been shown to improve overall alarm systems by making them less annoying and more meaningful [14, 15, 27]. A new standard for medical alarms is the IEC 60601-1-8 which works to standardize medical alarm design [30]. These improved tones could potentially eliminate alarm ambiguity, counteract alarm fatigue, and reduce the hospital noise level contributions of these devices.

7.2 Verbal speech alarms

One proposal for an improvement of alarms is the introduction of verbal speech alarms [28]. Although this may be effective at combatting alarm ambiguity, alarm fatigue, and alarm masking, it may negatively impact the noise level in the hospital setting [27, 28]. Since talking is one of the largest contributors to overall ICU noise and patient disturbances, implementation of verbal speech alarms may only accentuate these negative effects on patients and hospital staff [8–12, 28]. Combining two of the greatest contributors of ICU noise would only accentuate the negative effects of increased noise in the hospital setting. Increasing alarm effectiveness is important, however, the effects on the patients must be considered as well. Therefore, more research must be done to evaluate the relative effects of newly engineered alarm systems on the patient's environment before they are introduced into the larger medical environment. Finding the balance between increased effectiveness and patient care is important to improving medical technology in the modern world.

7.3 IEC 60601-1-8

IEC 60601-1-8 is an international standard for auditory medical alarms that serves to unify the design of auditory tones. The type of tone that is allowed is dependent on the type of alarm, the urgency of the alarm, and any additional information that must be transmitted by the sound of the alarm [30]. Some major problems with this standard are that the sounds themselves are often susceptible to alarm masking with the close unification of alarm types, as well as staff having difficulty learning the meanings of the alarms [30]. The IEC 60601-1-8 standard is consistent with the fact that while an alarm may theoretical prove to be successful, it is not until it is implemented into practice that its actual effectiveness can be evaluated.

8 Conclusion

Identifying the noise sources in the hospital environment that are most responsible for the negative effects of noise should be the focus of noise reduction efforts. Once these sounds are identified, they can be modified to reduce their individual contributions as well as how they interact with each other to produce a unique sound environment. While medical alarms are frequently identified as major noise contributors, their individual contribution is often low, however, their noises comprise a large amount of the noises that are responsible for the negative effects of noise. Focus should be placed on altering alarm design to improve effectiveness, reduce ambiguity and fatigue, and develop a design that is effective when implemented. Modifying alarm design will improve both the hospital soundscape as well as patient safety and clinician productivity.

Compliance with ethical standards

Conflict of interest None of the authors of this paper has a financial or personal relationship with other people or organizations that could inappropriately influence or bias the content of the paper. It is to specifically state that there are no conflicts of interest.

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