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TOWARDS NEW METRICS TO CHARACTERIZE THE ACOUSTIC ENVIRONMENT IN INTENSIVE CARE UNITS

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ABSTRACT

Soundscape is a recent notion, complementary to environmental noise control. It regards the total auditory experience of the acoustic environment based on descriptors ranging from pleasant to annoying, and from eventful to uneventful. This approach is used outdoors, but indoors too, for example in offices and hospitals. In Intensive Care Units (ICUs) many specific dominant sounds are prevalent; not only permanently active medical equipment such as ventilators, dialysis machines, but also alarms, and conversations by staff members. In such cases a special instance of the soundscape tool is required. The current work focuses on the processing and analysis of 24h long acoustic sets of sound data, collected continuously in the Adult ICU at Erasmus Medical Center. In addition to standard noise metrics like equivalent, peak sound levels and statistical indices, this research explores alternative measures such as restorative periods, fast rises, traffic noise index (TNI) and more metrics based on distributional variables. By adapting metrics from the realm of environmental noise to the ICU context, this work aims to provide a more comprehensive characterization of the acoustic environment. These insights will also facilitate relationships with qualitative soundscape descriptors to be collected in later stages of the project.

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1. INTRODUCTION

From the time it became possible to measure sound levels, Noise Rating (NR) Curves and later the A-weighted equivalent sound level have increasingly been used to describe an auditory ambiance, in particular in regulating noise annoyance, for instance in recommendation ISO-R-1996 (1971) [1][1]. The European Noise Directive inherits from this recommendation and serves as the primary instrument for evaluating the population's exposure to noise pollution. The standard [1] also highlights maximum allowable sound levels, leading to the notion that lower sound levels are better, and neglecting the positive traits of ambient sound. Background sound increases speech privacy, can make people aware of their surroundings, church bells can function as "soundmarks" in cities [2]. And some sounds are called pleasant by most people, like birdsong, fountains, rustling leaves by the wind, and babbling brooks.

Later on, the soundscape approach was introduced to acknowledge the perceived qualities of the acoustic environment, initially in urban environments by ISO 12913-1:2014 [3], and nowadays it is being adapted in indoor settings such as shopping malls, train stations, airport halls, atria, and from atria in hospitals to wards and even Intensive

[1]The current version is ISO 1996-2016

Care Units [4-5]. Soundscape tries to catch all elements, from pleasant to annoying, from eventful to uneventful, in an adequate description of the way people experience the sound around them in context [3]. Ideally, the properties of all relevant sound sources contributing to the sound in a specific place could be known: sound levels in (third) octave bands and their variation in time. From these data, the time history of the sound could be determined and classified. The assessment of the appreciation of the soundscape is certainly not easier. Adequate questionnaires and methods [6] to take the peculiarities of the interviewees are necessary.

This paper focuses on the physical aspect of the acoustic environment in ICUs: the measurable sound as recent findings [7] suggest that modern ICUs do not comply to the WHO guidelines regarding suggested noise levels. As part of the Smart and Silent Intensive Care Unit (SASICU) project, we aim to characterise the acoustic environment in order to relate to the sound-induced experiences of patients and staff in an attempt to define the effectiveness of the novel non-medical interventions to provide a more silent environment. Thus, as a first step, we are interested to assess and develop new metrics that can represent the specificities of the acoustic environments of ICUs.

2. METRICS FOR CHARACTERIZING THE ICU SOUNDSCAPE

Most commonly the A-weighted equivalent sound level is used as the metric to review sound levels. It should be determined over a relevant period of time. Often the periods are daytime L_d (7:00 19:00), L_e (evening, 19:00 – 23:00) and L_n (nighttime, 23:00 – 7:00); these values can be combined to the L_{den}, taking the activities in a dwelling as a guideline: working in daytime, relaxing in the evening, and sleeping at night. In Figures 3 and 4 some examples of the fluctuations of the sound level are shown.

A more sophisticated approach is needed in ICUs, as the rhythm of life is quite different from dwellings, offices and parks as well. In terms of noise sources, hospital soundscapes contain transient sounds influenced by alarms, medical systems, automatic doors, moving carts and equipment, as well as personnel. In this context, the L_{Aeq} metric does not always adequately reflect the relative peaks of noise, making it a limited metric for characterizing hospital soundscapes [8]. As alarms are known to cause awakening compared to other sound sources, the difference between the background and peak noise also referred to as sound level changes (SLC), or fast rise, is also introduced to the medical literature by emphasizing the difference of 17.5 dBA to more likely cause arousals from sleep [9]. Previous research [10] has tried to develop new metrics based on traditional percentile level metrics such as occurrence rate [OR(N)], defined as the fraction of time that a level exceeds N decibels. Moreover, another index called "restorative periods" was introduced by authors [10], which involves specific criteria that must be met for a specific period in order to be considered restorative for the patient as explained in the next section.

2.1 Restorative periods

ICU patients can be exposed to different types of sounds during their hospital stay and feel fatigued due to interruptions to their sleep or their rest. During short intervals of time, the sound levels can be relatively low, and little activity is noted. These intervals can be a temporary relief for the patient. However, alarming events are concerning, as a critically ill patient can hear many dozens of alarms per day [11]. These alarms may either cause anxiety as their meaning may not be clear to the patient, or may make falling asleep difficult, interrupting the circadian cycle. Thus, rest is an ICU patient's fundamental right to stabilize and recover quickly. Therefore, we are interested to study how we can measure quiet moments as much as noisy moments in order to foster restoration. Restorative periods are defined as at least 5 minutes periods when the $L_{Aeq(5min)}$ is less than 50 dbA [8]. Ryherd and colleagues [10] proposed also other criteria for restorative periods as such:

- $L_{Aeq} < 50$ dB
- $L_{AF,max} < 55$ dB
- $L_{Cpk} < 75$ dB
- duration at least 5 minutes

The results of each measurement can be shown graphically in a 24 h timeline. In the ongoing research, the duration values will be varied.

2.2 Indication for frequency of alarm occurrence

Alarms are typically common to the ICU acoustic environment causing a term like "alarm fatigue" to be coined; it describes the psycho-physical effect of alarms on healthcare professionals [12]. In a typical ICU ward, studies document an average of several hundred of alarms per patient per day [13]. While it is known that routine patient care activities and speech contribute the most to the ICU acoustic environment [14] alarms tend to happen often and disturb more due to their tone-like character and spectral-temporal quality which are sharp, loud, repetitive, and persistent causing a sense of urgency to respond [15].

Figure 1 illustrates an example of three patient monitoring alarms in a consecutive order and their corresponding impact on L_{AF} and L_{CF} values. This demonstrates how the difference between these two values can infer the occurrence of an incident/alarm, without the need for audio recordings. These incidents will be verified through the logging of alarms in other complementary studies. An incident is considered a potential alarm if it possesses the following property[1]:

$$L_{AF} > L_{CF} - 1.5 \text{ dB}$$

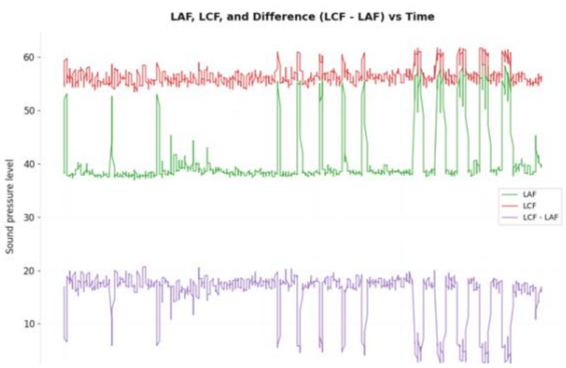

Figure 1. Patient monitor alarms

While the equivalent sound level is sufficient to characterize almost constant or slightly varying or fluctuating sound, the influence of short incidents and greater variations need further attention. In the context of (road) traffic noise—maybe the most ubiquitous source of annoyance—this was recognised half a century ago, and metrics were developed to take the variability into account.

In the data collected from this pilot study, the variation of sound levels is not immediately available but is determined from the statistical distribution (histogram of the relevant sound levels) in the relevant periods. Further processing involves the cumulative distribution and next the statistical exceedance levels like L_{95}, L_{90}, L_{50} etc. Finally, metrics known from traffic noise assessment are calculated, such as the Traffic Noise Index TNI, Noise Pollution Level NPL variants. In the Appendix, the indicators and their formulas, as compiled by Pronello and Camusso [16] are given.

Using these different indicators offers opportunities to compare their value in the special soundscape of these special spaces in hospitals. Especially ICUs deserve a dedicated measurement tool that allows for calculating restorative periods for better patient care instead of appropriating existing tools devised for outdoor purposes with different sound events and different acoustic qualities.

3. MEASUREMENT

As there are ethical limitations in gathering hospital / ICU data (non-acoustical as well as acoustical) due to privacy concerns underlining the necessity of new creativity in processing the available acoustical data. For the current study, a sound monitoring system (SoundEar 3-300) was chosen that records A- and C-weighted sound levels and C-weighted peak levels as displayed in Table 1.

Table 1. Available sound level data

Short	Frequency weighting	Response	Sample each
L_{Aeq}	A-weighted	equivalent	1 s
L_{Ceq}	C-weighted	equivalent	1 s
L_{Cpk}	C-weighted	peak	1 s
L_{AF}	A-weighted	fast	125 ms
L_{AS}	A-weighted	slow	1 s
L_{CF}	C-weighted	fast	125 ms
L_{CS}	C-weighted	slow	1 s

We used the continuous acoustic data of 24 hours, collected in one of the rooms in the Adult ICU of Erasmus MC during the 24th of September 2024. A calibrated class II sound level meter microphone (SoundEar 3-300) was hung on the ICU pendant, centrally to the patient's location and nearly 1m above the patient's head in order not to prevent the normal care flow as shown in Figure 2. The device was connected to the unobtrusively placed electronic device to process and record the data. The data containing the parameters shown in Table 1 was retrieved retrospectively via a USB-memory stick in a CSV-format and was processed using algorithms coded in Python 3.11. No listenable audio was recorded.

[1]The value of 1.5 dB was chosen from a test run on the discriminatory quality of this criterion. May be adapted later.

The L_{Aeq}-values were used as such, determined over different time periods, like 10, 15 minutes, 1 hour, about 8 hours (one work shift). The L_{Cpk}-values indicated the occurrence of noisy incidents; together with L_{Aeq}-values they were used to determine restorative periods. The only available indication of frequency content of the measured sound was given by the difference between A- and C-weighted sound levels with equal responses. Almost equal values indicate a relatively high contribution of frequencies in the range of some kiloHertz.

Figure 2. SoundEar device installed in the ICU.

4. RESULTS

This section presents preliminary results from the pilot sound level measurements within an ICU room occupied by a single patient. These were used in the ongoing process of developing custom-written scripts in Python. Figure 3 illustrates the fluctuating sound levels throughout the day across the three shifts. The morning shift spans from 7:00 to 15:00, the late shift from 15:00 to 22:45, and the night shift covers the remaining hours. Figure 4 presents the same sound levels averaged over 10-minute periods. Although the data is less detailed, it provides a clearer visualization of how the changes align with the shifts, resulting in the morning shift with the highest sound levels, exceeding 57 dBA. Figure 5 illustrates the statistical distributions (L_{10} and L_{90}) of the sound levels determined using the Fast weighted data and TNI, as calculated by Eq.[1] in the Appendix.

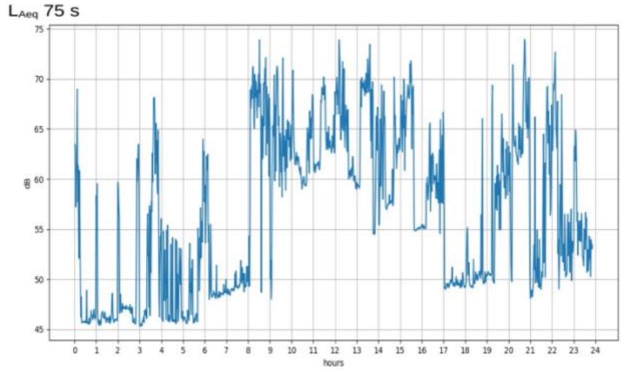

Figure 3. The equivalent sound levels per 75 seconds, vary greatly and irregularly.

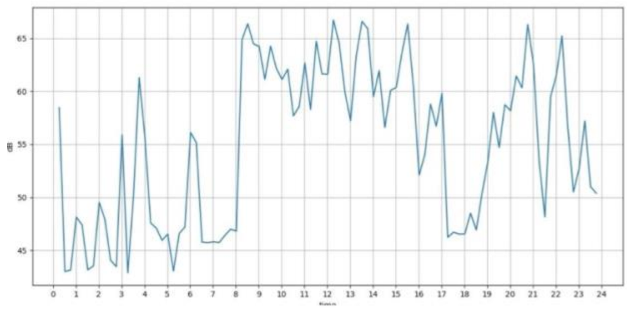

Figure 4. The equivalent sound levels per 10 minutes.

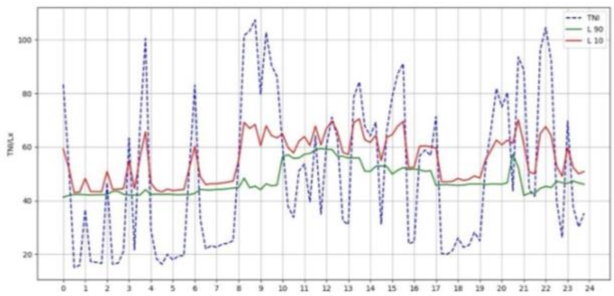

Figure 5. TNI, L_{10} and L_{90} values.

Furthermore, dedicated scripts were developed to analyze the restorative periods based on the criteria developed by Ryherd et al. [10]. The pilot data was used to generate the results shown in Figures 6, 7, and 8 for a minimum of 5, 10, and 15 minutes, respectively. The figures are used only to present that our script succeeds in identifying restorative periods.

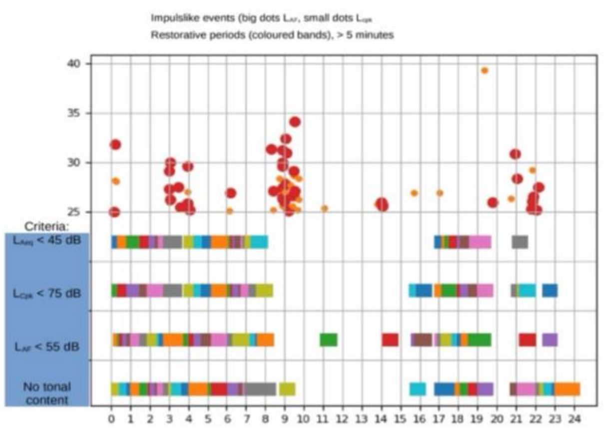

Figure 6. Restorative periods (minimum 5 mins) for the criteria given by Ryherd et al.[10] and tonal content (see 1.1.2) are shown in the coloured bands

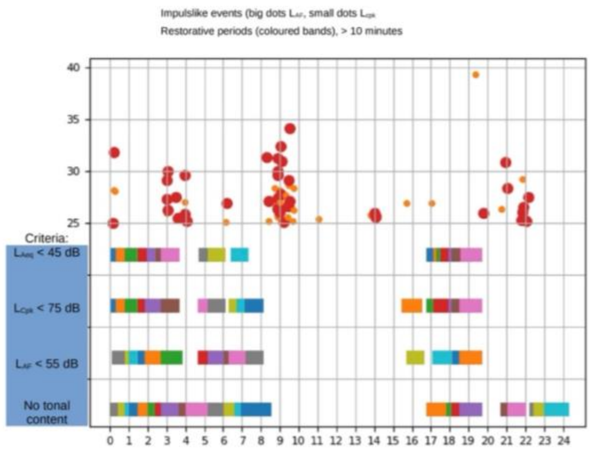

Figure 7. Restorative periods (minimum 10 mins.)

The colors in the figures are arbitrary; however, a change in color indicates a brief interruption of the restorative period. Figure 7 aligns well with the high peaks in Figure 4, which shows average sound levels over the same time scale. This might imply that considering periods of 10 minutes might be a more relevant timescale for restorative periods, aligning with the recovery patterns from auditory fatigue that were explored earlier [17]. Moreover, in the top part of the figures, events of fast rise of sound level are indicated by big and small dots, inferring (potential) incidents. The rise is given for the A-weighted fast values in big dots, and C-weighted peak values in small ones.

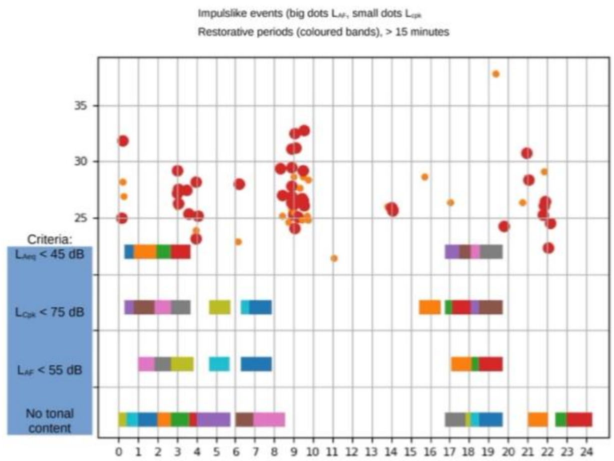

Figure 8. Restorative periods (minimum 15 mins.)

5. CONCLUSION AND DISCUSSION

Our overall aim is to provide acoustic metrics that are ecologically relevant to the ICU context as ICUs are one of the most chaotic environments amongst the socio-technological workplaces. With this pilot we explored whether we are able to determine moments of rest facilitated by lack of sound events and aimed to develop an algorithmic method suited for the ICU soundscapes with acoustic data collected during a typical ICU day.

This pilot study analyzed 24h of continuous acoustic data (A and C-weighted sound levels) collected from an ICU room at Erasmus Medical Center. It explored various metrics from existing literature on environmental noise to develop a data processing method that could further be correlated with the real soundscape experienced by ICU patients and nurses. Initial results indicate that it is possible to determine the restorative periods. This finding brings us one step further in determining the extent to which ICU sounds and especially alarms harms patient rest and possibly circadian cycles.

This study addressed information concerning the current baseline situation the ICU. After the initial measurements, an intervention will be effectuated, in reducing the number of audible alarms. After completion of the intervention, including a period of adaptation by the staff, a second series of measurements, similar to the first one, is intended, that will give insight into the measure of improvement of the intervention. Comparing the values of each indicator, before and after the intervention is sufficient to assess the effect on the soundscape of the ICUs.

As a next step we will use our script to calculate the frequency of occurrence for restorative periods in data collected during the clinical trials. Then we will be able to observe how many sonic interruptions there are and how much time do patients get to recover from sonic interruptions. Results of such analysis will also inform the clinical workflows encouraging healthcare providers and especially nurses to recognize the power of interruption caused by sound events and acknowledge the need for rest periods free of sound.

Further on, to improve the ICU soundscapes, we will investigate other environmental noise metrics like NPL1 and NPL2 (See Appendix) and adapt them to the current indoor environment of the ICU.

A theoretical possibility exists, that the reduction of medico-mechanical sounds turns out to be so effective, that some patients would experience loneliness and feeling disconnected [4]. If relevant and possible, this secondary effect might be taken into consideration.

6. ACKNOWLEDGMENTS

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APPENDIX

These indicators from the field of traffic noise will be used, where all levels are A-weighted, and determined over the relevant periods:

Traffic Noise Index

$$TNI = 4\,(L_{10} - L_{90}) + L_{90} - 30 \qquad [1]$$

Noise Pollution Level 1

$$NPL1 = L_{eq} + (L_{10} - L_{90}) \qquad [2]$$

Noise Pollution Level 2

$$NPL2 = L_{eq} + (L_{10} - L_{90}) + (L_{10} - L_{90})^2 / 60 \qquad [3]$$