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A preliminary analysis of the sources of noise in an open-plan neonatal intensive care unit

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ABSTRACT
The acoustic environment in neonatal intensive care units (NICUs) is known to be hardly conducive to the treatment and development of preterm infants. Many studies report the results of acoustic surveys in NICUs, where some studies also investigated the sources of noise. These studies employed a human observer to annotate the noise sources on site, which unfortunately makes the results vulnerable to the Hawthorn effect. Furthermore, most noise source surveys were carried out for a few hours at particular times of day, thus revealing only part of the complete situation. To overcome the shortcomings of the previous studies, the noise sources in an open-plan NICU were investigated in the current study by an offline annotation of 24-hour continuous audio recordings made inside and above an incubator. The results showed that a total of 17 noise sources could be identified in 30159 intervals that occupied 22.1/24 hours, where up to 7 concurrent sound events were present in each interval. The events produced by staff and non-patients' activities (excluding speech) were counted most frequently, 12878 times, and the alarms from life-supporting/-monitoring devices were present for the longest accumulated duration, 19.5/24 hours. Noise level data were also extracted from the calibrated recordings and analyzed in synchrony with the annotation results. The results showed that the strongest noise source was the patient's own noise (e.g., crying) inside the incubator and the other patients' noise above the incubator. Excluding the patient's own noise, the alarms and the non-patients' activity noises contributed to the total acoustic energy inside the incubator by 43% and 42% and above the incubator by 53% and 26%, respectively. It is suggested that a better management of alarm systems and an appropriate staff education may improve the acoustic environment in NICUs.

Keywords: NICU, Noise source, Average noise level, Audio annotation
I-INCE Classification of Subjects Number(s): 56

1. INTRODUCTION
Numerous studies point to the fact that the environment in healthcare facilities is far from being ideal for the treatment and recovery of patients. In particular, the acoustic environment in neonatal intensive care units (NICUs) has been one of the most important topics of research, because an excessive noise may disrupt the development of the preterm infants in many aspects, including hearing, language, and cognitive abilities (1). In the past, acoustic surveys were carried out to report that, for example, the noise levels inside unoccupied incubators may be as high as 68 dBA with a mechanical ventilator and 64 dBA without (2), and, in another study, preterm infants in incubators are exposed to the noise level of 56.4 dBA on average, almost always above the upper limit values suggested by some existing guidelines (3). Although "direct evidence linking noise to neonatal pathology is still unclear" (4), studies suggest that noise have at least short-term effects on the cardiovascular and respiratory

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systems of preterm infants and may also change their sleep/arousal states, especially when the noise is short in duration (5).

Given possible physiological and psychological effects of noise on the patients and the excessive noise levels measured in NICUs, some interventional studies were also carried out to measure the decrease in noise level in direct relation to, for example, the education of caretakers with or without the use of a feedback device (6), a noise-specific hospital policy (7), the improvement of building interior and layout (8), and so on. The important assumption made in these studies is that the sources of noise are known, and the interventions can effectively address them. Although noise sources were almost always named and discussed in most studies with acoustic survey results, however, only few studies employed relatively systematic methods to attempt cataloguing and quantifying the noise sources present in NICUs (6,9,10). In these noise-source studies, human observers were employed to catalogue audible sound events and to measure the noise levels associated with them. Although the identification of each noise source will be accurate by using both auditory and visual cues, the presence of an observer in the NICU may affect the behavior of caretakers, possibly lowering noise levels, which is typically referred to as the Hawthorn effect.

In the current study, calibrated audio recordings were made inside and above a selected incubator in an open-plan NICU, and a selected 24-hour segment was listened to offline and manually annotated by a research assistant, which eliminated the possible bias due to the Hawthorn effect. By combining the results of the annotation and the L_{Aeq} values extracted from the recordings, the source-specific noise level and acoustic energy contribution could also be estimated.

In sections 2 and 3, methods to obtain, annotate and analyze audio recordings are described in detail, followed by the results presented in section 4. In section 5, some general discussions are made regarding the measures to improve the acoustic condition for the NICU patients, and a summary will be given in section 6.

2. AUDIO RECORDING AND ANNOTATION

2.1 Recording in NICU

The current study was carried out at the NICU of University Hospital Antwerp, Belgium (Universitair Ziekenhuis Antwerpen). Two microphones were mounted inside and outside of a selected incubator (Isolette 8000, Dräger Medical Inc.; Lübeck, Germany): Inside, the microphone [B&K 4192 (mic.) with B&K 2669 (preamplifier) and B&K 2690-A (amplifier), Brüel & Kjaer; Nærum, Denmark] was located near the ceiling of the incubator, so that the patient-care activities may not be interrupted; outside, the second microphone of the same type was mounted with nylon strings to the fixture on the ceiling, 220 cm above the floor. Recordings were made in synchrony at the two positions at the sample rate of 44.1 kHz by using a computer and a sound card (MOTU UltraLiteMK3, MOTU inc.; Cambridge, Massachusetts, United States). The noise floor of the entire recording equipment was found to be ~30 dBA in an anechoic chamber, and for a 1-kHz pure tone, the upper limit was measured to be ~127 dB. Microphones were calibrated on site before and after the recording by using a calibrator (B&K 4231, Brüel & Kjaer).

In the end, three continuous recordings were made per channel (microphone) as follows:

1) Session 1 [~5 days]: Incubator empty
2) Session 2 [~12 days]: Incubator occupied by a patient with no respiratory support
3) Session 3 [~26.5 days]: Incubator occupied by a patient with continuous positive airway pressure (nasal CPAP; Infant Flow System, Becton, Dickinson and Company; New Jersey, United States)

where the information noted in the square brackets indicate the continuous recording periods.

2.2 Offline manual annotation

Most patients admitted to NICU require respiratory supports, and therefore, session 3 may be most representative of the acoustic environment. Since the relatively high-level noise from the CPAP device masks other sound events almost always, however, the recording made in session 3 was found not to be appropriate for the type of analysis to be carried in the current study (e.g., estimating the L_{Aeq} values for each noise category; see section 3.2). Therefore, the first 24 hours of the recording made in session 2 was selected for the manual annotation. A research assistant used Praat (11), a computer software developed for linguistic research, where she listened to both recordings made inside and outside the incubator simultaneously over headphones. All audible sound events including those overlapping with each other were annotated separately and as tightly as possible in time. For a more detailed description of the annotation criteria, readers are referred to (12).

Approximately 180 working hours were required to completely annotate the 24-hour recording, where the annotator used 19 noise source labels in 8 categories as listed in Table 1.

Table 1 – Noise source labels used in the current study

Category	Noise source	Remarks
Patient's own	Patient's own sound	Patient crying, etc.
Other Patients	Other patients' sound	Other patient crying, etc.
Non-Patients (v)	Patient-related speech	Conversation between hospital staff or others regarding patient care
	Other speech	Conversation between hospital staff or others, which is not related to patient care
	Unintelligible speech	Speech unintelligible from the recording
	Others' non-verbal sound	Non-patients' non-verbal sound, e.g., coughing, throat-clearing, etc.
Non-Patients (a)	Incubator	Noise generated when operating incubator, e.g., door opening and closing, etc.
	Staff activity	Noise generated by staff activities other than operating incubator
M. Devices	Medical device	Operational noise from medical devices, e.g. ventilator, etc., excluding alarms.
NM. Devices	Non-medical device	Noise from non-medical devices, e.g., telephone/beeper, etc.
Alarms	Patient monitor red alarm	Alarms from patient monitor, infusion pump, incubator, etc.
	Patient monitor yellow alarm	
	Patient monitor blue alarm	
	Infusion pump red alarm	
	Infusion pump yellow alarm	
	Ventilator alarm	
	Incubator alarm	
	Unidentifiable alarms	
Unidentified	Other unidentifiable sound	All other unidentifiable noise

3. DATA ANALYSIS

3.1 Statistics of sound events

From Praat, the annotation data was imported to Matlab (The Mathworks, Inc.), and the total number of the annotated intervals was counted per noise category by simply adding the occurrences of sound events. For the total duration, however, the time intervals labeled for the sound events belonging to the same category were first merged, thus, taking into account the overlapping intervals only once, and then the total duration of each category was obtained.

3.2 A-weighted acoustic energy contribution per noise category

According to the international standard and convention (13), the A-weighted energy-equivalent sound pressure level (L_{Aeq}) was extracted from the audio recording. After an A-weighting filter was applied to the recording, every 1050 samples were averaged to produce the $L_{Aeq,24ms}$ values at the rate of 42 samples per second. Given this high-resolution data combined with the timing information obtained by the annotation, the A-weighted acoustic energy contribution per noise category could be determined. First, the time intervals labelled for more than one noise category were removed, which left only the *exclusive intervals* for the selected category, i. The $L_{Aeq,24ms}$ values associated with the exclusive intervals were then converted to the linear scale, summed (resulting in the overall energy $E_{i,excl}$) and averaged over the total duration of the exclusive intervals, $T_{i,excl}$, as follows:

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

where e_i represented in the log scale may be regarded as the L_{Aeq} specific to the noise source i, or $L_{Aeq,src}$. Finally, the total A-weighted acoustic energy E_i was approximated by

$$E_i = e_i \times T_i \quad (2)$$

where T_i represents the total duration of all (*inclusive*) intervals.

4. RESULTS

4.1 Overall noise levels

Fig. 1 shows an overview of the noise level in the first 24 hours of session 2, which was selected for the annotation. From the $L_{Aeq,10m}$ values plotted against time, it appears that the incubator acted as a good noise isolator, where the noise level varied between 50 and 60 dBA above the incubator, but mostly below 50 dBA inside. Inside the incubator, however, high-level sound events could be observed, which occasionally raised the $L_{Aeq,10m}$ value up to ~75 dBA, well above those of the above-incubator measurement. By listening to the corresponding interval of the recording, these events were found to be associated with the patient's own noise (e.g., crying) in the incubator. Although short in duration, these events affected the 24-hour average noise level ($L_{Aeq,24h}$) significantly, which was found to be 56.7 dBA inside and 57.1 dBA above the incubator with little difference between the two.

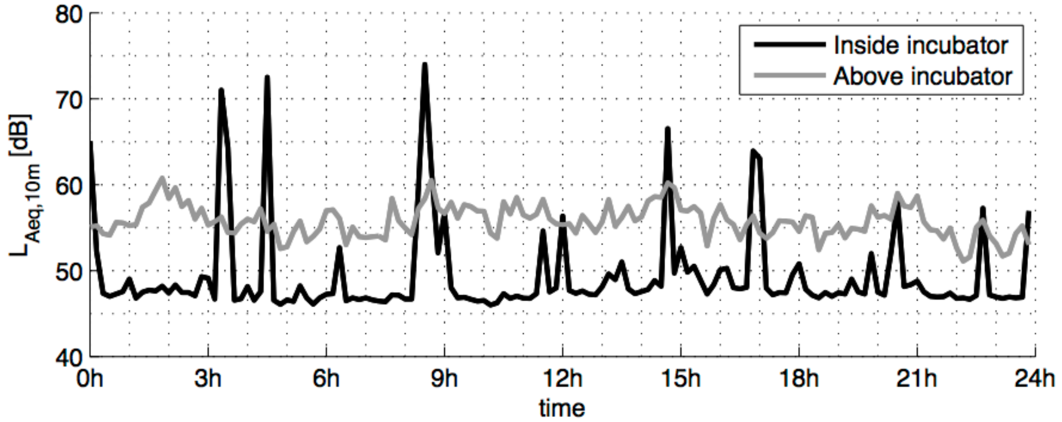


Figure 1 – LAeq,10m shown for the first 24 hours of session 2.

4.2 Sound event duration and occurrence

When the annotation was completed, a total of 30159 events were identified by the annotator, where 22.1/24 hours were labelled with up to 7 concurrent events. For each noise category, Table 2 shows the number of the labelled intervals and the total accumulated duration in hour. Non-patient's activities were found to be the most frequent event, occurring 12878 times in total at the rate of ~9 times per minute on average. Alarms were annotated 8879 times in total, equivalent to ~6 times per minute. Alarms were also found to be of the longest duration, 19.5 hours, which implies that one or more alarm sounds could be heard in this NICU more than 80 % of the selected 24 hours. Dividing the duration by the number of occurrences, the average duration of the alarm sound was ~8 seconds.

Table 2 – Occurrences and accumulated durations of sound events

Category	Occurrences	Accumulated duration [h]
Patient's own	1727	0.9
Other Patients	1220	1.8
Non-Patients (v)	4113	5.2
Non-Patients (a)	12878	7.7
M. Devices	63	0.1
NM. Devices	909	0.2
Alarms	8879	19.5
Unidentified	370	0.1
All categories	30159	22.1

4.3 L_{Aeq} per noise category

Fig. 2 compares the source-specific L_{Aeq} values ($L_{Aeq,src}$) inside and above the incubator. Confirming the findings described in section 4.1, the $L_{Aeq,\ src}$ value associated with the patient's own noise was highest inside the incubator, which was the only exception where the source-specific L_{Aeq} was higher inside the incubator than outside. As a matter of fact, the data shown in Fig. 2 agree well with the usual locations of the noise sources: Inside the incubator, the patient's own noise and Non-Patients (a) which is the noise incurred by the NICU staff were the two strongest sources; outside the incubator, on the other hand, the other patients' noise and the alarm sounds were the strongest together with Non-Patients (a). It is also interesting to note that Non-Patients (v) outside the incubator is not as strong as those noises mentioned in the preceding text: Caretakers and visitors may knowingly make their speech noise softer than usual, but make more (louder) noises by acting probably without realizing it.

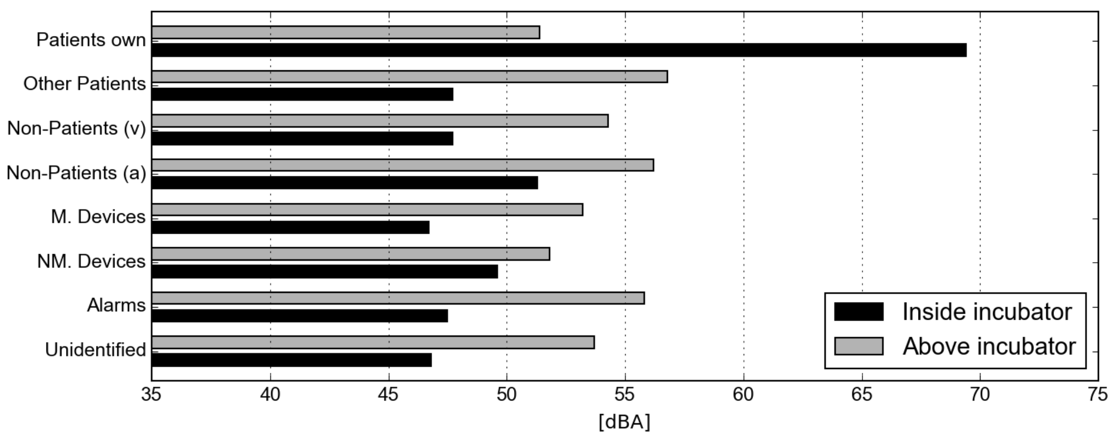
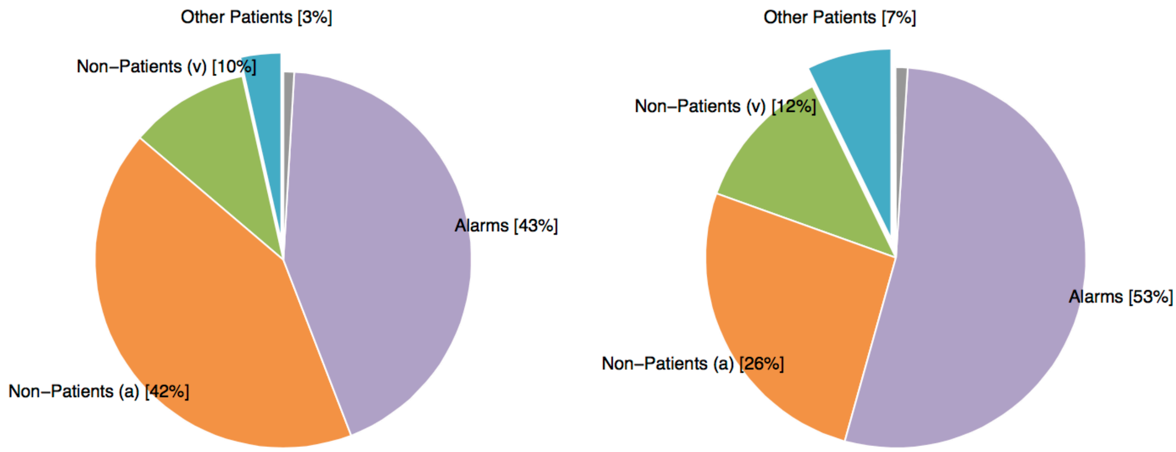


Figure 2 – $L_{Aeq,src}$ shown for the 8 noise categories.

4.4 A-weighted acoustic energy

Converted in the linear scale, the A-weighted acoustic energy is shown for each noise category in percentage, where the patient's own contribution was excluded to estimate the source-specific noise dose *as experienced by the patient*. Both inside and above the incubator, Non-patients (a) and Alarms were found to be responsible for most of the total energy: 85% inside and 79% above. Although the associated $L_{Aeq,src}$ values were not highest (see section 4.3), the noise events of these two categories occurred for the longest duration (see Table 1), thus, contributing most to the total acoustic energy. Comparing the inside- and the above-incubator data, Alarms are more dominant than Non-Patients (a) above the incubator, which is most likely related to the locations of the noise sources: Alarm sounds are mostly generated by the devices located outside, whereas the activities by caretakers take place inside and outside.



(a) Inside the incubator (b) Above the incubator

Figure 3 – A-weighted acoustic energy contribution per noise category

5. General discussions

5.1 Measures to reduce the noise dose

Based on the findings of the current study, ways to improve the acoustic environment for the incubated patients in NICUs may be proposed. As a matter of fact, the incubator appears to act as a good acoustic isolator as shown in Figure 1, where the $L_{Aeq,10m}$ values differed by ~10 dBA between the inside- and the above-incubator positions, when the patient's own noise is excluded. Therefore, it seems that keeping the patients in incubators may already protect them well from excessive external noises, especially in an open-plan shared room.

If it is difficult or inappropriate to keep the patients in acoustically well-isolated space, which is usually the case in NICUs, the dominant sources of noise as identified in the current study may be removed or reduced in level. Where the noises from other patients may not easily be abated, actions may be taken for other major sources indicated in Figure 3. Patient care activities taking place inside and near the incubator may be a good subject of staff education, where a better awareness may make them act more quietly. Compared to Non-Patient (a), the speech activities by staff and patients' family [Non-Patient (v)] make far less contribution to the overall acoustic energy, which is quite contradictory to the results of the similar study carried out in an adult ICU (12). Nevertheless, unnecessary conversations may be relocated away from the incubator, which will positively influence the acoustic environment for patients.

It is known in the literature that many alarm sounds in NICUs and ICUs are unnecessary or clinically irrelevant (14). The current study also shows that there are simply too many alarm sounds (8879 events) for far too long a period (19.5 hours), which may be reduced by better strategies for alarm management or by using graded alarm systems.

5.2 Acoustic environment in open bed

When the health condition improves, the patients in incubators are normally transferred to open beds for various reasons, most importantly to ensure easier and more intimate contact with parents. Although such transfers may be clinically justified, patients may have to confront a significant change in acoustic environment. Unfortunately, no measurement has been made in the current study for an open bed. Assuming that the sound field in this open-plan NICU does not depend much on the position in room or the height of the measurement position, however, the noise level measured above the incubator may arguably be similar to that experienced by the open-bed patients. As discussed in the preceding section regarding Figure 1, the noise level difference between inside and outside the incubator was approximately 10 dBA or more (when patient's own noise was excluded), which may be a very substantial environmental change for patients on transfer from incubator to open bed, especially when the difference is indicated in the average noise dose, L_{Aeq}. However, it is difficult to judge whether the benefit of parental interaction and other clinical advantage may surpass the acoustical disadvantage of the transfer, which may be a subject of further research.

6. Summary

In the current study, 24-hour recordings made inside and above a selected incubator were annotated and analyzed, and the source-specific average noise level and the A-weighted acoustic energy contribution were studied for a few representative categories of noise sources in an open-plan NICU. When accumulated, less than 2 out of 24 hours were found to be free of audible events, and 30159 events were annotated with up to 7 concurrent events. In the analyses where the L_{Aeq} values were associated with annotated intervals, the patient's own noise was found to be most dominant inside the incubator. Excluding the patient's own contribution, however, alarm sounds and non-patients' speech and other activities contributed most to the total A-weighted acoustic energy. Staff education and a better alarm system or management strategy was suggested for the improvement of the acoustic condition for patients.

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