Acoustic environments of the intensive care units during the COVID-19 pandemic

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Abstract

This study aims to investigate the typical noise levels and noise sources in an intensive care unit (ICU) during the COVID-19 pandemic. Acoustic experiments were conducted over 24 hrs in patient wards and at nurse stations in four Chinese hospitals. From the measurements, noise levels and sources were analysed in terms of the A-weighted equivalent sound pressure levels (L_{Aeq}) and A-weighted maximum Fast time-weighted sound pressure levels (L_{AFmax}) over three different time periods during the day (i.e. day, evening and night). Overall, noise levels (L_{Aeq}) for 24 hours in all hospitals exceeded the World Health Organisation's (WHO) guide levels, varying from 51.1 to 60.3 dBA. The highest maximum noise level reached 104.2 dBA. The single-bedded wards (side rooms) were quieter than multi-bedded wards, and night time noise levels were quieter than daytime and evening across all hospitals. It was observed that the most dominant noise sources were talking/voices, door-closing, footsteps, and general activities (e.g. noise from cleaning equipment and cutlery sound). Footsteps became an unexpected dominant noise source during the pandemic because of the staff's disposable shoe covers which made footsteps noisier. Patient alarms and coughing varied significantly between patients. Talking/voices produced the highest maximum median values of the sound exposure level (SEL) and the maximum noise level at all sites. Noise levels in all the patient rooms were more than the WHO guidelines. The pandemic control guidelines had little impact on the noise levels in the ICUs.

Keywords: noise level, intensive care unit, COVID-19 pandemic, footsteps

1. Introduction

The coronavirus disease 2019 (COVID-19) was first identified in December 2019, and it quickly became a public health emergency of international concern, subsequently escalating to a pandemic in March 2020 [1]. A series of policies and strategies were published to prevent and slow down the spread of the virus. Those policies were similar across various countries and included staying at home, limiting traffic mobility, stopping non-essential commercial activities, social distancing, banning public gatherings, and wearing personal protective equipment (PPE). These measures for controlling COVID-19 significantly affected the environment as well as the community. In particular, the substantial decrease in traffic flow during the lockdown made urban areas quieter. The noise level from road traffic in Paris (L_{den}) for example, reduced by 7.6 dBA on average from pre-pandemic levels. In contrast, complaints about annoyance by neighbour noise significantly increased [1, 2].

The measures for controlling the COVID-19 pandemic have also influenced the environments of frontline staff in hospitals. During the pandemic, healthcare workers were required to wear disposable hats, face mask, goggles, protective clothing, and disposable shoe covers [3] . These guidelines had numerous negative impacts. Hampton, *et al.* [4] reported that wearing PPE significantly reduced speech discrimination scores even though the decreases in the speech transmission index (STI) when wearing a face mask was less than 10% [5]. Rosner [6] highlighted the adverse impacts of prolonged face mask use on healthcare workers, such as headache, skin breakdown, and acne. The use of PPE could also have affected acoustic environments in hospitals because wearing shoe covers leads to a considerable change in the spectral features of walking sounds [7]. In addition, all the hospitals adopted a proactive infection control approach to the sanitation of the environment to minimise the risk of transmission. For instance, in Chinese hospitals, a disinfection solution containing 2000mg/L effective chlorine was used daily to disinfect the floor of the inpatient room and the surfaces of chairs, bedside tables, door handles and other objects [3]. Chinese hospitals without enough air disinfecting machines were asked to keep windows open [3] which also might have increased noise levels.

Several studies before the pandemic have examined noise-related issues in hospitals. For example, many researchers have demonstrated that noise in hospitals negatively affected patients' well-being, the productivity of professionals, and the occurrence of medical errors [8-11]. de Lima Andrade, *et al.* [12] recently conducted a systematic review of literature about noise levels in hospitals between 2015 and 2020. They found that daytime noise levels ranged from 37 to 88.6 dBA, while night time levels varied from 38.7 to 68.8 dBA. More recently, Jeong and Jakobsen [13] reported that noise levels in emergency departments ranged from 50 dBA to 59 dBA. These findings confirmed that all the results exceeded the World Health Organisation's (WHO) recommendations (i.e., 35 dBA during the day and 30 dBA at night). In particular, noise levels in an obstetric ward occasionally reached 100 dBA [14]. Among various departments, the intensive care unit (ICU) has been considered the nosiest due to alarms from medical equipment and noise generated by intensive medical therapies. For clarity the ICUs described later here would be familiar to a high income country intensivist, typically using equipment such as ventilators, observation monitors, breathing machines, syringe pumps, and suction and dialysis machines [15]. Noise in ICUs has dramatically increased as a consequence of the greater availability of healthcare equipment; thus, the effect of noise on patients and staff has become a serious issue [16]. A large number of previous studies have focused on noise levels in ICU, neonatal ICU, and paediatric ICU wards [17-22] and have reported that noise levels exceeded the WHO guidelines for both daytime and night-time. For example, Delaney, *et al.* [17] reported that noise levels in an ICU exceeded WHO recommendations by 37%, with a mean sound level overnight of 54.89 dBA (SD = ±6.08).

However, most studies were conducted in high income countries with only very few studies being carried out in lower income countries. In particular, personal medical needs have been growing rapidly in China so there was a shortage of beds nationally. In many countries, single-bedded wards in ICUs have become more common due to the benefits of improving sleep, reducing noise, and providing privacy for patients and for family visits [23, 24]. In contrast, the majority of public hospitals in China have limited single-bedded wards (single patient side-rooms) in their ICUs; thus, patients are exposed to noise more frequently. Therefore, it is necessary to investigate noise levels in Chinese ICUs and compare them with those measured in other countries.

This study aimed, therefore, to explore noise levels and sources in ICUs in four Chinese hospitals during the pandemic. First, noise monitoring was conducted for 24 hours in single and multiple-bedded wards and nurse stations. A-weighted equivalent and maximum sound pressure levels (L_{Aeq} and L_{AFmax}) were computed for different durations (i.e. day time, evening, and night- time). Second, noise sources and the number of noise events were analysed. The sound exposed level (SEL) and maximum sound pressure levels (L_{AFmax}) of dominant sound sources were then calculated

2. Methodology

2.1. Sites

Acoustics measurements were carried out in ICUs at four Chinese hospitals between December 2020 and April 2021. As shown in Figure 1, all the hospitals were located in close proximity to major traffic roads. Floor plans and the types of rooms were different across the hospitals (see Figure 2) but all the rooms had an identical interior ceiling height of 2.8 m. For instance, there were 2-bedded, 5-bedded and 6-bedded rooms in Site A, while Site D had 1-bedded and 18-bedded rooms. The areas of the rooms and patients information are listed in Table 1. All the ICUs had two 12-hour shifts where the day shift began at 9 am and the night shift at 9 pm. The ICU nurses had two meetings, one in the morning (9 am) and one in the afternoon (3 pm) to receive a short briefing about patients.

Figure 1

Figure 2

Table 1

According to the Nurse's Daily Work Guideline during the COVID-19 pandemic, mechanical ventilation systems, such as high-efficiency particulate absorbing filters or ultraviolet germicidal irradiation units should have been installed in the ICUs. However, Site A and Site C did not have them so all the windows and doors were kept open for natural ventilation [3]. Even when risk levels had fallen, hospitals maintained a high level of precautionary measures. Protective clothing and goggles were not worn but face masks and disposable shoe covers were still mandatory inside the ICUs. In addition, all the ICUs had strictly controlled ventilation and family visits were not allowed during the research. This study was approved by the ethics committees of the local hospitals and the Central Ethics Committee of the University of Liverpool (approval number: 7984).

2.2 Measurement procedure

Noise measurements were undertaken over 24-hour in each ICU. Noise levels in the patients' rooms and nurse station were measured from one morning through to the next morning for 24 hours. Noise level was recorded using a half-inch free-field microphone (Nti Audio, MA220) attached to an audio and acoustic Analyzer (Nti Audio, XL2) connected to a power supply. The microphone was mounted on a tripod and positioned 0.5 m above the patient's head, 1.0 m above the floor level and as far away as possible from reflecting surfaces (e.g. walls). The noise levels were monitored continuously and all data were transferred to an external hard drive prior to the next recording period. Before the data collection, the entire measurement system was calibrated using an acoustic calibrator (Bruel &Kjaer, Type 4230).

2.3. Data analysis

From the 24-hour sound recordings, the A-weighted equivalent sound pressure level (L_{Aeq}) and A-weighted maximum sound pressure level with Fast time-weighting (L_{AFmax}) were calculated at one-minute intervals. The recordings were analysed using dB Trait software from 01dB-metravib. In the present study, the 24-hour period is divided into the day (07:00–19:00), evening (19:00–23:00), and night (23:00–07:00); therefore, noise levels were calculated for three different periods as well as for 24 hours. An attempt to subjectively determine the noise sources through observation were then recorded by the research team during the measurements [25]. Noise levels of individual sound sources were then analysed in terms of sound exposure level (SEL) which accounts for duration of exposure.

3. Results

3.1 Noise levels

Logarithmic averages of $L_{\mathrm{Aeq,1min}}$ and L_{AFmax} for the complete 24-hour period - day, evening, and night - are listed in Table 2. It was found that all the A-weighted equivalent sound pressure levels for a 24-hour period measured at four ICUs exceeded the WHO's guide levels (35 dBA of L_{Aeq} in areas where patients are treated or observed, and a corresponding L_{Amax} of 40 dBA) varying from 51.1 dBA to 60.3 dBA, with a highest maximum noise level of 104.2 dBA. The single-bedded rooms were the quietest and the 18-bedded room was the noisiest in terms of overall noise levels for a 24-hour period. As shown in Table 2, noise levels during the daytime were greatest, followed by the evening and then the night-time, except single-bedded rooms in Sites B and D. In addition, the highest maximum noise levels exceeded 87 dBA in every room, which appeared to come from talking inside and activities (e.g., noise from cleaning equipment and cutlery sound). The percentages of $L_{\mathrm{Aeq,1min}}$ and L_{AFmax} for the full 24-hour period of day, evening, and night are found in Supplementary Table S2.

Table 2

Noise levels measured over the 24-hour period were similar across the rooms; thus, only the results of a single-bedded ward at Site B are plotted as a function of time in Figure 3 as an example. The black and grey lines represent $L_{\mathrm{Aeq,1min}}$ and L_{AFmax}, respectively. Most quiet periods were at night-time, which increased on the following day. The quiet periods changed in different wards, but all the patient wards had a quiet period between 10 pm and 4 am. Specifically, the average night-time noise levels at Site B were about 15-22 dB quieter than the max noise level of the day. In contrast, noise levels in single bedded wards at Site B fluctuated considerably, exceeding 76 dBA due to talking from staff, whereas the noise level decreased to about 54.7 dBA in the absence of talking. It was observed that maximum noise levels in single-bedded rooms were greater than 70 dBA even at night.

Figure 3

3.2 Noise sources

The numbers of events of dominant noise sources were analysed for the single-bedded and six-bedded rooms and the results are listed in Table 3. During the observations, only the noise exceeding 40 dBA was recorded as a noise event [26]. The numbers of noise events were different across sites even in the same sized patient rooms. Overall, human interactions occurred more in multi-bedded wards single-bedded wards. For both single and six-bedded rooms, more than 50% of noise events occurred during the daytime but more noise events occurred during the night-time than in the evening in most rooms.

Table 3

<u>Voices</u>

Only the six-bedded rooms at Site A had significantly more noise events at night than in the daytime. In particular, talking and voices at night occurred significantly more than in the daytime. However, it was noted that nurses were trying to speak as quietly as possible, leading to lower voice noises ($L_{\mathrm{Aeq,1min}}$) at night than in the daytime. It was also found that approximately 20% of the noise events during the daytime consisted of talking/voices emanating from patients and staff. In the single-bedded rooms at Site B, door-closing was the most frequently heard noise source, followed by footsteps, talking/voices, and equipment alarms. On the other hand, talking/voices was the most dominant noise source in the single-bedded ward at Site D, followed by general activities (e.g., cleaning), footsteps and talking from outside the room.

<u>Patient factors</u>

The number of equipment alarm (high-risk) events at Site B was more than twice that of Site D. This may have been due to the different pathologies or severities of disease, suggesting that the patients' health condition had a direct impact on the noise events. Site B had a total of 1,222 noise events, versus the 783 noise events at Site D. Dominant noise events in the six-bedded rooms were different across the sites. Talking/voices was much more dominant than other sources at Site A, whereas footsteps, door-closing, and talking/voices occurred with similar frequency at Site B. The numbers of footsteps and door-closing events at Site B were significantly greater than those at Site A. This could be explained by two hypotheses. First, at Site A, without a mechanical ventilation system, windows and doors were kept open so there were no door-closing events. Second, Sites A and B had quite different staffing models [27]. Site A is a semi-closed ICU that is managed by ICU physicians and specialists, while Site B is a closed ICU which means that the patients are managed by full-time ICU staff [27]. The closed ICU (Site B) required far more healthcare staff than other ICUs. The higher intensity of the work, greater admission and staff handover events at Site B resulted in more talking, walking and door-closing than at Site A. In addition, there were more than 100 throat-clearing events by patients at Site B due to a single patient with pneumonia.

Figure 4 shows boxplots illustrating the SEL from major noise sources: (1) talking/voices inside and outside, (2) patient alarms inside and outside, (3) footsteps, (4) door-closing, and (5) general activities. Among the major noise sources, talking inside had the highest median value at all sites and patients' rooms, followed by alarms. The median SELs of talking from the outside of rooms were much lower than of talking inside. The median SELs of footsteps showed a large variation, from 52.7 dBA to 77.4 dBA, across the sites and rooms. Even though both Sites B and D had automatic doors, the median SELs of a door-closing varied from 59.7 dBA to 76 dBA because some of the doors were improperly installed or in disrepair (e.g., the door swayed unsteadily when closing).

Figure 4

Boxplots illustrating the maximum noise levels (L_{AFmax}) from major noise sources are shown in Figure 5. The talking inside still had the highest median value at all sites and patients' rooms, followed by alarms and activities. Similar to the SEL, the median L_{AFmax} level of talking outside of rooms was lower than talking inside. The L_{AFmax} of footsteps in a single-bedded ward at Site D varied from 50.7 dBA to 79.8 dBA, whereas Site B showed a much smaller L_{AFmax}, ranging from 50.9 dBA to 61.8

dBA. The median level of alarms at different sites varied from 72.3 dBA to 75.4 dBA. But, overall, talking inside and general activities showed the largest ranges of L_{AFmax} compared to other sources, implying that the SPLs varied widely varied according to the medical situations within the rooms.

Figure 5

4. Discussion

4.1. Noise levels and sound sources

The World Health Organisation (WHO) Guidelines for Community Noise includes advice on noise levels in hospitals and suggests that the noise level in hospitals should not exceed 35 dBA (L_{Aeq}) in areas where patients are treated or observed, with a corresponding L_{Amax} of 40 dBA [26]. The present study shows all measured noise levels in the ICU patients' rooms in four Chinese hospitals exceeded the WHO guideline by at least 20 dB during the pandemic. The L_{Aeq} for 24 hours in different wards varied from 51.1 dBA to 60.3 dBA and the highest maximum noise level reached 104.2 dBA. This result is consistent with previous findings in the UK [28], in which L_{Aeq} values measured at five different ICUs were above 45 dBA at all times and varied between 52 dBA and 59 dBA for more than 50% of the measurement times. Similarly, sound levels exceeded the WHO guideline during all day periods (daytime 56.1 ± 5.5, night-time 55.1 ± 5.7 and evening 53.6 ± 5.6) in the Netherlands [29], while, in the U.S., the mean noise levels in hospitals were greater than 42 dBA even at night and the noise levels in ICUs reached 90 dBA [30]. Furthermore, peaks of the noise levels were above 60 dB even in intensive care sites in Brazil [31]. This indicates that the noise levels demonstrated in Chinese hospitals are similar to those in numerous other countries, even though the current study was conducted during the pandemic. In addition, this study showed a good agreement with previous studies on normal wards [32-36], in which noise levels in hospital wards also exceeded the WHO guidelines.

It was found that the noise levels in the single-bedded wards were lower than those in the multi-bedded wards, as demonstrated in a previous ICU study [33]. However, this is in contrast with findings in general wards suggesting single-bedded rooms produced greater noise levels than multi-bedded rooms[34]. This may be because patients in the aforementioned study [34] were predominantly placed in single-bed rooms if they had a diagnosis of dementia and pneumonia and were prone to more coughing and shouting. Jerlehag, *et al.* [34] previously demonstrated that six-bedded wards were noisier than four-bedded rooms, suggesting that the noise levels increase with an increase in patients.

This study also examined the noise levels during a 24-hour period: daytime, evening, and nighttime. In general, the noise levels at night were quieter than those in the daytime and evening, except for the single-bedded rooms at Sites B and D. However more noise events occurred at night. This was possibly because noise levels produced by the same source were quieter at night than during the daytime and evening. For example, Figure 6 shows the SEL of talking/voices (inside) in six-bedded wards across the daytime, evening and night-time. The median value of the SEL at night at Site A was 73.6 dBA, while it increased to 78.7 dBA in the daytime. Similarly, at Site B, the median value at night was at its lowest. This implies that the staff in the ICU tended to speak more quietly and for less time than in other time periods to avoid sleep disturbance of the patients at night. However, staff behaviours at night could have been different across the ICUs because of aforementioned working environments and stress levels. Thus, a further study would be useful to investigate qualitatively (potentially ethnographically) how ICU staff behave to minimise noise events and levels at night and how the working environment and stress levels influence their behaviours.

Figure 6

The Nurse's Daily Work Guideline during COVID-19 pandemic [11] affected the working environment in ICUs, requiring staff to wear plastic shoe covers and face masks, keep at least one metre apart during communication, and open windows for natural ventilation. This guideline also affected the acoustic environments in terms of noise sources and their noise levels. In the present study, the most dominant noise sources were talking/voices inside the ICU, door-closing, footsteps, and general activities. All these sources were frequently observed in ICUs, even before the pandemic;

however, footsteps were not previously mentioned as a dominant source. For example, MacKenzie and Galbrun [35] reported that talking and door-closing were dominant sources, while Darbyshire, *et al.* [36] discovered that a significant proportion of loud sounds may originate from equipment alarms which were sited at the bedside, followed by talking inside and activities. Also, Scquizzato, *et al.* [37] found that complaints related to undesirable noises were alarms, parametric monitors, and noise caused by the companions of other patients and the multidisciplinary team. Footstep noise in the ICUs became much noisier during the pandemic due to the staff's plastic shoe covers. In the current study, the average value of L_{Aeq} for footsteps across all the sites and rooms was 55.4 dBA (range: 47.2 - 63.6 dBA). According to Shimoda, *et al.* [38], the average noise levels produced by nurses' footsteps when wearing sneakers and sandals at a walking speed of 1 m/sec were 46.0 dBA (range: 42.3 - 49.3 dBA) and 48.1 dBA (range: 43.5 - 54.0 dBA), respectively. Their research also discussed the noise levels of nurses' footsteps (i.e. nurse shoes) at different walking speeds [38]. They highlighted that walking speed did not significantly affect the noise levels of footsteps. As shown in Figure 7, the durations of footstep noise also varied across the rooms. The six-bedded room at Site B had the highest median value (22 s), followed by a single-bedded room at Site D and a six-bedded room at Site A. This result suggests that the room size is not the only factor affecting the duration of footstep sounds. During the pandemic, several new machines were introduced to the ICUs. One of them was an ozone bed unit disinfection machine which was adopted to achieve efficient elimination of bacteria and viruses on bedsheets by vacuuming, filling with ozone, and disinfecting the patient's beds. Sites A, B, and D also used the bed sterilizer (LAOKEN), which was employed one hour after a patient's discharge and produced a noise level of 47.6dBA. However, the noise events from these machines were rare during the noise measurements.

Figure 7

The current study revealed that door-closing was one of the major noise sources in ICUs in China. The number of door-closing events depended on the number of times that the ICU staff came in and out of the room. Door-closing events were anticipated to correlate with the patient's condition. For instance, the staff come in and out more frequently for patients with more severe conditions. However, the number of door-closing events in the single-bedded ward at Site B was twice that of Site D, even though the patients' status at both sites were similar. This may be because the two sites had different policies and guidelines for dealing with patients. For further analysis, we monitored the staff's behaviours after opening/closing doors for one minute. There was no communication with patients or medical activities for 67% of door openings at Site B, and the staff came to the single-bedded ward only to check the patient's status. Also, 24.4% of the door openings were followed by another door opening/closing event within one minute (i.e. checking another patient). In contrast, the staff at Site D checked the patient less frequently than those at Site B and their visits were mostly associated with medical activities.

4.2 Effect of ICU models on noise sources and levels

Currently, there are three ICU management models in China: closed, semi-closed (joint care), and open [27]. The closed model means that patients are managed full-time by ICU staff. On the other hand, the open model indicates the ICU is only responsible for monitoring [39] and all the units in these hospitals share a single ICU. Sites B and D had a closed management model and there were enough medical staff to deal with different diseases. In contrast, Sites C and A adopted the semi-closed management model due to staff shortages and economic problems. Sites B and D (closed ICUs) experienced more noise events, related to talking/voices (inside), footsteps, door-closing, and general activities compared to Sites A and C (semi-closed ICUs). Also, the noise levels at Sites B and D were higher than those at Sites C and A with the same types of patient wards even after account for patient factors.

4.3 Effect of patients' illness on noise sources and levels

In the present study, throat-clearing (Table 3) was commonly found in patients who were diagnosed with pneumonia and acute respiratory distress syndrome in both single and six-bedded wards and this produced many noise events. Similarly, Jerlehag, *et al.* [34] reported noise events from coughing/throat-clearing from patients with pneumonia in geriatric wards.

There were multi-parameter patient monitors with an alarm system in all the rooms to record the health information of patients (e.g. vital signs). Monitors and alarm types varies across sites and wards (see Supplementary Table S3). The monitors had two types of alarms for low and high risks. The high-risk alarm was one of the dominant noise sources across the four sites. There were a total of 358 high-risk alarms inside patients' rooms. In particular, the single-bedded ward at Site B recorded 151 high-risk alarm events because of patient deterioration. The median values of SEL for high-risk alarms were different across the sites, varying from 61.9 dBA to 69.1 dBA, whereas the maximum levels were quite similar, ranging from 75.6 dBA to 78.3 dBA.

4.4 Limitations and suggestions for further research

There are several limitations to this study. Firstly, room acoustic parameters, such as reverberation time, were not collected. The ceiling heights of the sites were the same but the finishing materials, which might affect room acoustic conditions, were slightly different. For instance, Site B had an acoustic ceiling with high absorption coefficients, whereas Site A had a gypsum board ceiling. The noise levels from the same or similar sources could be different due to the finishing materials; thus, additional measurements could be conducted after the pandemic. Secondly, the current research was limited to 24 hours of recording at each ward as a case study, so it was affected by specific patients and environments. Also, staff may have changed their behaviours as a result of the study (Hawthorne effect). This could be mitigated by an adaptation period for the staff to familiarise themselves with the equipment. Thus, longer preparation and monitoring (e.g., a full week) could produce more robust data and may be less susceptible to short-term events and patients' illness types [35]. Thirdly, the present study showed greater noise levels in multi-bedded wards than in single-bedded wards. But it was not possible to examine how different numbers of patients and staff affected the noise levels. In the future, it could be useful to measure population density to estimate noise levels from different numbers of people [40]. Additionally, as with other noise studies in this field, outside of the headline results about intensity of noise and its sources, the results demonstrated here are difficult to generalise to other ICUs with discrete patient cohorts, architecture and staffing models. Lastly, this study focused on the physical acoustic environments rather than how people experience and perceive noise in the ICUs. So, it is necessary to understand how ICU staff perceive noise sources and acoustic environments during the pandemic. This may be achieved through a questionnaire survey, focus groups and interviews.

5. Conclusion

In the present study, noise monitoring was performed over 24 hours in the ICU patients' rooms at four Chinese hospitals during the COVID-19 pandemic. The measurements were recorded in different-sized wards from a single-bedded room to an 18-bedded ward. The average and maximum noise levels over 24 hours (day, evening, and night) were analysed and noise sources were identified. Noise levels in all the patient rooms were all more than the WHO guidelines during both the daytime and night-time. This result in China is consistent with previous studies that were conducted in high income countries before the pandemic. The single-bedded wards were quieter than multi-bedded wards across all the sites. Also, noise levels at night-time were the lowest, followed by evening and daytime in most rooms. Talking/voices inside the wards was most frequently heard, followed by footsteps, door-closing, and general activities. The pandemic control guidelines, such as the use of mechanical ventilation and disinfection control, had little impact on noise events and levels in the ICUs; however, wearing disposable shoe covers made footsteps noisier, so it became one of the dominant noise sources during the pandemic. Among the dominant noise sources, the median values of SEL and maximum noise levels for talking/voices were the greatest, followed by the high-risk alarms. It was found that more noise generated by talking/voices inside the wards, footsteps, door closing, and general activities was recorded in the closed management ICUs (Sites B and D) than in the semi-closed management ICUs (Sites A and C). In the future, longitudinal noise monitoring is required and voice use/strain or disorders could be investigated to explore the impacts of PPE on verbal communication in ICUs.

6. References

1. Tong H, Aletta F, Mitchell A, Oberman T, Kang J, (2021) Increases in noise complaints during the COVID-19 lockdown in Spring 2020: A case study in Greater London, UK. Science of The Total Environment 785: 147213
2. Lee PJ, Jeong JH, (2021) Attitudes towards outdoor and neighbour noise during the COVID-19 lockdown: A case study in London. Sustainable Cities and Society 67: 102768
3. Hui W, (2020) Hospital during the COVID-19 pandemic: Daily work protection points for frontline nurses (in Chinese). Nursing of Integrated Traditional Chinese and Western Medicine 6: 177
4. Hampton T, Crunkhorn R, Lowe N, Bhat J, Hogg E, Afifi W, De S, Street I, Sharma R, Krishnan M, (2020) The negative impact of wearing personal protective equipment on communication during coronavirus disease 2019. The Journal of Laryngology & Otology 134: 577-581
5. Jeong J, Kim M, Kim Y, (2020) Changes on Speech Transmission Characteristics by Types of Mask. Audiology and Speech Research 16: 295-304
6. Rosner E, (2020) Adverse effects of prolonged mask use among healthcare professionals during COVID-19. J Infect Dis Epidemiol 6: 130
7. Geiger JT, Hofmann M, Schuller B, Rigoll G (2013) Gait-based person identification by spectral, cepstral and energy-related audio features. In: Editor (ed)^(eds) Book Gait-based person identification by spectral, cepstral and energy-related audio features. IEEE, City, pp. 458-462
8. Loupa G, Katikaridis A, Karali D, Rapsomanikis S, (2019) Mapping the noise in a Greek general hospital. Science of The Total Environment 646: 923-929
9. Montes-González D, Barrigón-Morillas JM, Gómez Escobar V, Vílchez-Gómez R, Rey-Gozalo G, Atanasio-Moraga P, Méndez-Sierra JA, (2019) Environmental noise around hospital areas: A case study. Environments 6: 41
10. Loupa G, (2020) Influence of noise on patient recovery. Current Pollution Reports 6: 1-7
11. Hsu T, Ryherd E, Waye KP, Ackerman J, (2012) Noise pollution in hospitals: impact on patients. JCOM 19: 301-309
12. de Lima Andrade E, da Cunha e Silva DC, de Lima EA, de Oliveira RA, Zannin PHT, Martins ACG, (2021) Environmental noise in hospitals: a systematic review. Environmental Science and Pollution Research 28: 19629-19642
13. Jeong C-H, Jakobsen HC, (2021) Influence of architectural layouts on noise levels in Danish emergency departments. Journal of Building Engineering 42: 102449
14. Fredriksson S, Hammar O, Torén K, Tenenbaum A, Waye KP, (2015) The effect of occupational noise exposure on tinnitus and sound-induced auditory fatigue among obstetrics personnel: a cross-sectional study. BMJ open 5: e005793
15. Konkani A, Oakley B, Penprase B, (2014) Reducing hospital ICU noise: a behavior-based approach. Journal of healthcare engineering 5: 229-246
16. Konkani A, Oakley B, (2012) Noise in hospital intensive care units—a critical review of a critical topic. Journal of critical care 27: 522. e521-522. e529
17. Delaney L, Parke J, Robinson R, Da Fonte N, Lopez V, (2014) What hath night to do with sleep; noise levels in ICU—Preliminary findings. Australian Critical Care 27: 52
18. Andrade-Méndez B, Arias-Torres D, Gómez-Tovar L, (2020) Alarm fatigue in the intensive care unit: Relevance and response time. Enfermería Intensiva (English ed) 31: 147-153
19. Bani Younis M, Hayajneh F, Alshraideh JA, (2021) Effect of noise and light levels on sleep of intensive care unit patients. Nursing in Critical Care 26: 73-78
20. Darbyshire JL (2016) Excessive noise in intensive care units. In: Editor (ed)^(eds) Book Excessive noise in intensive care units. British Medical Journal Publishing Group, City, pp.
21. Plangsangmas V, Leeudomwong S, Kongthaworn P, (2012) Sound pressure level in an infant incubator. Mapan 27: 199-203
22. Baker CF, (1992) Discomfort to environmental noise: Heart rate responses of SICU patients. Critical Care Nursing Quarterly 15: 75
23. Kesecioglu J, (2015) Improvingthe patient’s environment: The ideal intensive care unit. Réanimation 24: S341-S343
24. Caruso P, Guardian L, Tiengo T, Dos Santos LS, Junior PM, (2014) ICU architectural design affects the delirium prevalence: a comparison between single-bed and multibed rooms. Critical Care Medicine 42: 2204-2210

25. Park SH, Lee PJ, Lee BK, (2017) Levels and sources of neighbour noise in heavyweight residential buildings in Korea. Applied Acoustics 120: 148-157
26. Berglund B, Lindvall T, Schwela DH, Organization WH, (1999) Guidelines for community noise
27. Medicine CSoCC, Association CM, (2006) Guidelines for management of acute lung injury/acute respiratory distress syndrome: an evidence-based update by the Chinese Society of Critical Care Medicine (2006). Zhongguo wei zhong bing ji jiu yi xue= Chinese critical care medicine= Zhongguo weizhongbing jijiuyixue 18: 706-710
28. Darbyshire JL, Young JD, (2013) An investigation of sound levels on intensive care units with reference to the WHO guidelines. Critical Care 17: 1-8
29. Vreman J, van Loon LM, van den Biggelaar W, van der Hoeven JG, Lemson J, van den Boogaard M, (2020) Contribution of alarm noise to average sound pressure levels in the ICU: An observational cross-sectional study. Intensive and Critical Care Nursing 61: 102901
30. Busch-Vishniac IJ, West JE, Barnhill C, Hunter T, Orellana D, Chivukula R, (2005) Noise levels in Johns Hopkins hospital. The Journal of the Acoustical Society of America 118: 3629-3645
31. Cavalheiro AM, Pires CL, Sarmento FA, R Ferraz LJ, Lucino NM, (2015) Reduce and optimize critical care unit noise. Critical Care 19: 1-24
32. Aitken R, (1982) Quantitative noise analysis in a modern hospital. Archives of Environmental Health: An International Journal 37: 361-364
33. Xie H, Kang J, (2012) The acoustic environment of intensive care wards based on long period nocturnal measurements. Noise and Health 14: 230
34. Jerlehag C, Lee PJ, Park SH, Jones T, Carroll N, (2018) Acoustic environments of patient room in a typical geriatric ward. Applied Acoustics 133: 186-193
35. MacKenzie D, Galbrun L, (2007) Noise levels and noise sources in acute care hospital wards. Building Services Engineering Research and Technology 28: 117-131
36. Darbyshire JL, Müller-Trapet M, Cheer J, Fazi F, Young J, (2019) Mapping sources of noise in an intensive care unit. Anaesthesia 74: 1018-1025
37. Scquizzato T, Gazzato A, Landoni G, Zangrillo A, (2020) Assessment of noise levels in the intensive care unit using Apple Watch. Critical Care 24: 1-3
38. Shimoda T, Nishijima R, Yoshimura S, (2020) Examining Modifications of the Noise Generated by Nurses' Footsteps and the Use of Pass-By Objects: A Pilot Study. Open Journal of Nursing 10: 184-193
39. Liu C, (2017) Management mode of PICU: which is better. Chinese Pediatric Emergency Medicine: 801-804
40. Chao H, Cao Y, Zhang J, Xia F, Zhou Y, Shan H (2018) Population density-based hospital recommendation with mobile lbs big data. In: Editor (ed)^(eds) Book Population density-based hospital recommendation with mobile lbs big data. IEEE, City, pp. 37-44

Table 1. Areas of wards (m^2) and patients' information in each ICU.

Wards	Site A	Site B	Site C	Site D	Diagnosis of patients
Single-bedded		13.4*		10.9	Renal dysfunction
2-bedded	28.9	47.5			Postoperative rehabilitation and haemophilia
5-bedded	53.2				Renal dysfunction and myocardial infarction
6-bedded	58.8	55.2*			Gastrointestinal bleeding, pneumonia, and coronary heart disease
10-bedded		55.2	112.9		Spinal cord injury, renal dysfunction acute respiratory distress syndrome, high paraplegia, renal insufficiency, and gastric cancer
18-bedded				204.9	Colon cancer, renal dysfunction, uremia haemophilia, and cholecystitis
Nurse station	9.4	14.1	12.1	30.5	

*Average of two wards.

Table 2. Logarithmic averages of A-weighted equivalent ($L_{Aeq,1min}$) and maximum sound pressure levels (L_{AFmax}). The highest maximum noise level measured in each space is also presented. Standard deviations in values are in Supplementary Table S1 in appendix.

	Sites	Number of patients	$L_{Aeq,1min}$ [dBA]				L_{AFmax} [dBA]				
			Overall 24-h	Day 07.00–19.00	Evening 19.00–23.00	Night 23.00–07.00	Overall 24-h	Day 07.00–19.00	Evening 19.00–23.00	Night 23.00–07.00	Maximum value
Single-bedded	B	1	54.1	55.1	52.1	53.7	67.1	68.4	65.1	66.5	95.2
	D	1	51.1	54.3	49.2	51.1	63.6	64.5	58.1	62.5	91.8
2-bedded	A	2	54.5	55.3	54.2	53.3	68.0	66.2	67.4	70.4	91.2
	B	2	56.5	58.9*	55.5	54.1	69.9	72.7	69.1	67.0	93.9
5-bedded	A	3	54.2	55.1	54.5	52.3	63.6	67.0	66.5	58.1	89.9
6-bedded	A	3	54.5	56.2	54.3	52.8	64.9	67.8	64.6	61.6	89.9
	B	4	56.7	57.8	56.0	55.2	68.2	70.1	67.3	66.0	87.6
10-bedded*	B	7	57.9	60.2	57.3	55.3	70.7	74.3	70.5	66.4	92.9
	C	8	57.5	59.6	55.7	55.6	70.0	72.8	69.4	66.9	92.7
18-bedded*	D	15	60.3	62.7	60.8	54.2	71.6	73.9	71.3	68.5	104.2
Nurse station	A		55.1	55.6	56.5	53.9	66.9	69.5	70.9	62.0	92.3
	B		58.8	60.8	59.7	56.0	71.2	73.5	72.0	68.1	92.7
	C		58.6	59.7	56.3	58.3	70.1	71.5	67.5	69.7	91.7
	D		59.2	62.7	60.8	54.2	71.9	74.9	73.6	67.4	88.6

*Averaged values for two locations

Table 3. Number of noise events for 24-hour across the wards. Asterisk indicates the sources which last longer than one minute. a) single-bedded wards and b) six-bedded wards

a) Single-bedded wards

Noise sources	Site B				Site D			
	Day	Evening	Night	Total	Day	Evening	Night	Total
Talking/voices (inside)*	110	25	34	169	49	52	74	175
Footsteps	109	32	47	188	57	18	23	98
Door-closing	135	50	73	258	55	10	47	112
General activities	75	20	38	133	29	25	8	62
High-risk alarm (inside)*	94	36	21	151	23	16	34	73
High-risk alarm (outside)*	64	13	15	92	50	9	13	72
Talking/voices (outside)*	46	9	12	67	63	4	18	85
Clearing throat (patients)	27	10	18	55	20	7	20	47
Noise of clean	56	13	15	84	35	5	12	52
Wheel	10	4	5	19	6	0	1	7
Phone ringing	3	1	2	6	0	0	0	0
Printer	0	0	0	0	0	0	0	0
Total	729	213	280	1222	387	146	250	783

b) Six-bedded wards

Noise sources	Site A				Site B			
	Day	Evening	Night	Total	Day	Evening	Night	Total
Talking/voices (inside)*	86	51	139	276	194	85	60	339
Footsteps	9	10	56	75	195	87	84	366
Door-closing	0	0	0	0	120	52	70	365
General activities	16	21	82	198	69	18	41	184
High-risk alarm(inside)*	37	18	38	93	26	4	11	41
High-risk alarm (outside)*	32	10	8	50	35	5	7	47
Talking/voice (outside)*	17	34	77	128	36	8	12	56
Clearing throat (patients)	13	16	42	71	57	15	41	113
Noise of clean	10	20	31	61	25	7	20	52
Wheel	11	6	27	44	3	2	2	7
Phone ringing	2	2	4	8	0	0	0	0
Printer	0	0	0	0	0	0	0	0
Total	233	188	504	1004	760	283	348	1570

Figure Captions

Figure 1. Site plans of four sites: a) Site A, b) Site B, c) Site C, and d) Site D.
Figure 2. Floor plans of four sites: a) Site A, b) Site B, c) Site C, and d) Site D. Brown circles represent the sound level meter locations and arrows indicate transportation paths with and without patients.
Figure 3. Noise levels at Site B for a 24 hours period. Black lines represent $L_{Aeq,1min}$ and grey lines represnt L_{AFmax}
Figure 4. Boxplots of sound exposure level (SEL) for dominant noise sources.
Figure 5. Boxplots of A-weighted maximum sound pressure levels (L_{AFmax}) for dominant noise sources.
Figure 6. Boxplots of sound exposure level (SEL) for talking/voices (inside) in six-bedded wards across daytime, evening, and nighttime.
Figure 7. Characteristics of footsteps at four sites: duration, SEL, and L_{Aeq}.