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Absence of Evidence or Evidence of Absence? ICU Acoustics Re*Search for a Needle in a Haystack*

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Abstract

The role of hospital acoustics and soundscapes has gained increasing attention, as creating restorative environments for patients and less stressful conditions for healthcare providers are closely linked to the quality of care. Despite this growing interest, the field remains underdeveloped; strong design guidelines and recommendations are still scarce. Intensive Care Units (ICUs), characterized by complex and dynamic sound sources, are among the most extensively studied healthcare environments. However, clinical studies investigating the relationship between the ICU acoustic environment and patient outcomes have yielded mixed, inconclusive findings. Conducting rigorous randomized controlled trials in these settings is inherently challenging due to patient vulnerability, ethical constraints, and the presence of numerous confounding variables. This raises some critical questions: To what extent do current acoustic indicators influence patient clinical outcomes? Are we measuring and analyzing the right variables and outcomes? This paper reviews the clinical literature, examines both acoustic indicators and patient outcomes, identifies key methodological limitations, and outlines future directions, including soundscape-based interventions, multisensory approaches, and more context-sensitive acoustic characterization.

Keywords: *ICU, acoustic indicators, patient outcomes, sleep*

1. Introduction

Research has shown that *healthy buildings* can positively affect occupants' comfort and quality of life throughout their life cycle, while also addressing social needs and supporting productivity [1]. This is particularly crucial in highly functional and utilitarian environments, such as healthcare facilities, and especially in critical care areas like ICUs, where health promotion is of critical importance. Nowadays, the topic of acoustic comfort in hospitals and hospital soundscapes is a point of convergence among the clinical, acoustical, and environmental disciplines. These developments align with broader shifts toward preventive medicine [2], patient-centered care [3], and evidence-based design [4], in which the built environment (including the acoustics domain) is no longer viewed as separate from the healing process but as an integral part of it.

ICUs are among the most complex and critical healthcare environments, where patient recovery and clinical outcomes are the primary concerns. They are also among the most extensively studied settings regarding noise and acoustics [5]. With the growing shift toward lighter sedation practices, increasing attention is being paid to non-pharmacological interventions [6] that can support patients' physiological and psychological well-being, particularly those related to environmental conditions such as sound. Noise in the ICU is considered a major environmental stressor, affecting patients' sleep quality, risk of delirium, mood, and anxiety [7], as well as healthcare providers' stress levels, cognitive load, and vocal fatigue [8]. This has produced a large body of literature, mainly based on observational cross-sectional studies, that yields mixed results regarding acoustic and patient outcomes across sleep, psychological, clinical, and physiological domains. This raises the question of whether these inconclusive results stem from varying study designs and research methodologies, the use of different metrics, or the limited impact of the acoustic environment on occupant outcomes.

This paper outlines the clinical evidence on ICU acoustics and the key patient outcomes affected by

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environmental factors, such as sleep and delirium. It critically examines methodological approaches, acoustic indicators, and reported outcomes, and discusses potential reasons of discrepancy in the literature. Using the analogy of searching for a needle in a haystack, it reflects on the difficulty of identifying meaningful relationships in such complex environments. Finally, it outlines directions for future research that may lead to more robust and conclusive evidence.

2. Review of Evidence

This section reviews studies conducted in ICUs focusing on acoustic indicators and patient outcomes. Some studies employ an observational design and focus primarily on sleep outcomes in their natural setting, without manipulating any variables, in order to draw correlations. Some other studies use the gold standard of clinical research, such as randomized controlled trials or quasi-experimental designs, to examine the causal effects of a particular environmental intervention on patients. A synthesis of the observational and interventional studies mentioned below is presented in Table 1.

Table 1. Observational and interventional studies investigating the impact of the acoustic environment on patient outcomes

Ref.	Acoustic metric	Patient outcomes	Result
Observational studies			
[9]	Acoustic interruption	Sleep (RCSQ)	Significant
[11][12]	L_{Aeq}	Sleep (RCSQ)	Significant
[13][14]	L_{Aeq}, L_{Amin}, L_{Amax}	Sleep (self-reported)	Non-significant
[15]	L_{90}, Restorative periods	Sleep (RCSQ)	Significant
[19][20]	L_{Aeq}, L_{Amin}, L_{Amax}	HR, RR, BP	Significant
[21]	L_{Aeq}, Acoustic Peaks	Delirium	Non-significant
Interventional studies			
[22]	L_{Aeq}	Sleep (PSG)	Non-significant
[23]	L_{Aeq}, L_{AFmax}, Acoustic interruption	Sleep (self-reported)	Non-significant
[24]	Median sound levels	Sleep (RCSQ)	Non-significant
[24]	Median sound levels	Delirium	Significant
[25]	Sound levels	Delirium	Mixed
[25]	Sound levels	Sleep (RCSQ)	Non-significant
[26]	Sound levels	Sleep (RCSQ)	Significant
[27]	Sound levels	Sleep (RCSQ)	Significant

RCSQ = Richard Campbell Sleep Questionnaire; PSG = polysomnography; HR = heart rate; RR = respiratory rate; BP = blood pressure;

2.1 Observational studies

Almberg et al. [9] investigated the impact of acoustic interruptions on sleep quality, reporting a significant decrease in self-reported sleep scores with increasing occurrences of sound events exceeding a 20 dBA difference. These findings are likely linked to sudden, intermittent sounds, particularly medical alarms, which have been identified as dominant noise sources in ICU environments [10]. Interestingly, the same study also found a weak but statistically significant association between higher ambient sound levels and improved sleep scores. This suggests a potential masking effect, in which continuous background noise may reduce the disruptive impact of intermittent sound events.
However, findings across the literature remain inconsistent. Several other cross-sectional studies have reported a negative association between sound levels and sleep quality [11], [12], while others have found no significant relationship [13], [14]. For example, Simons et al. [15] demonstrated that higher background noise levels (L90) were associated with poorer subjective sleep quality, as measured by the Richard Campbell Sleep Questionnaire (RCSQ). The study also used the concept of *restorative periods* [16], which were shown to positively predict sleep quality during nighttime hours [15]. This highlights the importance of context-sensitive acoustic metrics in ICU settings [17], [18].
Beyond sleep, some studies have examined physiological responses to sound exposure. A cross-sectional study [19] found that increases in sound levels were significantly associated with elevated heart rate (HR) and blood pressure (BP) measures, including systolic, diastolic, and mean arterial pressure, although no significant associations were observed for self-reported psychological or physiological outcomes [19]. Similarly, other studies have reported simultaneous increases in heart and respiratory rates (RR) with increasing sound levels [20].
In contrast, evidence linking acoustic conditions to clinical outcomes remains limited. For instance, one study found no significant association between average sound levels and the likelihood of delirium [21]. Overall, observational studies provide some indication of a relationship between the acoustic environment and patient outcomes, particularly regarding sleep and physiological outcomes. However, interpreting the contribution of specific sound sources remains challenging. For example, alarms may have a limited impact on overall sound levels, as their brief duration is not well captured in time-averaged L_{Aeq} values, potentially masking their clinical effect [17].

2.2 Interventional studies

Nevertheless, correlation does not imply causation, and more methodologically rigorous research is needed. In this context, a limited number of studies have employed experimental approaches, such as randomized controlled trials and quasi-experimental designs, to investigate the causal effects of acoustic conditions on patient outcomes.

Boyko and colleagues [22] implemented a "quiet routine" including reduced alarm volumes, dimmed lighting, and limiting non-essential treatments, and assessed sleep using polysomnography (PSG) in mechanically ventilated, non-delirious patients. The intervention had no significant effect on either sound levels or sleep scores, with normal sleep patterns observed in fewer than half of patients.
Similarly, Tronstad et al. [23] evaluated a sound reduction bundle comprising staff education, visual warnings, and alarm reconfiguration. Despite reducing alarm occurrences by more than 80%, overall sound levels and patients' subjective sleep quality did not differ significantly between pre- and post-intervention conditions. Van de Pol et al. [24] applied a nocturnal sound reduction protocol using an interrupted time-series design. While subjective sleep scores remained similar between groups, the post-intervention group required significantly less sleep-inducing medication and showed a reduction in delirium incidence [24].
In a larger randomized controlled trial involving 177 patients, a sleep enhancement protocol was compared with standard care [25]. No significant differences were observed in median total sleep scores or individual sleep dimensions. The protocol was associated with a high posterior probability of reducing delirium, with a lower incidence in the intervention group.
In contrast, some interventions demonstrated significant effects. One study [26] implemented a sleep care guideline, including reducing telephone and medical device volumes, responding to alarms promptly, lowering staff conversation levels, and reorganizing care activities, which reduced sound levels by nearly 7 dB (from 57 to 50) and improved self-reported sleep quality. Similarly, a sleep-promotion protocol for 67 ICU patients [27] reduced nighttime noise and interventions, improving specific sleep dimensions on the RCSQ (depth, latency, awakenings) and overall sleep quality.
Overall, these intervention studies yield mixed results, highlighting the need for better-designed interventions and outcome measures to fully understand the role of ICU acoustic conditions. More controlled settings, such as the Smart and Silent ICU (SASICU) study [28], in which a specific sound source (alarms from medical devices) is removed from the patient's bedside using a pre–post design, could provide clearer insight into the impact of these sound sources and their clinical relevance.

3. Challenges in ICU acoustic studies

From an environmental acoustics perspective, the situation remains puzzling, as shown in Figure 1. Despite efforts to develop more context-sensitive metrics, such as acoustic interruption indices and restorative periods, findings remain mixed. This inconsistency likely stems from the high variability in ICU layouts and room acoustic features, research methodologies, measurement devices, and their placement. This raises a fundamental question: does the acoustic environment truly have no clinically meaningful effect, or does it have an effect that we are not yet measuring in the most relevant outcomes? In other words, are these inconclusive results evidence of absence, or merely an absence of evidence?

Figure 1. Framework representing the pathway from the acoustic environment to clinical outcomes in existing studies

3.1 Conventional acoustic metrics

One reason why current methods cannot yet fully explain the impact of the acoustic environment on hospital users is that the approaches employed are largely borrowed from the environmental noise realm and may not be fully compatible with or relevant to ICU contexts. Characterizations in terms of L_{Aeq}, L_{Cpeaks}, L_{Amax}, L_{Amin}, L_{10}, and L_{90} remain limited when the acoustic environment is highly unpredictable, with both impulsive and tonal characteristics, such as alarms [17], [18]. This is accompanied by a major challenge in acoustic measurements in hospitals, as sound signal recordings often contain verbal communication and therefore do not comply with hospital privacy requirements, regulations, and ethical concerns [29]. As a result, measurements are typically limited to sound pressure levels and, in some cases, to one-third-octave band spectra. However, given that unpredictability is the norm rather than the exception in ICUs, the lack of contextual information makes it difficult to identify sound sources or meaningfully interpret acoustic events based solely on level-based metrics. Hence, newer acoustic metrics that account for user experience [30], [31] should be further developed to enable more meaningful interventions.

3.2 Observed patient outcomes

Studies have shown that the acoustic environment can influence perceived stress [11] and noise annoyance [32]. However, these outcomes are not always the most clinically relevant, as they may act as mediators or moderators of more meaningful endpoints, such as sleep disturbances or delirium, thoroughly explained in Table 1. In clinical research, the primary focus typically lies on more objective or "hard" outcomes, such as sleep quality, delirium incidence, physiological parameters, length of stay, and circadian rhythmicity, as these more directly reflect patient health status and may also have clearer economic implications for the healthcare system. This distinction may partly explain the inconsistencies observed in the literature, as studies focusing on perceptual outcomes and those targeting clinical endpoints do not necessarily capture the same dimensions of the patient experience. Another important consideration is the lack of baseline measurements in healthy participants for comparison with ICU patients. Individuals in the ICU, a highly vulnerable population, often present altered baseline physiological parameters (e.g., HR and RR) due to their medical conditions.

4. Future directions

This paper highlights the complexity of the ICU environment and the challenges of developing a more holistic understanding of its dynamics, particularly when contextual and environmental factors are taken into account. With a focus on acoustic characterization in terms of temporal patterns, sound metrics, and sources, it should be noted that patient characteristics and personal factors may moderate soundscape and perceptual responses, which, in turn, may impact clinically relevant outcomes as outlined in the proposed conceptual framework in Figure 2.

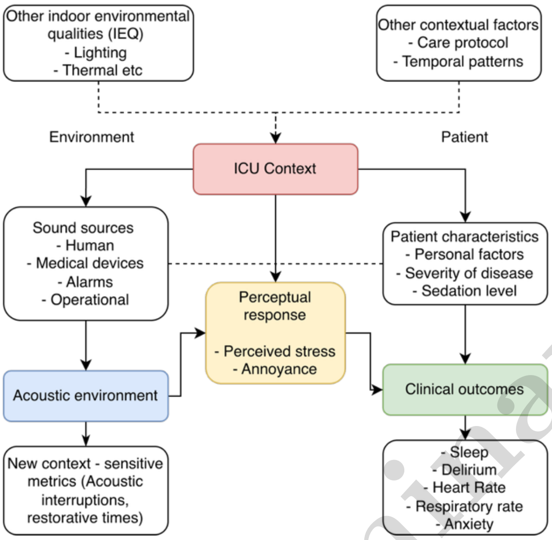

Figure 2. Proposed framework based on the pathway from the acoustic environment to clinical outcomes

4.1 Context-sensitive characterization

The future of hospital and ICU acoustic research lies not just in measuring how loud the environment is, but in understanding how it behaves in relation to the occupant. To address this gap, qualitative approaches, such as observations and interviews with key stakeholders, are essential to better capture the context in which these acoustic conditions occur. These methods can provide further insight into the specific characteristics of individual ICUs and how clinical care is actually delivered, especially since no two units are alike. Therefore, a more context-sensitive characterization of the acoustic environment that integrates mixed methods is needed [33].

4.2 Soundscape interventions

Although noise mitigation strategies are often viewed as straightforward solutions to the "cacophony" in care settings, soundscape studies indicate the importance of enhancing ICU acoustic environments with other sounds, which are also considered soundscape interventions [34]. While the ISO 12913 soundscape standard [35] is now well established in the literature of urban studies, in indoor environments, particularly healthcare settings, there is still no fully validated soundscape model, apart from the one first developed by Mackrill [36]. While this is one of the difficulties in assessment, it is also important to consider that the model must comply with the different *acoustic biotopes*, the patients, and the care provider, who have "contradicting" functions within the same space [37].

4.3 Multimodal approaches

Another unresolved issue is whether the effects of the acoustic environment can meaningfully be identified in isolation. For practical reasons, research often focuses on a single modality to examine its impact on occupant outcomes. Yet human experience is inherently multisensory. Non-acoustic factors, including personal characteristics and other environmental modalities such as lighting or thermal conditions, can influence perception, experience, and well-being in additive, antagonistic, or synergistic ways.
The recent ISO soundscape framework [38] emphasizes the need for a more holistic understanding of environmental experience. This requires considering both the specific context, whether an ICU, emergency department, or outpatient ward, and the specific occupant, whether patient or healthcare provider. The acoustic environment should not be treated as an isolated determinant of outcomes. It should be part of a complex system in which its effects can be moderated by context and personal factors, mediated by perceptual and cognitive processes, and shaped by interactions with other sensory modalities.
In this line, future research should move beyond single-variable approaches and develop models that account for multimodal or cross-modal interactions between environmental factors [39].

5. Conclusions

In conclusion, understanding the relationship between the acoustic environment and user well-being in healthcare settings remains a complex yet important challenge with clinical relevance. The current body of evidence leans toward an absence of evidence, largely driven by the methodological limitations discussed. At the same time, these null findings should not be mistaken for proof of no effect, but rather as an indication of the indirect and context-dependent nature of these relationships. ICU acoustic research may resemble searching for a needle in a haystack, but perhaps the issue is not only the needle itself, but how and where we are looking. With more context-sensitive metrics and clinically meaningful outcomes, there is still potential to better understand and ultimately make use of the role of the acoustic environment in supporting patient care.
While conventional acoustic metrics and patient outcomes have limitations, these can be addressed

through a more comprehensive characterization of ICU acoustic environments and the development of validated soundscape models, which can help further evaluate the effects of soundscape interventions. A holistic approach should also consider multimodal strategies, such as the combined influence of light and sound, given their direct impact on circadian rhythms. Moving forward, future research requires a broader perspective that draws on insights from medicine, psychology, architecture, acoustics, design, and clinical technology. Only through such interdisciplinary collaboration can we capture the complexity of ICU soundscapes, understand their impact on patients and staff, and develop interventions that truly improve occupant experiences and outcomes. Lastly, while many technological solutions may already be feasible, the human factor remains critical in healthcare settings. Successful implementation requires that healthcare professionals adopt and integrate these solutions into their workflows without increasing their workload or stress, while maintaining the primary objective of patient safety.

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