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THE ROLE OF CRITICAL ALARMS IN THE ICU ACOUSTIC ENVIRONMENT: A PILOT STUDY

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ABSTRACT*

While developments in medical device technology improve clinical monitoring by incorporating more sensitive features, they also lead to high ICU noise levels due to the increased number of alarms. This study seeks to understand the effect of critical alarms from various medical devices, such as patient monitors, infusion pumps, and mechanical ventilators, on overall sound pressure levels and existing noise metrics in the Adult ICU of Erasmus Medical Center. The study was conducted for ten days, during which two patients were admitted, and their usual care routines were maintained. A calibrated class II sound level meter was positioned above the patient's head to continuously record acoustical data in one of the single-patient ICU rooms. Acoustic parameters, including L_{Af}, L_{CPeak}, L_{Aeq}, were measured, and alarm logs were retrieved from the alarm management database. Patient monitor alarms were also analyzed by severity, as different alarms have distinct acoustic characteristics. Initial findings indicate that equivalent sound pressure levels exceed recommended thresholds, however, with only a limited contribution of alarms. Future research should focus on a more comprehensive and human-centered acoustic characterization of this critical environment, so that relevant associations between health outcomes and sound environment can be made.

Keywords: *intensive care unit, critical care, alarms, noise, soundscape*, *ICU*

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1. INTRODUCTION

The built environment of healthcare settings should be designed to support, sustain, and enhance the healing process [1]. A paradigm shift has occurred in the Intensive Care Unit (ICU), providing models of care that shift from provider-centric care to patient- and family-centered care [2]. An important strategy for creating a more humanizing ICU environment involves minimizing noise levels as experienced by patients, particularly by focusing on decreasing the number of bedside alarms, without hindering the care workflow [3]. Considering this, the present paper focuses on a pilot study carried out at Erasmus Medical Center, where alarm logs and sound pressure levels were recorded continuously. The main goal of the paper is to understand to what extent alarms contribute to the ICU acoustic environment by relating sound pressure levels to the alarm logging data from both technical and patient-related sound events.

1.1. The ICU soundscape

Considering the four indoor environmental qualities in the ICU (i.e., lighting, thermal comfort, air quality, acoustics), acoustics has gained increasing importance in recent years. This is particularly due to the advancement of medical equipment with more sensitive characteristics, which indirectly lead to a proliferation of audible alarms. This situation was also highlighted in a review conducted 30 years ago, where the authors noted that "*The previously serene milieu is gradually being debased by a sonic assault on the ears and psyche*" [4]. In a more recent study focused on patient experience, hospital noise emerges as the second most significant environmental factor impacting patient comfort and recovery, closely following hygiene concerns that are crucial in preventing infection risks [5].

Hospitals, particularly critical care departments, are complex environments for analyzing the soundscape due to their acoustic *biotopes*, where various sounds, listeners, and sound-related actions engage in a structured manner [6]. In this sonic ecosystem, users experience and respond to sounds differently based on their position, hearing ability, and role in this environment [6]. Being one of the most technically advanced spaces in healthcare, the ICU is often overlooked in terms of noise, in which communication through sound is crucial and urgent [7]. Research conducted [7] in this context do not comply to the WHO guidelines for noise levels during the day (35 dBA) and at night (30 dBA). This raises concerns about the necessity of alternative acoustic metrics that may be more relevant for this specific environment.

When acoustically characterizing critical environments, various methods of categorization exist regarding the types of sound sources. Some studies [8] cluster sounds based on their emitting source, while others characterize them based on their frequency spectrum [9]. Research conducted to identify the most prominent sound sources that contribute to the overall sound pressure levels in the ICU yielded inconclusive results, with some suggesting speech as a potential contributor [10] and some others critical clinical alarms [11]. Moreover, medical systems function separately, each triggering alarms at the patient's bedside. In today's healthcare environment, where patients are connected to multiple devices, this isolated approach remains outdated [12] and contributes to information overload, alarm fatigue, and unnecessary sleep disruptions for patients. Research [13] focuses on the effect of overall L_{Aeq} values and their relationships to patient experiences, sleep or other health outcomes. Only a few studies [14-15] have examined the effect of alarms on overall sound pressure levels, showing that alarms have a small contribution to averaged noise levels. However, authors [7] emphasize that the L_{Aeq} is not well suited to environments in which the sound is peaky or contains pure tone alarms highlighting the need of developing new acoustic metrics that could be linked to patient experiences and outcomes. Regarding the perceived acoustic environment, to date, no study has investigated ICU patients' experiences with the soundscape approach (a perceptual phenomenon described and measured by ISO 12913-2:2018) during their ICU stay due to the challenges it brings to making subjective measures with such a vulnerable population.

1.2. Alarmscapes

We coin the term '*alarmscape*', as a subcategory of the (perceived) acoustic environment created by various alarms emitted by various devices in a healthcare setting, particularly in ICUs. Research indicates that the overwhelming number of alarms in contemporary ICUs can lead to anxiety and stress in patients as well as alarm fatigue and cognitive overload amongst ICU nurses [16]. Authors are now presenting new alarm management strategies along with new metrics, including "alarm floods" which are defined as the occurrence of ten or more alarms within a ten-minute period at a single ICU bed [17]. Those metrics would help in establishing more robust correlations between alarms, noise, patient and nurse experiences.

The present research is part of the Smart and Silent ICU (SASICU) project, conducted at Erasmus Medical Center Rotterdam. The project's objective is to improve patient health and well-being by introducing a smart alarm management system which would reduce the psychological and physical harm caused by alarming events. Phase I involves collecting baseline measurements through continuous sound level data and alarm logs to study their correlation with patients' well-being, psychological and physiological stress levels, sleep quality, and symptoms of depression and anxiety. Following a between-subjects study design, Phase II will evaluate the same outcomes after a non-medical technical intervention designed to suppress alarm sounds at the patient's bedside will be implemented in the ICU. In order to speculate about the role of medical audible alarms on the ICU soundscape and patient experience, the current study focuses on assessing the influence that alarms from various medical devices have on the acoustic metrics that are utilized to characterize the indoor environments of ICUs during a pilot study.

2. METHODOLOGY

The data collection took place between September 16th- 25th 2024 in a single patient ICU room, located in Unit C of the Department of Adult ICU at EMC, which will serve as the setting for both phases of the study. The room was occupied by two patients consecutively. Only acoustic data and alarm logs were gathered (without any identifiable patient information) from the hospital databases. Since no patient data was collected, ethical approval was not necessary.

A Class II sound level meter, Sound Ear 3-300, was installed inside the room, which has a floor area of approx. 22.7 m^2 and a volume of 68.1 m^3 as shown in Figure 1. The room was equipped with a bed, Dräger patient monitor, Dräger mechanical ventilator and B-Braun infusion pumps. The microphone was hung from the static part of the ICU pendant, centrally located above the patient's head, approximately one meter above it, in order not to disrupt the normal routine care. As depicted in Figure 1, the room's materials include a floor covered with linoleum, white-painted walls, and mostly perforated white metal panels for the suspended ceiling. As explained in a previous study [18] the layout of the unit was changed and several changes in architectural layout were made, introducing well insulated acoustic doors. The doors between the room and the corridor were usually kept closed.

Figure 1. ICU single-bed room (*left -floor plan and microphone position; right- image of the room*)

2.1. Acoustical measurements

Before data collection, the SoundEar 3-300, being a Class II sound level meter, was previously calibrated with a Class I Brüel & Kjaer type 2270 Sound Level Meter. Bland-Altman plot and correlation analysis were conducted to assess the agreement between the two devices and identify any specific systematic bias in the data regarding $L_{Aeq(1min)}$ and $L_{CPeak(1min)}$. All differences fall within 95% limits of agreement, with SoundEar consistently showing slightly higher values. Both the measurement pairs show strong correlations with Spearman's ρ values ranging from 0.922 to 0.976, indicating good agreement between the devices.

The continuous acoustic data collected by SoundEar 3-300 included L_{Af}, L_{As}, $L_{Aeq(1s)}$, L_{Cf}, L_{Cs}, $L_{Ceq(1s)}$, and $L_{CPeak(1s)}$. Even though, the SoundEar device was previously calibrated by the manufacturer (+/- 1.4 dB), before each measurement, the microphone was calibrated using a Bruel & Kjaer type 4231 Acoustical Level Calibrator before the pilot study. The room was occupied by the first patient between 17.09.2024 and 19.09.2024 and the second patient occupied the room from 19.09.2024 in the afternoon until 25.09.2024. Data collection was halted when the second patient was still in the room. Regarding the acoustic data, we processed the most used acoustic metrics, L_{Aeq} and L_{Cpeak}, every one minute, 10 minutes, one hour, one shift, and daily. The morning shift begins at 07:00:00 and ends at 14:59:59; the late shift runs from 15:00 to 22:44:59, and the night shift covers the remaining hours.

2.1. Alarm log measurements

The alarm log data was retrospectively retrieved from the ASCOM Unit Analyze database, and additional queries were performed by the IT department to enhance the data analysis. The ICU room was equipped with a patient monitor (Dräger Infinity M540), a mechanical ventilator (Dräger Evita 800), and B-Braun Space1 infusion pumps. The patient monitors are components of the Infinity Acute Care System (IACS) designed for the multi-parameter physiological monitoring of adults, including ECG/heart rate, respiratory rate, oxygen saturation, and invasive pressure [19].

The three devices generate both audible and visual alarms at the patient's bedside, on the nurses' pagers, and at the nurses' station in the unit corridor. Each medical device, while functioning independently, follows its own protocol within the ICU room regarding how it is connected to the ports/plugs in the room. Nonetheless, healthcare providers may occasionally change the port to which a particular medical device is connected, leading to alarm logs that indicate an alarm's occurrence and its timestamp; however, this does not identify which medical device triggered the alarm.

For the current study, the information provided by the alarm log file regarded the device emitting the alarm, its timestamp, and its duration at the nurses' pager, which, if not accepted by the nurse (a very rare situation), is the same as the duration at the patient bedside. The current database provides more detailed information from patient monitors regarding the type (SpO_2, heart rate, respiratory rate etc.) and severity of alarms categorized as Life-Threatening (L-T) or red alarms, serious (SER) or yellow alarms, meaning they are exceeding the range limits set by the healthcare provider, and technical blue (ADV) alarms. However, this information is unavailable for the two other medical devices: the ventilator and the infusion pumps.

Following similar studies [17], descriptive statistical analysis of alarm logs was conducted per shift and per day, alarms per device and severity (only for patient monitors), average temporal distributions of alarms and duration of alarms. The data was analyzed in Python 3.12.7 in Visual Studio Code using *pandas, numpy, glob, os, matplolib and seaborn* libraries. The data was cleaned in Data Wrangler, an extension to Visual Studio. While we acknowledge the importance of analyzing broader time frames to assess and generalize the impact of critical alarms on acoustic metrics, the short duration of these alarms means their contribution is often overlooked when averaged over an extended period, potentially masking their real acoustic impact. In order to understand the role of critical alarms on acoustic metrics, we focused on a single day (24 hours with acoustic data recorded every second, L_{Aeq}, L_{CPeak}, L_{10}, and L_{90} averaged from L_{Af} values) along with the occurrence of alarms per second resulting in almost 86400 rows in the dataset. We employed a multivariate linear regression in SPSS 29.0.2.0 to analyze the contribution of each alarm (considering the emitting devices and severity of patient monitor alarms) on averaged A-weighted sound levels. The duration of alarms is included per each row of that alarm until it stops. Additionally, situations where two or more alarms were present were excluded from further analysis as distinct scenarios.

3. RESULTS

3.1. Acoustical measurements

3.1.1. Characterizing alarms

A preliminary measurement was conducted by which all potential alarms from the three medical devices were simulated and emitted in an empty ICU room of the same department, used only for research and training purposes. The layout of the room was the same, with a bed and linens (to ensure that the sound absorption in the room would not change) and a manikin in order to simulate a quasi-realistic situation. The patient monitor was set at a 5% volume and emitted three alarms: blue (ADV), yellow (SER), and red (L-T). At a background noise level of 38-39 dBA, the sound pressure levels varied relatively for each active alarm, as shown in Table 1. Regarding the patient monitor alarms, each tone of the blue alarm lasts less than 1 second, followed by a 15-second pause between tones. The yellow alarm lasts nearly 2 seconds, with a 6-second pause. The red alarm continues for 4 seconds per tone, with a 4-second pause in between. The infusion pump featured four distinct alarms; however, this information is absent from our alarm log file since we only receive data indicating whether an alarm occurred or not for this device. While set at a default volume, its slightest alarm had a duration of nearly two seconds, with 6-second pauses (Infusion pump -1).

Figure 2. L_{Aeq}, L_{CPeak} of patient monitor alarms

The alarm that indicates that a pump is almost empty (Infusion pump-2) lasts 2 seconds, with a pause of approximately 29 seconds. The alert signaling that the pump is empty, which is the most critical alarm produced by this device, consists of a blend of high and low tones, lasting a total of 5 seconds, with approximately 1 second of pause in the middle. The final alarm that the infusion pump can emit is the reminder alarm, which signals that the pump is empty. This alarm is similar to the first two alarms of the device.

Concerning the ventilator alarms (at 10% volume), the less severe alarm lasts for 4 seconds, followed by a 4-second interval. It is important to note that when the ventilator is connected to the patient and operational, the background noise level without alarms rises to approximately 46 dBA. The second alarm indicating over-respiration from the ventilator, lasts around 2 seconds with a 2-second break. The last alarm from the ventilator takes place during hyperventilation, lasting for 14 seconds, followed by a 2-second pause before the final 2 seconds.

Table 1. Alarm characteristics

	L_{Aeq} (dB)	L_{CPeak} (dB)	Duration (s)
Monitor–blue (ADV)	+8.8	+3.8	~1
Monitor–yellow (SER)	+ 13.1	+3.4	2
Monitor – red (L-T)	+16.2	+3.6	4
Infusion pump - 1	+18.5	+3.4	2
Infusion pump - 2	+21.6	+6.1	2
Infusion pump - 3	+25.4	+12.6	~5
Infusion pump - 4	+25.3	+7.9	2
Ventilator - 1	+9.7	+1.8	4
Ventilator - 2	+7	+1.2	2
Ventilator - 3	+8.1	+3.3	~14

3.1.2. Acoustic environment

The acoustical analysis involved examining the data from the nine days during which the room was occupied, focusing on A-weighted average and C-weighted peak sound pressure levels measured over 1 minute, 1 hour, shifts, and daily intervals, along with statistical metrics calculated from LAF values such as L_{10} and L_{90}. L_{10} indicates the sound level that is exceeded 10% of the time during measurements, while L90 represents the level exceeded 90% of the time, often referred to as background noise levels. The results are first calculated for each day and then averaged for shifts and as an overall. The averaged results are presented in Table 2. As illustrated in both Table 2 and Figure 3, the overall L_{Aeq} level surpasses the recommended values by WHO for both night and daytime levels. Overall, the "background noise level" was 42.1 dBA, and the average A-weighted level was 56.8 dBA. Differences are observed among shifts, with the night shift being the least noisy one (L_{Aeq} = 49.9 dB).

Table 2. Acoustical metrics averaged for the nine days.

	L_{Aeq}	SD	L_{CPeak}	SD	L_{10}	L_{90}
Overall (9 days)	56.6	6.8	74.8	5.6	56.8	42.1
Morning shift (7h 30min)	58.1	7.0	76.6	6.0	59.3	42.4
Late shift (7h 45min)	57.1	6.9	75.2	5.5	58.6	42.7
Night shift (8h 15min)	49.9	4.0	69.6	3.4	48.4	41.8

3.2. Alarm logging results

The whole alarm logging file contained a total of 961 alarms that occurred during the nine-day study period in one patient room. The average number of alarms per day was 106.8. No outlier alarms with a prolonged duration were omitted from the analysis, as they are still considered to be influencing the acoustic environment within the room. The total alarm durations lasted 25709 seconds (approximately 3% of the whole time). Patient-1 had a total of 202 (nearly 25%) alarms over two days, and Patient-2 had 759 alarms over seven days. The Patient-1 who occupied the room during the first two days was not ventilated, as seen in Figure 6 no ventilator alarm occurred. On the fourth and fifth day, we observe the emergence of a new device categorized as "Other" which could potentially be the ventilator (the ventilator port may have been altered during shifts, and the protocol mentioned previously might not have been adhered to) or another specific device, such as the dialysis machine, that may have been employed based on the patient's specific circumstances. The majority (n=708, 73.7%) of alarms consisted of monitor alarms, amongst which 90 (12.7%) of them were blue technical alarms, seven (1%) were red alarms, and 611 (86.3%) were yellow alarms, meaning that at least one of the patient parameters was out of the range set by the healthcare provider. Furthermore, regarding duration, the average length of an alarm was 26.7 seconds (SD=59.7), with a mode of 3 seconds and a median duration of 9 seconds. The mean value is skewed because of an outlier yellow alarm having a duration of 1129s at nearly 07:30 hours in the morning. This could be a situation where the nurse might have been inside the room during care

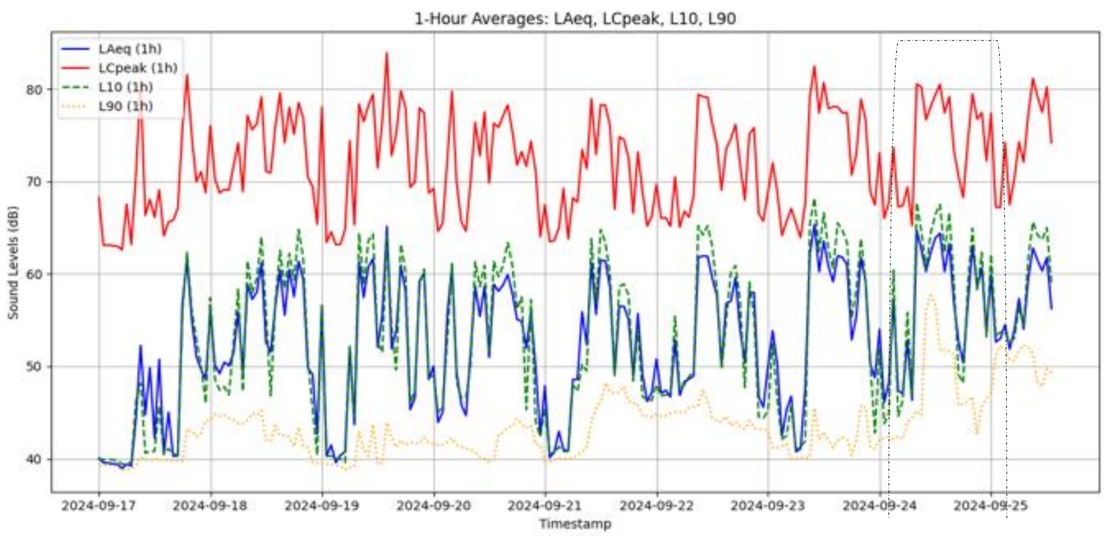

Figure 3. Sound levels (1h) concerning the nine days of the study period

procedures, hence the alarm is not silenced. The duration distribution of number of alarms (with a cutoff at 50s) is shown in Figure 5.

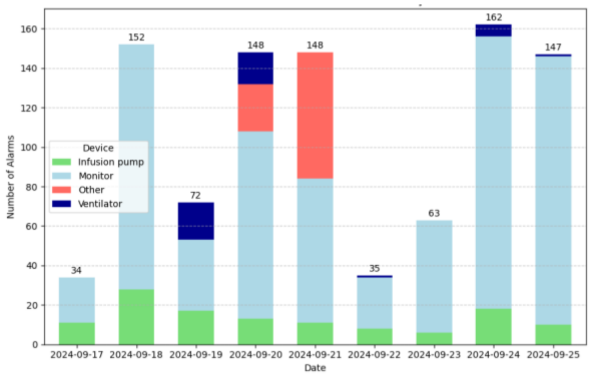

Figure 4. Number of alarms during the measurement period per day and device type.

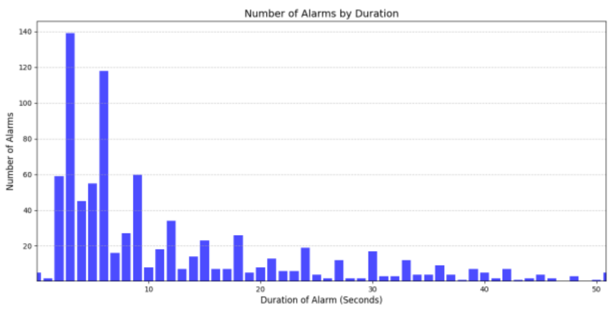

Figure 5. Duration of alarms (cutoff to 50s).

3.3 Role of alarms on sound levels

Figure 6 provides a more detailed analysis of sound level variations over the 24-hour period (20.09.2024) we focused on for this pilot, averaging the metrics into 10-minute intervals. The pattern aligns with the nurses' working shifts, represented by different background colors. The average L_{Aeq} for the entire day is 55.7 dB, while the L_{CPeak} is 74.0 dB. The L_{Aeq} for the late shift is 56.6 dB, the morning shift is 56.4 dB, and the night shift is 53.3 dB. In terms of alarms, 148 alarm events occurred, with 95 of them being emitted by the monitor alarms and 53 from the remaining medical devices. The overlapping between the occurrence of various alarms and the corresponding L_{Aeq} values is plotted in Figure 7 for the morning shift, sometimes showing an alignment with elevated A-weighted sound levels. The multiple regression analysis (95% confidence interval) suggests that when there are no alarms, the L_{Aeq} remains constant at nearly 47.5 dB. The result implies a weak but still significant correlation between alarm occurrences and variations in sound levels (R^2=0.005, $p < 0.001$, *SE*=6.7). This is also visible in Figure 7 displaying many elevated fast rise levels when no alarm occurs, suggesting the potential other sound events (e.g., impact sounds) cause the peaks. The alarm with the biggest impact on sound levels is the red (L-T) monitor alarm ($b=+17.3$; $p<0.001$) with an increase of nearly 16-17 dB also shown in Table 1. The second most impacting alarm is the blue (ADV) alarm with a rise of 8.5 dB ($p < 0.001$) comparable to the one shown in Table 1. For the remaining alarms the regression coefficients were as follows: Monitor yellow (SER) $b=+1.0$ $p<0.001$; Infusion pump $b=+3.6$ $p<0.001$; Ventilator $b=+3.4$, $p<0.001$; and other $b=+1.9$ $p=0.048$. These initial findings might suggest that the opening, filling, and closing of the infusion pump are "noisy" events that accompany the pump alarms, minimizing the alarm to background sound levels difference, hence a smaller coefficient. This could apply to ventilator alarms, which occur when the mechanical ventilator functions and emits significant "artificial breathing" noises. The "Other" alarms did not significantly impact the regression model, likely due to their low occurrence during the investigated period.

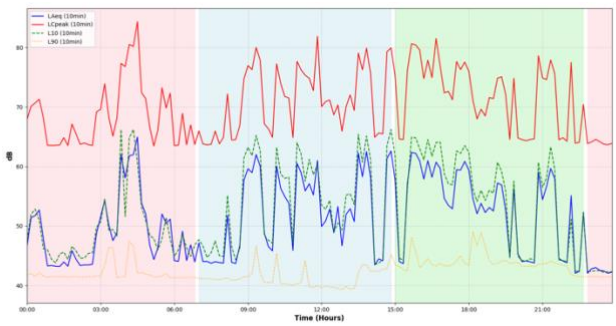

Figure 6. Sound levels per 24h averaged per 10 mins.

4. DISCUSSION AND CONCLUSION

This research investigated the effect of clinical alarms on sound measurements in a single-patient ICU room at Erasmus Medical Center. Consistent with earlier studies [15-16], the role of critical alarms on A-weighted averaged sound levels is limited, yet still significant.
Surprisingly, a previous study [15] revealed that alarms negatively impacted sound levels in ICU corridors. This

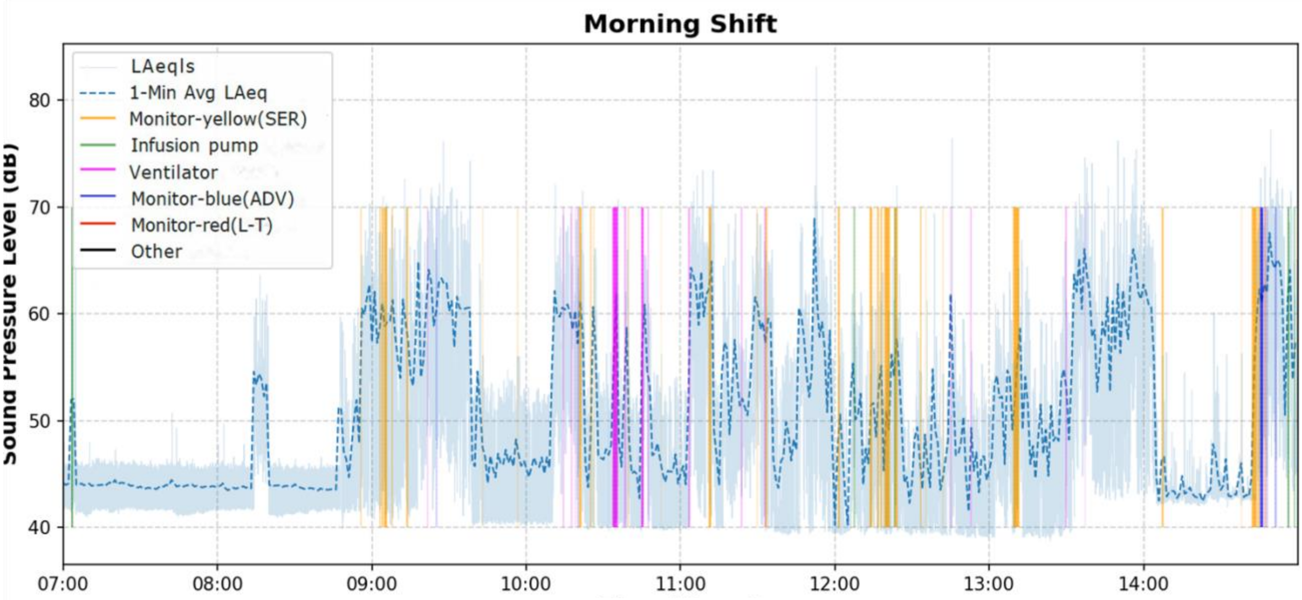

Figure 7. Alarm occurrence overlapped with sound levels during the morning shift.

likely occurred because nurses interrupted their activities to focus on the alerting alarm. As the current study, focused on single-bed and occupied ICU rooms rather than ICU corridors, our findings reveal that alarms significantly increased the average A-weighted noise levels. The patient monitor alarms, particularly the red (L-T) and blue (ADV) ones, were the biggest predictors of this effect. Other studies [9] have focused on evaluating the relative contribution of various sound sources to the acoustic environment from subjective observations. Authors [9] considered alarms as events that accounted for 18% of the overall number of subjectively assessed events. Considering that alarms arise as a main annoying sound source in relation to their duration [20], yet this effect is not easily discernible in L_{Aeq} levels as they are averaged in time, while alarms are very short in duration.

The current study also suggests that other metrics, rather than the conventional ones used for environmental noise assessment, should be considered in addition to soundscape assessments conducted by both the main stakeholders of the space (the patient and the healthcare provider) when characterizing and suggesting soundscape interventions for these critical spaces. Overall, these results are promising to support the patient wellbeing by finding the root cause of the sound-induced disruptions targeted at alarms.

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