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Research Article

Contribution of alarm noise to average sound pressure levels in the ICU: An observational cross-sectional study

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ABSTRACT

Objectives: To explore sound levels, alarm frequencies and the association between alarms and sound levels.
Design: A single center observational cross-sectional study.
Setting: Four intensive care units.
Main outcome measures: Contribution of alarms: red (life threatening), yellow (indicate excess of limits) and blue (technical) to sound pressure levels dB(A) at nursing stations.
Results: Mean sound pressure levels differed significantly between day (56.1 ± 5.5), evening (55.1 ± 5.7) and night periods 53.6 ± 5.6; $p < 0.01$. 175,996 alarms were recorded of which 149,764 (85%) were yellow, 18,080 (10%) were red and 8,152 (5%) were blue. The mean sound levels without alarms (background) is 56.8 dB(A), with only red: 56.0 dB(A), only yellow: 55.6 dB(A), only blue: 56.0 dB(A) and mixed alarms: 56.3 dB(A). Yellow alarms ($b = -0.93$; 95% CI: −1.26 to −0.6; $p < 0.001$) were weakly but significantly associated with mean sound levels and lead to a slight decrease in noise level (1 dB), Red alarms ($b = -0.3$; 95% CI: −1.237 to 0.63; $p = 0.52$). The R Square of the model with all alarms was 0.01 (standard error of estimate, 6.9; $p < 0.001$).
Conclusions: Sound levels were high during all day-periods. Alarms exceeding limits occurred most frequently. However, the contribution of alarms to sound levels measured at the nursing station is clinically limited.

Implications for clinical practice

- The contribution of alarms to mean noise levels in the intensive care unit is limited.
- Alarm management still needs attention because of the large number of alarms that cause disturbances.
- Alarm interventions should focus on reducing alarms exceeding limits
- Noise reducing interventions should focus on other causes than alarm frequency.

Introduction

Patients admitted to the intensive care unit (ICU) undergo complex critical care treatment and are consequently surrounded by equipment and monitors contributing to high sound pressure levels (Konkani and Oakley, 2012). In addition, many medical and nursing ICU staff members work together with numerous visiting consultants resulting in an additional sound burden (Hsu et al., 2012; Morrison et al., 2001). In the ICU environment many activities are being carried out accompanied by excessive noise, while many tasks carried out by healthcare professionals require a high level of concentration. Importantly, mean sound pressure levels

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(L_{Aeq}) of 40 dB (A) may cause interruption in activities requiring concentration and induce a higher potential for error (Konkani and Oakley, 2012). The World Health Organization (WHO) and the Environmental Protection Agency (EPA) set standards for sound levels in hospitals with a recommendation for patient treatment areas: sound pressure levels should not exceed 35 dB(A) (WHO) and 45 dB(A) (EPA) during daytime hours, 30 dB(A) (WHO) and 35 dB (A) (EPA) for nighttime hours (Berglund et al., 1999; EPA, 1974). The WHO guidelines are most commonly used. There is a clear trend for increasing hospital noise since the sixties and excessive sound pressure levels in ICUs are often reported in the range between 50 and 70 dB(A) (Busch-Vishniac et al., 2005; Darbyshire and Young, 2013; Konkani and Oakley, 2012; Pugh and Griffiths, 2007; Tainter et al., 2016). According to healthcare professionals, one of the strongest contributing factors of noise in the ICU environment are monitoring alarms as they occur very frequently (Morrison et al., 2003; Petersen and Costanzo, 2017; Ryherd et al., 2008). Additionally, ICU nurses experience high levels of stress towards clinical alarms (Sowan et al., 2015) and suffer alarm fatigue, which means that the staff becomes desensitised because of an excessive number of alarms and may disable or silence alarms without checking the patient (Paine et al., 2016). Consensus dictates the importance of reducing sound pressure levels and the numerous alarm signals (Winters et al., 2018), however, it is unknown what the actual contribution of noise from monitor alarms in the ICU is to sound pressure levels in general in the ICU. We focused on the most busy area in the ICU; the central nursing station. The aim of this study was to explore sound pressure levels and to get insight in the alarm frequencies. Furthermore, to determine the association between sound pressure levels and the alarms.

Methods and materials

Design and study period

An observational repeated cross-sectional study was carried out between February 17th and March 17th 2015.

Setting

The study was carried out in four randomly chosen units (general ICU, cardiovascular ICU, paediatric ICU and an intermediate care unit (IMCU) out of the seven units of the department of intensive care medicine of the Radboud University Medical Center, a 950-bed university hospital in the Netherlands. The three ICUs have a similar architectural design with each eight, exclusively single patient rooms located in a u-shaped design, surrounding an open Central Nursing Station (CNS) which is fully equipped with a central monitoring system (Philips IntelliVue Information Center YX, Philips Healthcare; Amsterdam, The Netherlands). In the CNS area is also a semi-open medication preparation station where staff can walk in and out with only a limited physical barrier (Appendix A). The IMCU has two double and six single rooms, with a slightly different design and one central nursing station, and two small nursing stations. Each patient room in the ICU is equipped with a bed, documentation centre, mobile utility arm, vital signs monitor, mechanical ventilator, and several volumetric pumps. The nurse-patient ratios in the ICU are 1:1 and in the IMCU 1:3.

The (sliding) doors of the patient rooms are usually open for observation, except for those patients who need to be treated in isolation. Since no patient data was collected, no ethical approval was required.

Data collection

Sound equipment and measurements

Sound pressure levels were recorded using a microphone with a data logger device (industrial sound pressure level decibel meter PCE-322-A PCE Instruments, UK Ltd.) calibrated by the manufacturer with an accuracy of ± 1.4 dB. The A-weighted filter was used as it attenuates the curve that describes loudness frequency for the human ear. During a 48-hour period, sound pressure levels were measured in A-weighted dB (A) at 1-second epochs. We specifically chose a period of only 48 hours to ensure minimal interference with the busy nursing activities at the central post. During the measurement period the unit occupancy rate was > 95%.

The microphone, attached to a table in the CNS, was directed to the medication preparation unit, situated in the central post area, where most activities are carried out and frequently is pointed as the noisiest place in the ICU (Kol et al., 2015). Bedside alarms were generated simultaneously at the central Philips IntelliVue monitors. The microphone was circulated between the four units on separated days and was recalibrated in between. The noise indicator LAeq (equivalent continuous sound pressure level), was chosen since this number equals the noise level per time interval. We measured L_{Aeq} per day, evening and night period defined as: daytime: 07.00 till 15.00, evening- time: 15.00 till 23.00 and nighttime: 23.00 until 07.00 respectively, which corresponds to the nurses shifts (Berglund et al., 1999).

The distribution indicators L_{10} and L_{90} were chosen per day period: day, evening, night. These sound parameters are defined as sound pressure levels exceeded for 10 percent (L_{10}) and 90 percent (L_{90}) of the time, used as average measures typical for the "maximum" and "background" levels, respectively (Berglund et al., 1999), and less sensitive to outliers because we measured at 1-second epochs.

Equipment and alarms

Alarms were continuously recorded of all 36 beds during a period of one month to perform an extensive analysis of alarms to answer our research question. All ICU beds are equipped with Philips IntelliVue monitors type MP–70 revised H.0 and type MP-50 revised H.0 in the IMCU. At each bed a mechanical ventilator (Servo-i ventilator (Maquet) is connected to the bedside monitor using a Vuelink system, including alarms from the mechanical ventilator.

All monitor alarms produce an audible and visual alarm at the monitor in the patient rooms as well as in the CNS. The other life supporting devices in the rooms also produce audible and visual alarms that can be heard from outside the room, often amplified by an intercom system. The CNS's are equipped with a Philips IntelliVue Information Center YX for monitoring of all bedside alarms.

The priority of the alarms are divided according to the severity of the monitored parameter. Alarms triggered by life-threatening events have the highest priority (red alarm) and must be responded to immediately. Alarms, that indicate excess of limits (yellow alarm) and technical alarms (blue alarm), like disconnection of monitor leads, have a lower priority. Red alarms exert a louder volume than yellow and blue alarms.

In addition to the system mentioned above, a nurse duty server (manufacturer Ascom, Baarn Switzerland) sends the red alarms, the doorbell and the nurse calls from patients, to a wearable device (Ascom i62). This device provides the nurses with an audible and tactile signal.

We used alarm tracking software (PHILIPS Alarm Software IntelliVue Information Center, Philips Healthcare; Amsterdam, The Netherlands) for data collection of all alarms including type of alarm, time and date, unit, patient bed and priority of alarm.

Statistical analyses

Descriptive statistics to analyse alarms and sound pressure levels were used. Extreme outliers in the sound pressure levels database, defined as measurements in distance $\leq$ or $\geq$ 3 standard deviations from the mean sound pressure level, were excluded. Comparisons between time periods and locations were performed with one-way analysis of variances (ANOVA) with a post-hoc Tukey test.

Time and date synchronisation was carried out of the 48-hours measured sound pressure levels with data of the alarms measured in this time period using custom-written MATLAB scripts (Matlab R2014b, The MathWorks Inc. Massachusetts, USA). Per time interval (1-second) we classified all alarm types in the categories "Red, (life threatening), Yellow (alarms exceeding limits) and Blue (technical) alarms. We computed variables: only Red alarms (all Red alarms), only Yellow alarms (all Yellow), only Blue alarms (all Blue alarms).

To determine the association between alarms and mean sound pressure levels, we performed an univariate and to guarantee thoroughness, multivariate linear regression analysis in which the three independent variables: 'all RED alarms', 'all Yellow alarms', 'all Blue alarms' were added in the model one by one to predict the value of the dependent variable noise in dB(A). We expressed the degree to which each of the three variables 'all RED alarms', 'all Yellow alarms', 'all Blue alarms' were related to the independent variable noise dB(A). Since also the duration may have an effect we also added the duration of the alarms in this analysis. For all statistical analysis SPSS 25.0 (SPSS Inc., Chicago, IL, USA) was used. We considered as statistically significant those variables that have a p-value of < 0.05.

Results

Sound pressure levels

The overall L_{Aeq} (Day-Evening-Night) was 55.4 ± 5.7 dB(A) (Table 1). The overall noise indicator for relative quiet L_{90} ('min') and for relative loudness L_{10} ('max') range from 44.1 to 59 dB (A). Differences in reported L_{Aeq} by day (56.1 ± 5.5), evening (55.1 ± 5.7) and night periods 53.6 ± 5.6 were statistically significant ($p < 0.01$). The L_{Aeq}'s Day-Evening-Night also varied between type of unit as depicted in Fig. 1.

Acoustical alarms

A total of 175,996 alarms were recorded of which 149,764 (85%) were alarms, that indicates excess of limits (yellow), 18,080 (10%) were life threatening alarms (red) and 8,152 (5%) were technical issues (blue). Exceeding heart rate limits (HF) n = 35,655 (20.3%), transcutaneous low oxygen saturation (SpO2) n = 33,429 (19%) and low or high mean arterial blood pressure (mABP) n = 26,983 (15.3%) were the most frequently occurring yellow alarms. There are some differences between the most common alarms per unit (Table 2). On average there were 170 alarms per day, per bed. Average alarms per day per bed were different per unit with the lowest average number in the general ICU (129 alarms) and the highest number in the IMCU (239 alarms). There were no statistical differences between the number of alarms on week days and on weekend days.

Table 1
L_{Aeq} by day/evening/night at the central nursing station.

	Mean, SD	L_{10} "maximum noise"	L_{90} "background noise"
Overall	55.4 ± 5.7	59.0	44.1
Daytime	56,1 ± 5.5	59.8	45.2
Evening-time	55.1 ± 5.7	58.7	43.7
Nighttime	53.6 ± 5.6	56.2	42.3

L10 and L90 are the sound pressure levels exceeded for 10 percent ('maximum') and 90 percent ('background') percent of the time, respectively.

Contribution and association of acoustical alarms to sound pressure levels

The mean L_{Aeq} with no alarms (background) is 56.8 dB(A), with only red alarms: 56.0 dB(A), only yellow alarms: 55.6 dB(A), only blue 56.0 dB(A) and mixed alarms: 56.3 dB(A). Associations univariate and multivariate for Yellow alarms (b = −0.93; 95% CI: −1.26 to −0.6; $p < 0.001$ and b = −0.99; 95% CI: −1.32 to −0.65; $p < 0.001$, respectively) to sound pressure levels were statistically significant, for Red alarms (b = −0.3; 95% CI: −1.237 to 0.63; p = 0.52 and b = −0.75; 95% CI: −1.69 to 0.19; p = 0.12, respectively) and Blue alarms (b = −0.33; 95% CI: −1.48 to 0.82; p = 0.58 and b = −0.78; 95% CI: −1.93 to 0.38; p = 0.19, respectively).

The R Square of the model with all alarms was 0.01 (standard error of estimate, 6.9; $p < 0.001$).

In Fig. 2 the number of alarms and concomitant sound levels are plotted for an 8 h day shift (5 min interval), at the central nursing station in the paediatric ICU (at 3.03.2015). A stretched Figure for only 2 hours per minute detail (08.00 a.m. – 10.00 a.m.) is presented in Supplemental Fig. 1.

Discussion

In this study we demonstrated that mean sound pressure levels in our ICU were high and above the recommended WHO-guidelines. On average there were 170 alarms per day per bed of which alarms, that indicate excess of limits (yellow alarms) occurred most frequently. Furthermore, the contribution of alarms to the mean sound pressure levels at the central nursing station is limited. Although this was statistically significant, alarms only contribute for 1% of the total sound pressure levels.

Sound pressure level

The mean sound pressure levels of 56.1 and 53.6 dB(A) that were measured during daytime and nighttime, respectively, are comparable to other studies (Busch-Vishniac et al., 2005; Konkani and Oakley, 2012). Importantly, a 3–5 dB change is (just) discernible for the human ear (Darbyshire and Young, 2013) so the differences between day-periods are, although statistically significant, clinically only of a limited impact. Despite efforts to reduce the mean sound pressure levels, these are still too high according to the WHO (Berglund et al., 1999; Busch-Vishniac et al., 2005; Darbyshire and Young, 2013; Pugh and Griffiths, 2007; Tainter et al., 2016). It can be noted that the WHO-threshold is aimed at hospital noise in general but there is no specific guideline for the intensive care unit setting.

The negative impact of noise on nurses' perceived stress, annoyance and on the quality of staff communication, is known (Hoehn et al., 2000; Konkani and Oakley, 2012; Morrison et al., 2001; Ryherd et al., 2008; Topf and Dillon, 1988). Despite these safety concerns, there is no evidence that elevated noise levels actually contribute e.g. to medical errors, which therefore remains an important topic for future studies (Hoehn et al., 2000).

Alarms

The number of alarms that were recorded in this study are in concordance with other studies (Paine et al., 2016; Winters et al.,

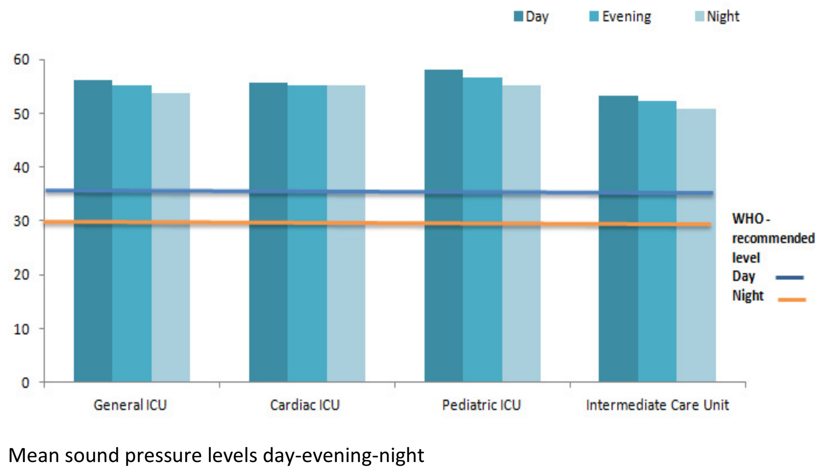

Fig. 1. L_{Aeq} Day-Evening-Night per unit. All differences by day, evening and night periods were statistically significant ($p < 0.01$), except the cardiac ICU: day vs evening $p = 0.44$, day vs night: $p = 1.0$, evening vs night: $p = 0.88$.

Table 2
Most common alarms per day/bed.

Alarm	General ICU	Cardiac	Pediatric ICU	Intermediate Care Unit	Total
ABPm, n (%)	30 (19.4)	53 (9.0)	27 (26.2)	125 (20.9)	235 (19)
SpO2, n (%)	30 (18.9)	22 (16.3)	36 (12.6)	57 (25.2)	145 (20.3)
HR, n (%)	34 (11.3)	44 (11.8)	23 (11.3)	93 (19.7)	194 (15.3)

SpO2 = transcunatenous oxygen saturation, HR = heart rate, ABPm = mean arterial blood pressure.

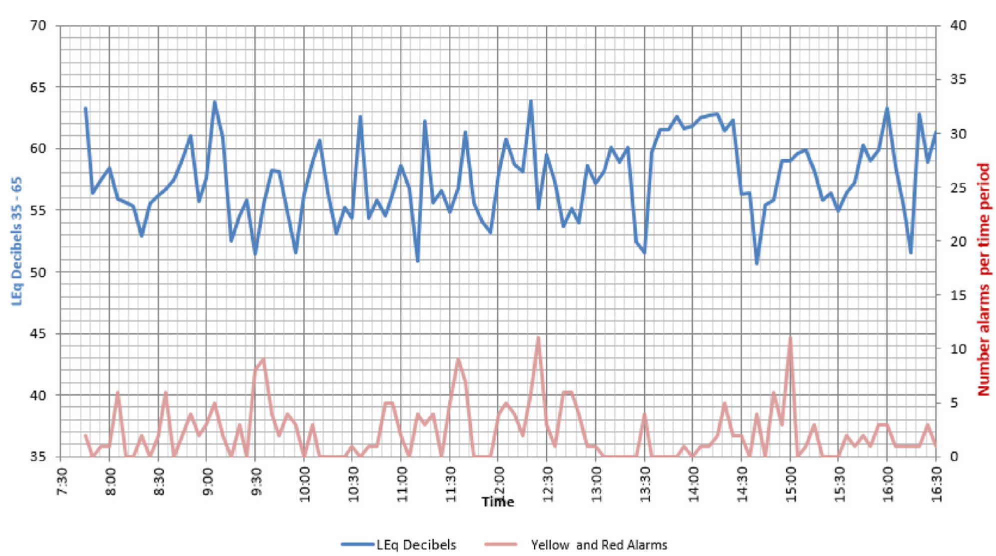

Fig. 2. Alarm frequency plotted against sound pressure levels measured at the central nursing station in the paediatric ICU, during a day shift (March 3, 2015) per 5 min detail.

2018). The high number of alarms measured in the IMCU can may be explained by the lower nurse:patient ratio, and mobility level of the patients in the IMCU, which may lead to electrodes and cables being disconnected more frequently.

The proportion of alarms that require an intervention is only 1%–26% in adult ICU settings and 3%-13% in the pediatric ICU (Paine et al., 2016). We found that 85% of the alarms were alarms, that indicate excess of limits (yellow alarms) and although we did not study whether these alarms actually required attention or a clinical intervention immediately, we have no indication that this would be different from other studies (Paine et al., 2016). Furthermore, since alarms contribute to distractions of healthcare professionals (Park et al., 2014) reduction of non-actionable alarms is of high priority. Using a bundled quality improvement approach including e.g. alteration in monitor presets, electrode change, alarm customization, alarm management education, change in policy and the use of notification delays, could reduce the excessive number of non-actionable alarms (Winters et al., 2018).

Yellow alarms were significantly, but limited, negatively associated with sound pressure levels. This negative association is likely caused by the distraction of the nurses by an alarm, interrupting her work, which lowers the sound pressure level for a short moment. This supports the assumption that alarms causes distractions during daily work activity.

In our study, we introduce a new perspective. It is known that high ambient sound levels contribute to avoidable errors, made by medical staff (Konkani et al., 2014). To indicate environmental sound levels, the average sound pressure level value (L_{Aeq24}) is widely used. According to medical staff, alarms are one of the main sources of noise (Hsu et al., 2012; Ryherd et al., 2008).

Alarms have sound characteristics that may be ideal for attracting the attention but also that humans find disturbing and leads to experienced annoyance during their daily work activities. This is confirmed in observational studies in ICUs, which identify alarms and pagers as major disruptive noise sources (Darbyshire et al., 2016).

However, alarm devices generate very little sound, except when alarms are activated (>50 dB) (Darbyshire et al., 2019). So we were mainly interested in the actual proportion of noise coming from alarms, knowing that in many studies alarm reduction is part of the intervention bundle to reduce average sound pressure levels (Nannapaneni et al., 2015; Patel et al., 2014).

We found some evidence that alarms in themselves barely contribute to mean sound pressure levels in the ICU. In Fig. 2 and Supplemental Fig. 1, the two curves (alarm count and noise levels), do not follow the same pattern, and show no synchronization at any point in time of alarm with noise level. Additionally, both in univariate and to guarantee thoroughness in multivariate analysis, we see no coherence of significance between alarms and noise.

So we do support the statement that, in order to reduce sound pressure levels, the most promising and consisting interventions are behavioural modification of the staff, redesigning work processes or the actual workspace (Crawford et al., 2018; Kawai et al., 2017; Khademi Gh, 2015; Kol et al., 2015; Luetz et al., 2016). Additionally, engineering controls (e.g. equipment shielding) seems to be more effective in reducing intensive care noise that behavioral modification alone (Crawford et al., 2018).

Limitations

Some limitations of our study need to be addressed. First, this was a single centre study, however, the sound and alarm measurements were performed on four different ICU locations and the sound and alarm measurements were consistent with other studies. Second, although we collected a large number of alarms (>175,000) during one month, we only recorded the sound pressure levels for a relatively short time interval (two days). We certainly recognise that sound recordings over a longer period would strengthen our findings. Third, in our study we only focused on the central nursing station because this is a very busy area where several activities are taking place at the same time, which requires concentration (like medication preparation). Additionally, in this area many alarms are generated by the central monitoring system. Fourth, we were limited by our technique which was unable to provide an in-depth analysis of the complexity of intermittent alarm sound.

However, as described, we sampled per second time interval. So, despite we do not have e.g. absolute alarm peak levels, our sample size per second is that high that we believe that we were able to detect these sounds. Fifth, the accuracy for the microphones used in this study is described as accurate to ± 1.4 dB and this could have affected our results. Sixth, it would be of interest to also measure the effect of alarms on sound pressure levels at the patients' bedside. Probably here, the association between alarms and sound pressure levels is more pronounced. As a final limitation, we only focused on alarms although studies point out that high noise levels can be created by a variety of sources, of which general activity and talking by hospital staff are identified as important contributors to noise levels (Konkani and Oakley, 2012; Konkani et al., 2014; MacKenzie and Galbrun, 2007).

Conclusion

The mean sound pressure levels in the central nursing stations are high and exceeding WHO limits. Furthermore, this environment is affected by many alarms, but the contribution to mean noise levels is limited. Therefore, noise reducing interventions in the central nursing stations should also focus on additional causes of sound such as the conversations undertaken by medical professionals and visitors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Statement

This study is not subject to review in the sense of an ethical approval, since no patient data are collected.

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Appendix A. Supplementary data

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