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Citation for published version (APA):

Park, M. H., Kohlrausch, A. G., Bruijn, de, W. P. J., Jager, de, P. C., & Simons, K. (2013). Source-specific analysis of the noise in an intensive care unit. In *Proceedings of the 42nd International Congress and Exposition on Noise Control Engineering, September 15-18, 2013* (pp. 1-9). Internoise.

Document status and date:

Published: 01/01/2013

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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15.-18. SEPTEMBER 2013

NOISE CONTROL FOR QUALITY OF LIFE

Source-specific analysis of the noise in an intensive care unit

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ABSTRACT

High noise levels in hospitals are often linked to various negative effects on patient outcome and work performance of clinical staff. Despite growing research attention on the adverse acoustic conditions in healthcare environments, few studies offer on-site surveys collected for a relatively long period with a clear description of the measurement protocol, and furthermore, the sources of noise in hospitals are not well documented in the literature. In the current study, the soundscape of an ICU (intensive care unit) room was analysed based on a ~3-day calibrated audio recording, from which acoustic parameters were obtained off-line. In addition, a selected 24-hour recording was annotated, which enabled a source-specific analysis, excluding the patient-generated/-involved contributions. The results showed that the acoustic energy of the noise in this ICU room was attributed to speech and other activities by staff (57%), alarms (30%) and the operational noise of medical devices (13%). In addition, the analysis of the number of loudness peaks showed similar but more uneven proportions: staff (94%), alarm (5%) and device noise (1%). The current study suggests that, to a considerable extent, the noise in ICUs may be attributed to potentially modifiable factors, *e.g.*, staff's speech and activities.

Keywords: Noise, Noise source, Intensive Care Unit

1. INTRODUCTION

In contrast to a common belief, studies show that patients admitted in hospitals, especially in intensive care departments, are exposed to a surprisingly high level of noise, well above the guideline value recommended for healthcare environment, for example, by the World Health Organization [1]. The noise levels in intensive care units (ICU) were found not only to be excessively high, but also to vary only slightly between day and night, potentially affecting the quality of patients' sleep, which is often referred to as one of the possible causes of ICU acquired delirium [2].

Although the noise issues in hospitals have recently attracted considerable research attention, only a few studies present the results of acoustic survey with a well-documented measurement protocol.

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Furthermore, even fewer studies attempted to investigate the sources of the noise in the ICU. MacKenzie et al. [3] carried out a quantitative analysis of the ICU noise sources, where a team of observers took turn for 24 hours in registering two acoustic parameters every minute while making note of the source of noise corresponding to $L_{Amax,1min}$ (maximum A-weighted sound pressure level in one minute). As the authors also reported, the presence of a human observer could potentially affect (reduce) the noise level by influencing the behaviors of hospital staff, while the low time resolution of the collected data (every 1 minute) may make it difficult to reveal the exact contribution of each noise source to the overall noise level.

In the current study, a calibrated audio recording was made in an ICU for approximately 3 consecutive days, and a selected 24-hour recording was manually annotated using 28 source labels, which allowed for a detailed analysis of the sources of ICU noise and a source-specific analysis of the acoustic parameters.

A description of measurement protocol, data post-processing and audio annotation will be given in section 2, followed by section 3 where the results of the analyses will be discussed. Finally, a summary is given in section 4.

2. METHODS

2.1 Sound recording at ICU

The sound recording was made in an ICU patient room at Jeroen Bosch Hospital (JBZ) in 's-Hertogenbosch, the Netherlands in January 2011. The ICU had a typical racetrack layout with 12 single patient rooms located around an open central nursing station. In one of the typical rooms, a measurement microphone (B&K 4192 with B&K 2690 preamplifier) was placed on the railing system attached to the room ceiling, approximately 1.5 m above the patient bed (head side). A MOTU UltraLite-mk3 Hybrid soundcard was used to interface the microphone (pre-amplifier) and a laptop, where Cockos Reaper Digital Audio Workstation was used on the laptop to record the microphone signal at a sample rate of 44.1 kHz. With the selected preamplifier gain setting, the noise floor of the recording devices measured in an anechoic chamber was 30 dBA.

Whereas a measurement using a sound level meter may produce and store only preselected acoustic parameters, recording raw audio data allowed for extracting any desired parameter by post-processing, and was also essential for the annotation. To prevent privacy violation, several measures were taken, and informed consent was obtained from patients, family members and staff members, who may be identified in the recording.

In total, a continuous recording was made for ~67 hours (~3 days). During the recording period, the room was occupied by two patients, both admitted for respiratory insufficiency due to heart failure, and the room was empty for ~11 hours between the two patients. According to the ICU staff, 'typical' patient care activities were carried out in the ICU during the recording period without exceptionally urgent situations. The two patients were mechanically ventilated (both invasive and non-invasive) during the recording period.

2.2 Extraction of acoustic parameters

As discussed in section 2.1, any desired acoustic parameter can be extracted from a calibrated audio recording by an appropriate post-processing. Two parameters are mainly discussed in this report: A-weighted energy-equivalent sound pressure level (L_{Aeq}) and perceived loudness. L_{Aeq} can typically be obtained for a given time interval by first applying the A-weighting filter to an audio signal, taking the root-mean-square (rms), and then converting the result to a logarithmic scale with reference to the rms value of a calibration signal [4].

The perceived loudness, represented in the unit of sone [5], was calculated in this study by using the model proposed by Chalupper and Fastl [6] and implemented in PsySound3 [7]. Given the instantaneous loudness predicted by the model, a first-order low-pass filter was applied to the output with time constants proposed in Moore et al. [8] to obtain a long-term loudness, which may be a better representation than the instantaneous or short-term loudness in the context of noise disturbance to humans. The peaks of the long-term loudness curve were obtained, where a peak was defined to be a local maximum which is greater than 5 sone, and is more than twice greater (twice louder) than the nearby local minima.

2.3 Annotation of audio recording

From the approximately 3-day recording, a 24-hour interval was selected for the audio annotation, which was in fact the first 24 hours of the first patient’s ICU stay. Six research assistants manually annotated the audio using Praat [9], where time intervals containing audible events were labeled as precisely as possible. Once the annotation was complete, one of the six assistants reviewed the annotated files (TextGrid), checking the consistency of the annotation.

Table 1 lists the categories of sound events used for the annotation. As indicated in the table, the audio was annotated in detail first using 28 labels (subcategories), which were later clustered into 6 categories for the convenience of presentation. Since the recording at a certain moment may contain more than one sound event (*e.g.*, speech with a ventilator noise as a background noise), the research assistants were instructed to annotate all overlapping events wherever audible. Among the categories listed in Table 1, it is noteworthy that Patient (v) does not only include the patient’s own speech and non-verbal sounds, but also any speech activity where patients were involved (*e.g.* nurse(s) speaking to the patient). In this way, the sources of noise which may potentially disturb the patients can be more accurately identified (assuming that the noise generated by the patients themselves and the patient-involved conversation is not disturbing).

For a conversation (categorised either as Patient (v) or Staff (v)), spoken words or sentences were separately annotated when they were apart from each other with a significant interval ($> \sim 0.5$ second) regardless of the context of the conversation. Similarly, a continuous alarm consisting of a train of pulses with a short interval was annotated as a single sound event, but non-repetitive alarm sounds were annotated separately.

Table 1 – List of source categories considered for the annotation.

No.	Category of sound events	Abbreviation	Number of subcategories	Remarks
1	Patient (verbal/non-verbal)	Patient (v)	2	Verbal sound indicates speech; Non-verbal sound includes laughing, coughing, breathing etc.
2	Staff (verbal/non-verbal)	Staff (v)	4	
3	Alarms	Alarms	2	Remote/nearby alarms
4	Medical devices	M. Devices	4	Device operational noise
5	Staff (activities)	Staff (a)	15	Noise generated by staff activities, <i>e.g.</i> footsteps, object-dropping, etc.
6	Unidentified	Unidentified	1	

3. RESULTS

3.1 Overview of the entire recording period

For an overview of the 3-day recording period, Figure 1 shows the A-weighted energy-equivalent sound pressure level obtained in 1-minute time frames (4024 in total). From this figure, some first observations can be made for the acoustic condition in the ICU at JBZ.

- Patient-occupied/-unoccupied times are clearly distinguished (see also Ryherd et al. [10]). Since the patient room is typically kept open, this implies that the main noise sources which contribute to the high noise level may be localised in the patient room, while sources outside the room have minimal influence.
- The noise level during the occupied day is consistently high. However, the night time sound pressure level (SPL) seems to vary from day to day. (This daily change of the night-time SPL

- $(L_{Aeq,1min})$ was confirmed to be significant with $p < 0.05$ for the period of the first patient's stay).
- Regardless of day/night times, the sound level seems to be high for the first few hours after the admission of a new patient, possibly due to the initial checkups and treatments and thus frequent staff visits.

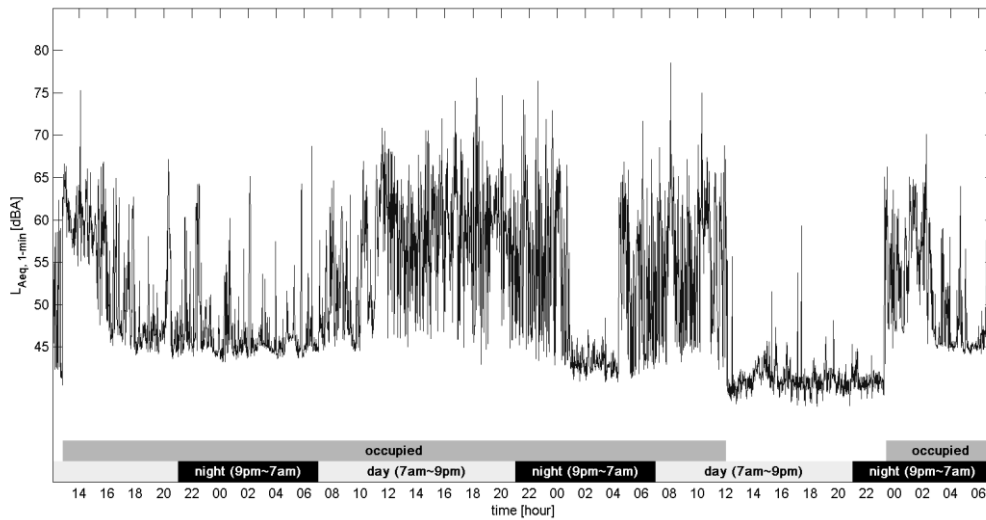


Figure 1 - A-weighted energy equivalent sound pressure level ($L_{Aeq,1min}$) is shown for the entire duration of the sound recording. Above the horizontal axis, day/night times (arbitrarily defined) and occupied/unoccupied times are indicated.

Given the $L_{Aeq,1min}$ values shown in Figure 1, histograms are plotted in Figure 2 for the occupied day/night and the unoccupied day to depict the distribution of the sound pressure levels. The peak of the histogram is positioned at around 42 dBA for the unoccupied day, while the peak for the occupied night is shifted to 45 dBA with a longer right tail. The histogram of the occupied-day sound level is perhaps more interesting, as two distinctive peaks are clearly observed. The one found at approximately 47 dBA is close to the peak observed for the occupied night time, which may reflect the quiet periods without particularly prominent noise sources. On the other hand, the second peak of the occupied-day histogram positioned at around 62 dBA may represent the noise level associated with speech and other activities.

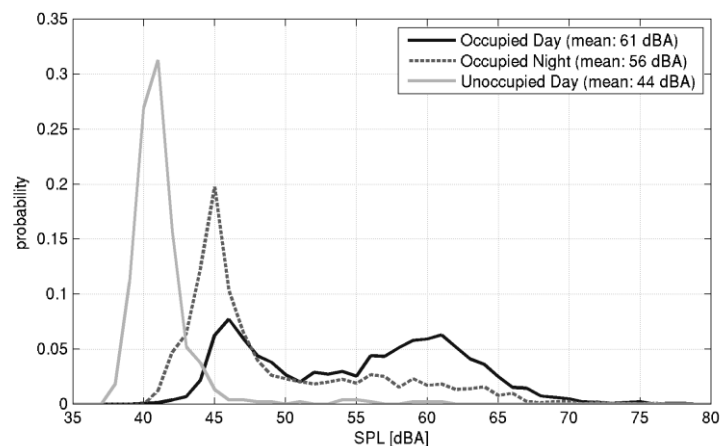


Figure 2 - Histograms of $L_{Aeq,1min}$ values for three distinguished periods: occupied day, occupied night and unoccupied day (unoccupied night is not shown for the lack of data). Histograms were obtained and normalised per period, and therefore, the absolute value of the probability may not be comparable between periods. The mean values indicated in the legend are the L_{Aeq} of the corresponding periods.

The average sound pressure level (L_{Aeq}) of JBZ (see the legend of Figure 2) is comparable to those reported in the literature. In Ryherd et al. [10], the L_{Aeq} of 7 surveyed ICUs ranges from 42 to 52 dBA when unoccupied, and from 54 to 64 dBA for the occupied period. Compared to these 7 intensive care units, the ambient noise level (when unoccupied) of JBZ is among the lowest, while the occupied sound level seems to be on par to the average, although none of the surveyed hospitals including JBZ meets the guideline proposed by the World Health Organization for the patient rooms ($L_{Aeq} < 35$ dBA) [1].

3.2 Source-specific analysis for the first 24 hours

Figure 3 provides an overview of the number and total/average duration of the sound events identified during the 24-hour period. Panel (a) shows the occurrence of each category of noise source, obtained simply by counting and averaging the number of annotated segments by the total time (24 hours or 1440 minutes). In addition, the time intervals associated with each sound event were accumulated and presented in panel (b). These two figures support the observations of previous studies that patients may be exposed to an excessive number of sound events for a significant proportion of their ICU stay day by day [3].

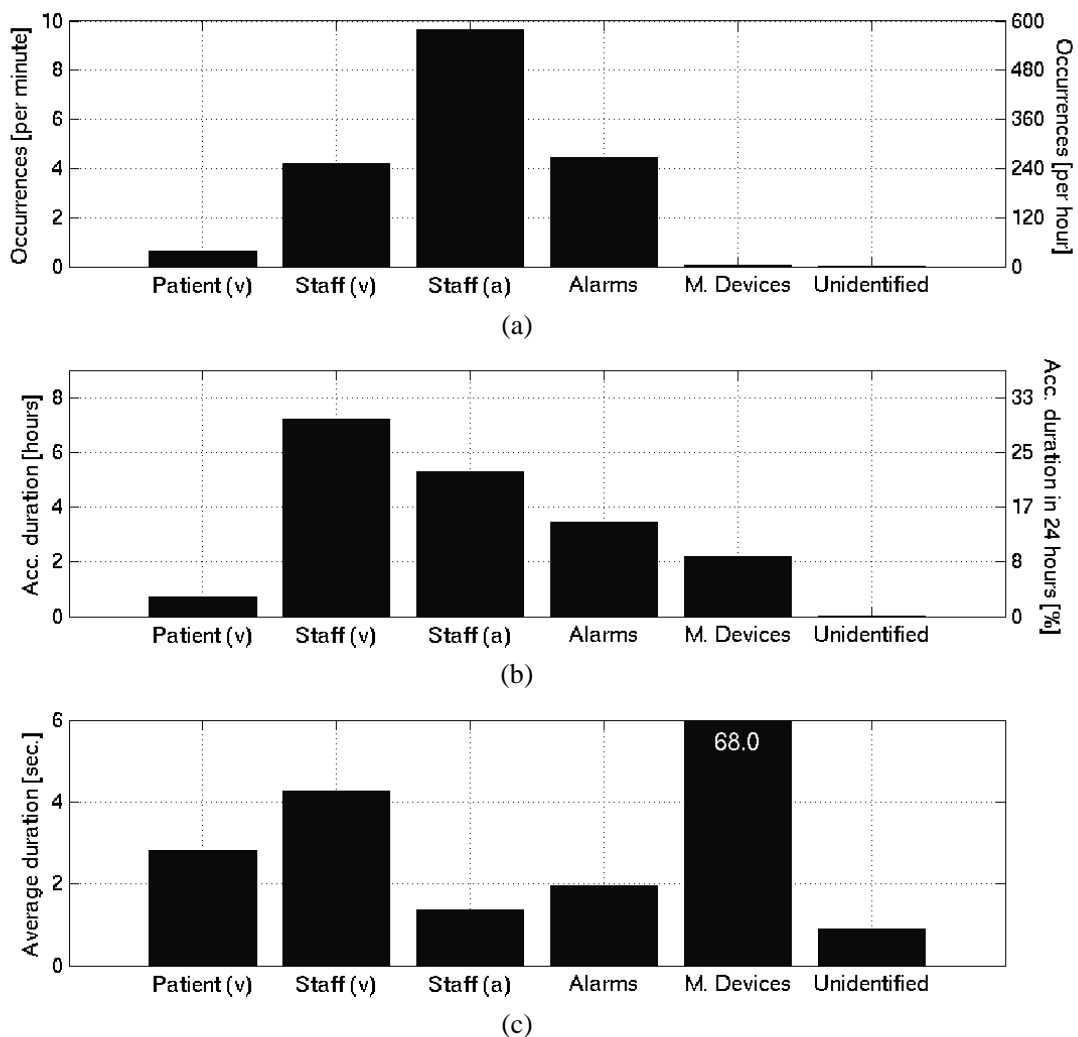


Figure 3 – (a) Occurrences of sound events averaged over 24 hours (1440 minutes). (b) Accumulated duration of sound events. (c) Average duration of sound events.

Considering that the research assistants annotated only clearly audible sound events, there may be up to 18 distinctive sound events per each minute (excluding Patient (v); see Figure 3(a)), which could potentially disturb the patients. Studying the occurrences of individual categories, staff members of the ICU spoke every ~15 seconds on average during the annotated 24 hours, carrying out

‘audible’ activities every ~6 seconds, while devices generated alarm sounds every ~15 seconds.

It is more striking to find that this particular patient was exposed to noise events for surprisingly long periods (see Figure 3(b)). For example, staff members carried out activities in the patient room, which made audible and perhaps very transient noises for an accumulated time period longer than 5 hours in a day. In addition, staff members spoke about topics that do not require patient’s involvement, which produced audible sound events for a total duration of longer than 7 hours (Staff (v)). A majority of staff conversations were related to patient care (based on the results of the sub-category annotation, which is not shown in this report), but some could have taken place away from the patient room since the patient was not directly involved.

The accumulated duration of M. Devices is mainly attributed to the mechanical ventilator, which operated continuously for ~ 2 hours in the beginning of the patient’s ICU stay. The contribution of this single event is also clear in Figure 3(c), where the average duration of M. Devices is exceptionally longer than those of other categories. It is also interesting to note that the average duration of Staff (v) is longer than that of Patient (v), which may be related to the fact that a majority of the patient’s own verbal/non-verbal sounds were relatively short: calling or responding to medical staff, indicating pains, etc. The average duration indicated in Figure 3(c) for alarm sounds may be an overestimation, since repetitive alarms (a train of pulses with a short regular interval) were annotated as a single event (see section 2.3).

The annotation was carried out in perfect synchrony with the audio data, and therefore the extracted acoustic parameters could also be analysed per identified source. For example, $L_{Aeq,24h}$ of a specific noise source may be obtained by adding and averaging the acoustic energy attributed to that source. Since more than one source label could be placed at a particular moment in the recording (see section 2.3), however, it is not possible to completely separate the contribution of each source. Therefore, the average contribution of each noise source was first estimated by analyzing the audio segments labeled exclusively with a single source, and the result was extrapolated to the time intervals with overlapping source labels.

For the extrapolation, it was assumed that the presence of one noise source does not influence the occurrence or the magnitude of other noise sources (for example, staff members do not necessarily speak louder when there is a background noise). This assumption may be challenged in many ways (*e.g.* Lombard effect [11]: speakers tend to raise their voices when there is a competing background noise). However, the assumption may still be worth considering, when it was found in this study that there were not so many competing noise sources in the ICU as equally loud, persistent and frequent as speech (see Figure 3).

Equations (1) and (2) illustrate how the extrapolation was carried out, for example, for the source-specific acoustic energy. $E_{i,excl}$ and $e_{i,excl}$ indicate, respectively, the total and average acoustic energy calculated for the audio segments with an exclusive source label i over an accumulated time interval $T_{i,excl}$, where $E_{i,incl}$ represents the extrapolated total acoustic energy attributed to a source i over the total accumulated, ‘inclusive’ time interval $T_{i,incl}$.

$$e_{i,excl} = \frac{E_{i,excl}}{T_{i,excl}} \quad (1)$$

$$E_{i,incl} \approx e_{i,excl} \times T_{i,incl} \quad (2)$$

Similarly, the number of loudness peaks attributed to each noise source was also obtained (by substituting N and n for E and e in the equations, where N and n indicate the total and average number of peaks, respectively). It is noteworthy that the extrapolation was performed individually for the 28 subcategories of noise source, and later clustered for the 6 main categories (see Table 1).

The validity of the extrapolation was examined by comparing the total acoustic energy and the number of loudness peaks estimated from the sum of the source-specific contributions to those obtained directly from all annotated intervals. For the total acoustic energy, the extrapolated sum was 88 % of the actual value, which is only 0.6 dB different on a logarithmic scale. For the number of loudness peaks, on the other hand, the extrapolation overestimated the actual number by ~10%, which may be attributed to the effect of sound masking.

Figure 4(a) shows the estimated contribution of each category of noise source to the overall sum of acoustic energy excluding Patient (v). Whereas 43 % of the energy is explained by the alarm and

operational noise from medical devices, the remaining 57 % is attributed to the staff members. Since the percentage values noted on this pie chart were calculated using the energy sum in linear scale, the corresponding $L_{Aeq,24h}$ in logarithmic scale are not as significantly different from each other, which is clearly illustrated in Figure 5. Furthermore, $L_{Aeq,24h,non-patient}$ was found to be 55 dBA compared to the overall $L_{Aeq,24h}$ of 57 dBA for the annotated 24 hours, where $L_{Aeq,24h,non-patient}$ was obtained by excluding the contribution of Patient (v) from the total energy, expected to reflect better the average sound pressure level of the ‘external’ disturbances to the patients.

The proportion between the categories of noise source is more uneven when the numbers of associated loudness peaks are considered. As illustrated in Figure 4(b), the alarm and operational noise from medical devices are responsible only for 6 % of the total number of loudness peaks, while up to 94 % was attributed to the staff speech and other activities. Considering that the sound events created by the staff activities are highly transient and that the sound of speech constantly changes in amplitude, the extremely disproportionate contribution shown in Figure 4(b) may not be so surprising, which might however contradict to a common belief that alarm sounds in ICU are the most obtrusive noise.

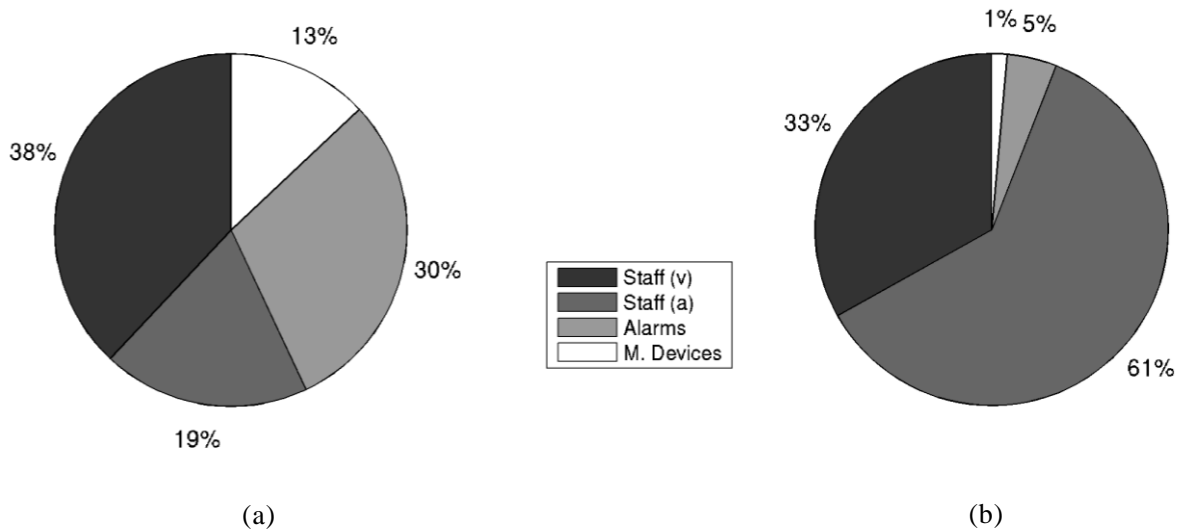


Figure 4 – (a) Contribution of noise sources to the overall sum of acoustic energy. (b) Proportion of the number of loudness peaks (above 5 sone) attributed to each category of noise source. Patient (v) was excluded in both pie charts.

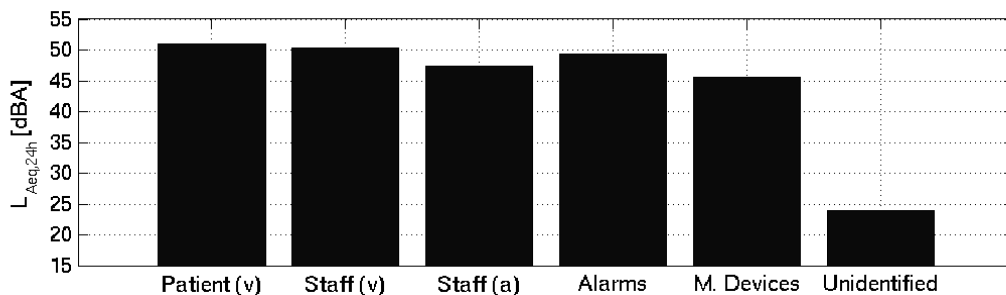


Figure 5 – $L_{Aeq,24h}$ for each category of noise source.

The two pie charts shown in Figure 4 appear to suggest that patients in the ICU surveyed in this study may be disturbed mostly by the noise generated by the staff members, which is however misleading. The figures may provide a good overview of the contribution of each category of noise source, but only in two aspects (total energy sum and number of peaks) among many others that are also relevant to the perceived disturbance of noise. For example, $L_{Aeq,24h}$ shown in Figure 5 illustrates that the difference between the source contributions observed in Figure 4(a) may not directly translate to a perceived level difference for which a logarithmic scale gives a better estimate. As a matter of fact, if L_{Aeq} is calculated only for the accumulated duration (see Figure 3(b)), instead

of the full 24 hours, the average sound pressure level (acoustic power in this case) of the alarm sound is found to be 58 dBA, higher than that of Staff (v) (56 dBA) or Staff (a) (54 dBA), apparently indicating that the alarm sounds are among the dominant sources of noise in the ICU in terms of the source strength in addition to its tonality which is highly related to the subjective rating of disturbance [12].

Nevertheless, the results of the source-specific analysis discussed in this report clearly disagree with a common belief that the alarm sounds are the most dominant source of ICU noise. The current analysis based on a detailed annotation of an ICU sound recording suggests that the staff-generated noises may be at least as equally dominant as alarms, if not more, given the high contribution in acoustic energy and loudness peaks and the long accumulated event duration.

As mentioned earlier, it is obvious that a majority of staff-generated noise may be essential for the operation of the intensive care unit, and it is needless to state that the patient health and safety should be the priority of any healthcare facility. However, when patients' well-being is considered to be increasingly important, for which possible ways to eliminate some of the distressing noise sources are sought for in ICUs, the current study suggests that it may be sensible to attempt to influence the behavior or the work routine of the staff members [13, 14], as most of the noise sources are either directly associated with them (Staff (v) and Staff (a)) or at least partly under their control (Alarms).

4. SUMMARY

In this study, a sound recording was made in an intensive care unit for approximately 3 days, from which the A-weighted energy-equivalent sound pressure level and the perceived loudness peaks were obtained and analysed. Furthermore, the first 24 hours of the recording were manually annotated using 28 labels for noise sources commonly found in ICUs, which allowed for an analysis of sound event occurrences and accumulated/average durations, and also for a source-specific analysis of the two acoustic parameters. In general, the results support the observations of previous studies that ICU patients are exposed to a high level of noise, also suggesting that disturbing sound events may occur very frequently for a significant portion of time. It was also found that, in the ICU surveyed in this study, the staff-generated noise contributed most to the total acoustic energy and the number of perceived loudness peaks, which implies that the noise issues in ICUs can be addressed to a certain extent by influencing the behavior or the work routine of the staff members.

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