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Sound Power Levels of Typical Medical Equipment in Intensive Care Units

Hui Xie^{1,2)}, Jian Kang^{1,3)}, Gary H. Mills²⁾

¹⁾ School of Architecture, University of Sheffield, Western Bank, Sheffield S10 2TN, United Kingdom.
j.kang@sheffield.ac.uk

²⁾ Sheffield Teaching Hospitals NHS Foundations Trust, Royal Hallamshire Hospital, Glossop Road, Sheffield S10 2JF, United Kingdom

³⁾ School of Architecture, Harbin Institute of Technology, Harbin 150001, China

Summary

This study systematically determined the sound power levels for the alarms of single medical equipment in Intensive Care Units (ICU), and investigated the sound environment with multiple pieces of equipment to reflect various healthcare scenarios. The measurements were made for six types of potentially noisy equipment according to ISO 3743-1, in a typical single-bed ward. It has been shown that the majority of alarms radiated from ICU equipment are dominated by middle and high frequency sounds, particularly the latter. The humidifier generates the highest sound power level, followed by the ventilator and the pump's infusion alarm, and the equipment volume setting is only effective for the monitor alarm. The length of all alarm signals is normally around 1 second, while the time interval is more varied. When multiple pieces of equipment are alarming simultaneously, the equivalent sound pressure levels of three representative scenarios considerably exceed the WHO guideline values. The instantaneous peak sound level could be more than 80dBA in the worst acoustic scenario. It is expected that such a basic equipment acoustic database would be relevant to a range of acoustic research and practice.

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1. Introduction

The importance of the acoustic environment in hospitals has been recognised worldwide, for patient recovery and for staff working efficiency. The World Health Organization (WHO) recommended that noise levels inside hospital wards should not exceed 30 dB LAeq and 40 dB LAmx during the night time [1]. Unfortunately, most recent studies reveal that the noise levels are always above the guideline values [2, 3, 4, 5, 6, 7]. In Intensive Care Units (ICU) in particular, the noise level may range from 50 to 75 dBA, with the highest night peak level even reaching 103 dBA [2, 3, 6, 8].

An ICU, also called Critical Care Unit or Intensive Therapy Department, is a special ward designed to provide intensive care treatment and monitoring for critically ill or unstable patients. Intensive care may be broadly defined as “a service for patients with potentially recoverable conditions, who can benefit from more detailed observation and invasive treatment than can be provided safely in an ordinary ward or high dependency area” [9]. It is usually reserved for patients with threatened or established organ failure, which may have arisen as a result of complication

of an acute illness, trauma, or as a predictable phase in a planned treatment programme [10].

Representing the highest level of continuous and concentrated patient care and treatment, an ICU is rather different from other wards in hospitals. There is a range of machines to assist the patient care and to provide organ support on the ICU, including mechanical ventilation or kidney support. When ICU patients are acutely ill, they are usually bedbound and will be connected to monitoring or life support systems [11]. These types of equipment have been identified as some of the most annoying ICU noise sources in the previous critical review and subjective interview studies [7, 8]. The specialised equipment in the ICU generates a variety of bleeps, alarms, and other sounds, which may occur simultaneously.

Although there is a wide selection of medical equipment available on the market, all medical equipment and devices which are intended to be used in specific ICU wards must comply with the current best practice guidance, particularly those relating to health and safety [12, 13, 14, 15]. Since unnecessary variation in the provision of health care tends to increase patient harm [12], the standardisation of common types of equipment is recommended in order to achieve a number of strong potential advantages, including ease of staff training and equipment availability, reduced maintenance costs, and lessened possible confusion of operation [13]. So it is expected that the results of this paper

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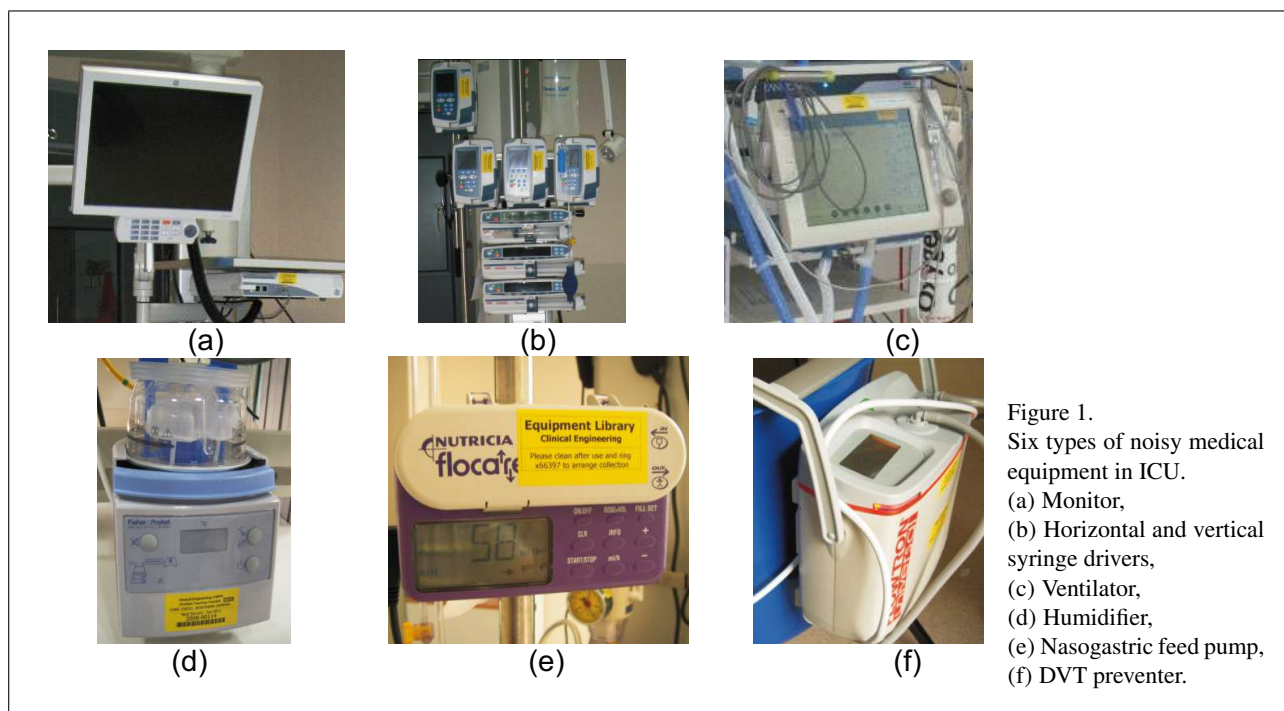


Figure 1.
Six types of noisy medical equipment in ICU.
(a) Monitor,
(b) Horizontal and vertical syringe drivers,
(c) Ventilator,
(d) Humidifier,
(e) Nasogastric feed pump,
(f) DVT preventer.

would be applicable to a number of medical equipment in the UK's NHS hospitals.

However, there is little information on the sound power level of typical medical equipment in ICU and also, the contribution from multiple and dynamic equipment to the whole acoustic environment has not been examined.

This study therefore aims to systematically determine the sound power level for single pieces of medical equipment in ICU, and investigate the sound environment with multiple pieces of equipment to reflect various health-care scenarios. Such a basic equipment acoustic database would be relevant to a range of acoustic research and practice, such as agent-based acoustic modelling, which is a powerful approach to simulate the complicated hospital sound environment and its interacting noise sources [16].

2. Methods

2.1. Typical medical equipment

Based on the intensive on-site observations [17] and suggestions given by the ICU consultants, six main types of medical equipment were chosen for the sound power measurement, including monitor, syringe driver or pump, ventilator, humidifier, nasogastric feed pump, and the regularly inflating pressure boots for Deep Vein Thrombosis prevention (abbreviated as DVT preventer below), as shown in Figure 1. Observations show that the most frequently used noisy pieces of equipment in ICU are monitors, ventilators and syringe drivers [17]. Their alarms are more likely to be triggered and thus, they play a greater role in the ICU sound environment than the other equipment. Two or even more operating conditions have to be considered for certain equipment in terms of the level and

type of alarm emitted. Brief explanations of the above ICU machines are given below.

During the patient stay in an ICU, different types of sensing device may be attached to various parts of a patient's body, and linked to bedside monitors. Several commonly monitored functions include heart rate, blood pressure, respiratory rate, oxygen saturation, and temperature. There are three types of audible alarm from the sensitive monitoring equipment, namely advisory, warning and crisis with increasing level of urgency. For example, if no heart beat or a very abnormal heart rhythm is detected by the monitor, the crisis alarm will go off repetitively. The default volume for the alarms is normally set to 70% by the hospital staff. Therefore, in this study, apart from the three types of alarms, the default volume of 70%, the maximum volume of 100% and the regulated minimum volume of 50% were also taken into account as multiple operating conditions for monitors.

Constant supplies of small amounts of intravenous medications or fluids are delivered directly into the patient's bloodstream by the sophisticated syringe drivers or pumps. A bag or syringe filled with medications, fluids or essential nutrients are connected to the patients via specialised IV lines or drips. The pumps can be further classified as vertical pumps and horizontal pumps from their appearances, as can be seen in Figure 1b. The syringe drivers have two types of alarms to alert staff about the delivery of medications or fluids, namely hold-on alarm and infusion alarm. The first alarm is simply due to a long idle time, whereas the second is related to problems preventing the medication supply, such as the presence of air bubbles, tube blockage or low levels of fluid remaining. Similar to the monitor, the volume of the syringe driver's alarm can be easily adjusted, but the default volume is rarely changed.

Unlike the monitor and pump, only one operating situation was specified for ventilator, humidifier, nasogastric feed pump and DVT preventer. The ventilator is an artificial breathing machine. It helps move oxygen-enriched air in and out of patients' lungs, when the sick patients cannot breathe on their own due to the failed lungs [18]. This is a complex machine, with alarms indicating whether or not suitable pressures, flows or volumes of air and oxygen are being delivered to the patient.

The humidifier has the ability to provide the right amount of moisture to the airway and the lungs. It delivers humidification by increasing water temperature in a system designed to improve patient comfort by eliminating the dryness of the compressed air. However, the risk is that the humidified air could become too hot or too cold, which may lead to alarms.

The nasogastric feed pump controls and measures the external feed being administered to patients through the nasogastric or nasojejunal tube, and it may alarm if any interruption in the feeding is signalled.

The DVT preventer offers non-invasive mechanical compression for the prophylaxis of DVT. This equipment is important as the ICU patients are relatively immobile and may have an abnormal tendency to form blood clots. Therefore it is important that the calves are massaged intermittently to promote flow through the leg veins. Its alarms are important to indicate that the normal pressures are being reached.

2.2. Measurement standard and method

The International Organization for Standardization published ISO 3740 series to describe several methods for determining the sound power levels of noise sources. Restricted by the mobility of medical equipment, all the measurements have to be made in the actual ICU ward. As examined in a previous study, an ICU single-bed ward without acoustic treatment can be approximately regarded as a diffuse sound field [19], so that it would be more appropriate to use the method for determining sound power in a diffuse field, rather than the free field method. Therefore, in this study the comparison engineering method, ISO 3743-1, was selected for the sound power measurement of medical equipment noise sources with a small size [20].

The test room was a single-bed ICU ward in the Critical Care Department, Northern General Hospital in Sheffield, UK. The room was fairly reverberant, with reverberation time (RT) of 1.44 s at 250 Hz, 2.31 s at 1 kHz and 1.58 s at 4 kHz. The procedure stated in ISO 3743-1 was followed to examine the suitability of this test room. Its volume was 73 m³, which was more than 40 times the volume of the reference box which encloses the medical equipment [20]. The largest dimension of all the medical equipment did not exceed 1 m, and the tested equipment had a volume of no greater than 2% of the room volume. During the measurements, the test room was kept as empty and quiet as possible, with no medical furniture, such as bed, tables and chairs. There were no acoustic ceilings or absorptive

coverings for the smooth hard walls. The absorption coefficient of the floor that is closest to the equipment did not exceed 0.06, and the remaining surfaces of the room were highly reflective within the range of interest. Overall, the test room was considered to fulfil the requirements of ISO 3743-1 [20].

The medical equipment under test were installed and operated as they were for normal healthcare usage. Six microphone positions were arranged with a distance of more than 0.5 m to any walls and ceiling, and the test positions remained the same for all the measurements. The period of each measurement was 30 s, and the measurement equipment used was the 01dB Symphonie dual channels system [21]. A 01dB DO12 Omni-directional sound source with M700 power amplifier with known sound power output was used as the Reference Sound Source (RSS) [21], and it was calibrated in accordance with ISO 6926 to meet the specified criteria [22].

Following the relevant requirements in ISO 3743-1, two sets of measurement were carried out, first with the medical equipment placed more than 1 m from any wall, then with the omni-directional loudspeaker under the same test conditions. The difference in the spatial average sound pressure levels obtained in the two sets of measurement is equal to the difference in the sound power levels of the two sources. In the measurements, the temperature and relative humidity were 22–24 °C and 49–53%, respectively.

The sound power level of the medical equipment within the frequency range of interest was calculated using

$$L_w = L_w(RSS) - \overline{L_p(RSS)} + \overline{L_p(ST)}, \quad (1)$$

where $L_w(RSS)$ is the calibrated sound power level of the reference sound source; $\overline{L_p(RSS)}$ is the average sound pressure level of reference source over the microphone positions; $\overline{L_p(ST)}$ is the average sound pressure level of medical equipment under test over the microphone positions [20].

All the equipment can be operated separately, so the sound power levels of equipment were measured one by one. Given the impulsive features of signals, and also to avoid the influence of background noise, $\overline{L_p(ST)}$ refers to the time-averaged sound pressure level over a specific period of measurement, namely around the time that the peak sound pressure level occurs. Over the measurement period of 30 s, the equipment signals were only included for the calculation of sound power levels, if the sound pressure level is less than 10 dB below the peak sound pressure level. This is similar to a method for sound event detection introduced in ISO 20906 for aircraft noise [23]. It is noted that within a measurement period, a number of peak sound pressure levels could occur.

Although only octave band is advised in ISO 3743-1, to obtain more detailed data, one-third octave bands were measured from 100 Hz to 10 kHz, which could be easily converted to octave band if needed.

In reality, it is common that several pieces of medical equipment are alarming at the same time, especially when

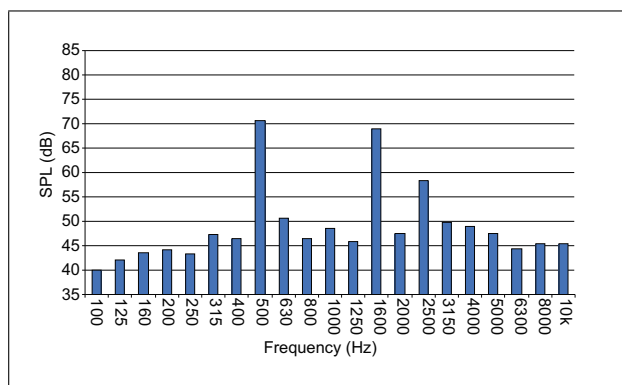


Figure 2. One-third octave band sound power level of monitor's crisis alarm at the default volume.

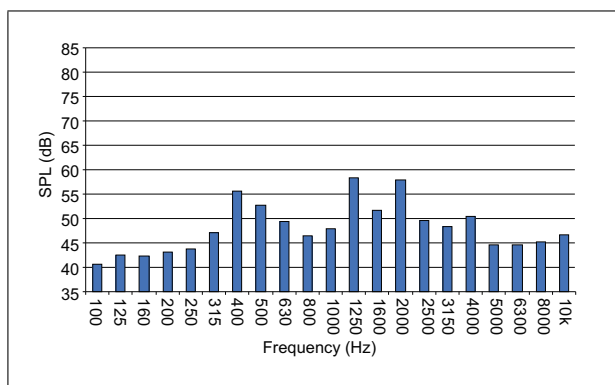


Figure 3. One-third octave band sound power level of monitor's warning alarm at the default volume.

nurses periodically turn the ICU patients from side-to-side every few hours to improve their blood circulation [7, 17]. For the investigation of complexity of real sound environment with multiple pieces of equipment, L_{eq} (the equivalent sound pressure level) is used, where the sum of sound pressure levels of multiple pieces of equipment can be made by

$$L_{eq} = 10 \log_{10} \left(10^{L_{eq1}/10} + 10^{L_{eq2}/10} + \dots + 10^{L_{eqN}/10} \right), \quad (2)$$

where L_{eqN} is the equivalent sound pressure level across the entire measurement period for a specific equipment source. The receiver's location and its distance to equipment were configured the same as the above sound power measurement. The distance between the equipment and the nearest receiver position was greater than 1.25 m and determined based on the room volume [20]. In other words, all the receiver positions were located in the reverberant sound field.

3. Results

3.1. Sound power level of individual equipment

The one-third octave band sound power levels of typical medical equipment from 100 Hz to 10 kHz are shown in Figure 2 to Figure 12. For monitor noise, with different types of alarm, similar spectral trends can be clearly observed in Figures 2–4, with the peak levels around 500 Hz and 2 kHz. For either horizontal or vertical pumps, the highest sound power levels of hold-on alarm concentrate on around 800 Hz, whereas infusion alarm emits more sounds at 1.25 kHz and 2.5 kHz, as shown in Figures 5–8. Different from other equipment, relatively more broadband sounds with high sound levels are generated from the ventilator, ranging from 800 Hz to 4 kHz, except an obvious gap at 1.25 kHz, as demonstrated in Figure 9. The humidifier's alarm features even more high-frequency components up to 6.3 kHz, and it is noted that the highest sound power level at single frequency among all the tested equipment is produced by humidifier, nearly 83 dB

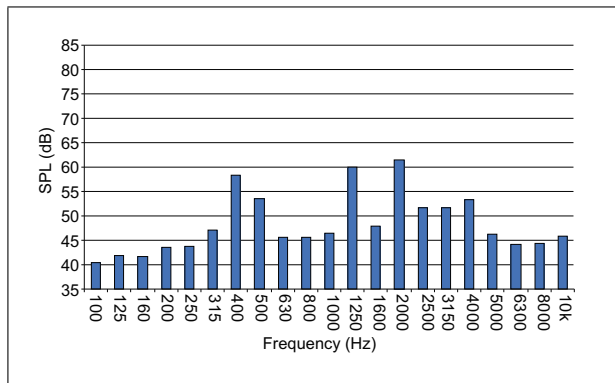


Figure 4. One-third octave band sound power level of monitor's advisory alarm at the default volume.

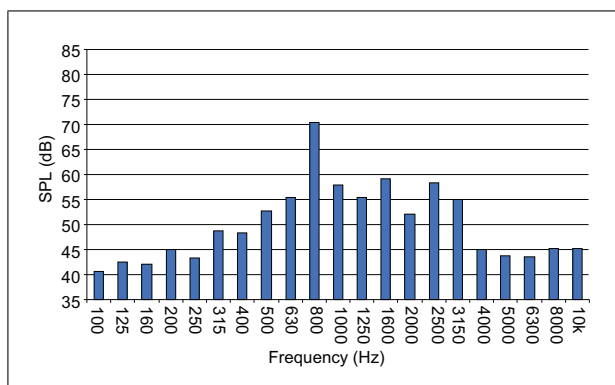


Figure 5. One-third octave band sound power level of hold-on alarm of horizontal pump at the default volume.

at 4 kHz, as illustrated in Figure 10. For both nasogastric feed pump and DVT preventer, the sound power level at various one-third octave bands generally does not vary as much as the other equipment, but certain frequencies, such as 2 kHz and 4 kHz, contribute considerably more than any other frequency bands, as shown in Figures 11–12. Overall, the majority of alarms radiated from medical equipment in ICU are dominated by middle and high frequency sounds, particularly the latter.

Table I gives the un-weighted overall sound power levels at 100–10 kHz, the average length of alarm as well as

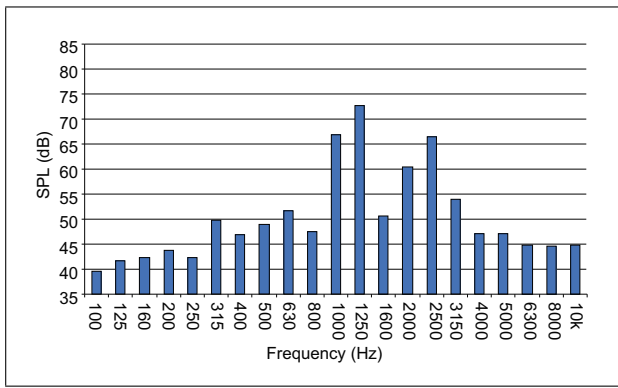


Figure 6. One-third octave band sound power level of infusion alarm of horizontal pump at the default volume.

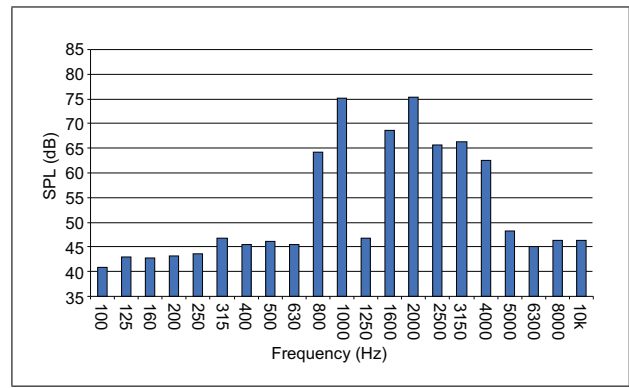


Figure 9. One-third octave band sound power level of ventilator.

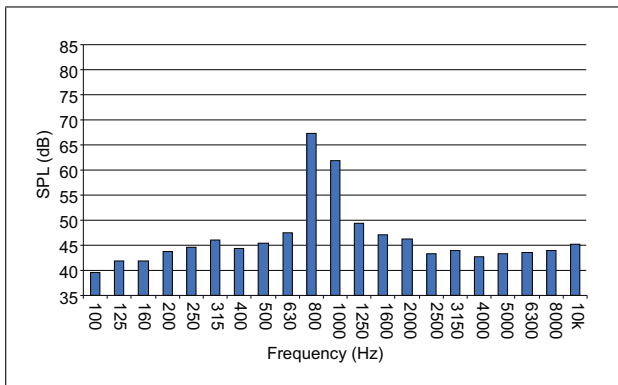


Figure 7. One-third octave band sound power level of hold-on alarm of vertical pump at the default volume.

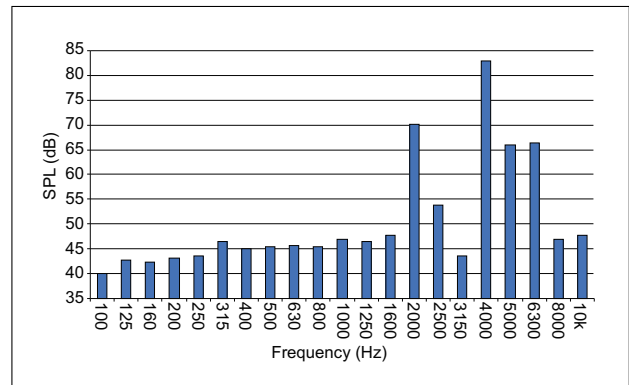


Figure 10. One-third octave band sound power level of humidifier.

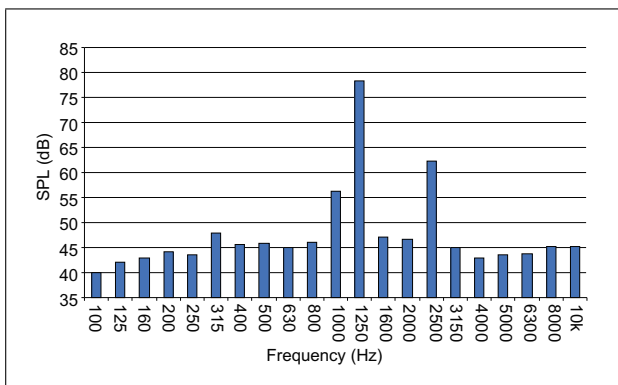


Figure 8. One-third octave band sound power level of infusion alarm of vertical pump at the default volume.

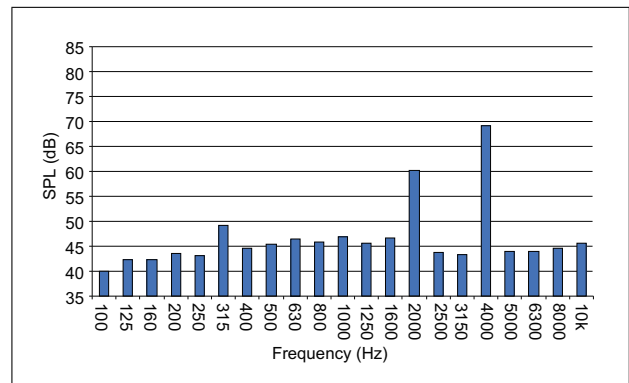


Figure 11. One-third octave band sound power level of nasogastric feed pump.

the average time interval between two adjacent alarms of the medical equipment. The signal length and time interval are clarified in Figure 13. Consistent with the highest level at single frequencies, the highest sound power level is also from the humidifier, as high as 83.3dB, followed by the ventilator and pump's infusion alarm, whereas the lowest level is originated from the warning alarm of monitor, less than 65 dB.

The effects of alarm volume setting on the sound power level is insignificant for the hold-on and infusion alarms of syringe drivers, since the difference between the de-

fault volume and maximum or minimum volume is merely around 0.5 dB. However, the volume setting must be taken into account for the monitor alarms, with a significant 6 dB difference in average.

In terms of temporal patterns of noise emitted by the medical equipment, normally each time most of the equipment only alarm for a short period, less than 1 s, although the ventilator's alarm sometimes lasts even 2 s as an exception. Not surprisingly, the time interval is dependent on the type of equipment, from 0.2 s of the monitor's crisis alarm to 6 s of the humidifier's alarm.

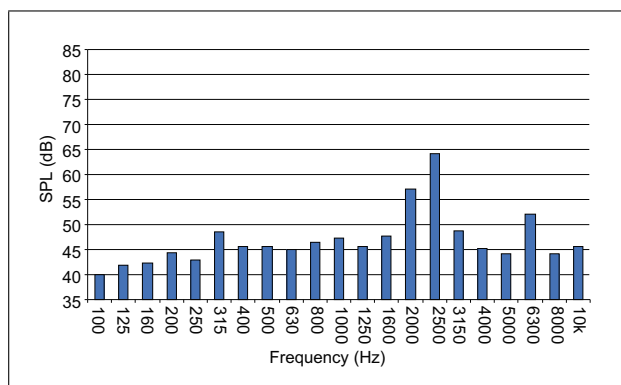


Figure 12. One-third octave band sound power level of DVT preventer.

Table I. Un-weighted overall sound power levels at 100 Hz–10 kHz and temporal patterns of medical equipment. L : Sound power level (dB), τ : Average signal length (s), $\Delta\tau$: Average time interval (s).

	L	τ	$\Delta\tau$
Monitor - crisis			
Default volume	73.1	0.7	0.2
Max. volume	78.2	0.7	0.2
Min. volume	66.3	0.7	0.2
Monitor - warning			
Default volume	64.4	0.6	2
Max. volume	70.4	0.6	2
Min. volume	57.9	0.6	2
Monitor - advisory	66.3	0.6	1.8
Horizontal pump - hold on			
Default volume	71.7	0.7	2.4
Max. volume	72.4	0.7	2.4
Min. volume	71.4	0.7	2.4
Horizontal pump - infusion	74.8	0.7	0.3
Vertical pump - hold on	68.8	0.6	2.4
Vertical pump - infusion	78.6	0.6	0.3
Ventilator	79.4	1.8	0.3
Humidifier	83.3	0.9	6
Feed pump	69.9	0.9	1
DVT preventer	65.9	0.4	3

3.2. Sound environment with multiple pieces of equipment

There would be a large number of combinations for multiple pieces of medical equipment, if all types of equipment are considered. For the sake of convenience, only three noisy but representative scenarios for the routine health-care are considered in this paper according to the actual occurrences of multiple alarms, based on the on-site obser-

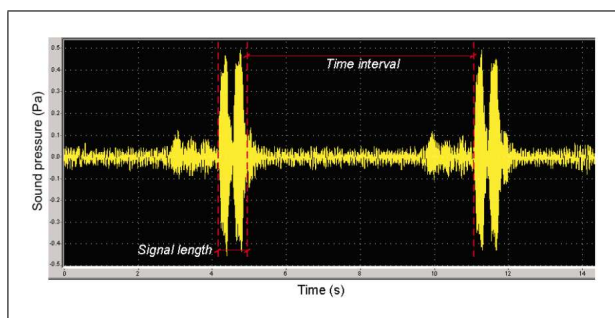


Figure 13. A typical time history of humidifier, showing signal length and time interval.

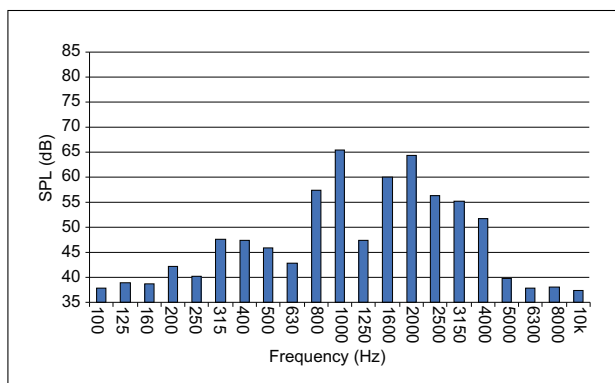


Figure 14. One-third octave band equivalent sound pressure level of ICU environment with ventilator and monitor's warning alarm.

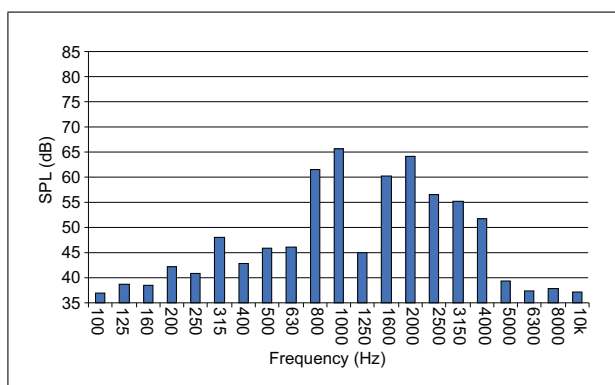


Figure 15. One-third octave band equivalent sound pressure level of ICU environment with ventilator and pump's hold-on alarm.

vation [17]. Those scenarios are the ventilator in conjunction with the monitor's warning alarm, the ventilator in conjunction with the pump's hold-on alarm, and the worst occasion which has ventilator, the pump's infusion alarm, and the monitor's advisory alarm. The equipment volumes are assumed as the default level, where applicable.

Figures 14–15 show the one-third octave band equivalent sound pressure levels of the above three scenarios with multiple pieces of equipment. It can be clearly seen that the ventilator is the most dominant noise source in the ICU sound environment, as the spectral trends are in good agreement with the sound power result of ventilator, particularly for the frequencies between 800 Hz to 4 kHz. The

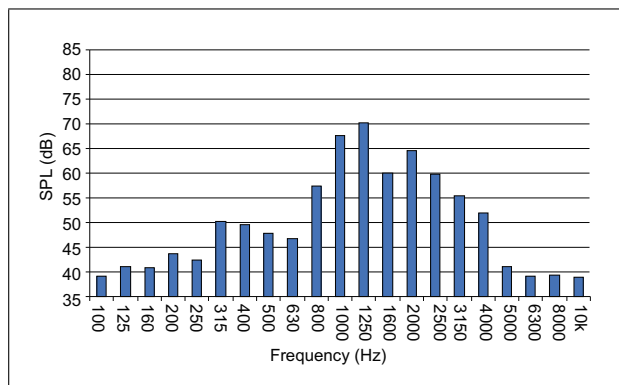


Figure 16. One-third octave band equivalent sound pressure level of worst ICU environment with ventilator, pump's infusion alarm and monitor's advisory alarm.

equivalent A-weighted sound pressure levels of those three environments are also calculated, which are 70.1 dBA, 70.4 dBA and 74.0 dBA, all of which significantly exceed the values of any sound events recommended by the relevant international standards (40 dB L_{Amax}) [1].

Apart from the equivalent sound pressure level, the instantaneous peak sound level is also a valuable indicator for the critical care sound environment. If the average distance between a patient and the three pieces of equipment was assumed as 0.8 m in an ICU ward, with regard to the worst acoustic scenario, the highest peak sound pressure level could reach 80.5 dBA, calculated using classic room acoustic theory based on diffuse sound field. Although the equipment alarms are designed to attract staff attention, this is still noisy enough to critically affect sleep disturbance, annoyance and communication interference [1, 8].

4. Conclusions

Based on the comprehensive measurements of sound power levels for the alarms of six types of medical equipment, it has been shown that the majority of alarms radiated from ICU equipment are dominated by middle and high frequency sounds, particularly the latter. The humidifier generates the highest sound power level, followed by the ventilator and pump's infusion alarm. The equipment volume setting is only effective for the monitor alarm. The average length of all alarm signals is normally around 1 second, while the time interval is more varied. Regarding the sound environment with multiple pieces of equipment, the equivalent sound pressure levels of all the three representative scenarios significantly exceed the relevant guideline values in the hospital environment. The instantaneous peak sound level could be more than 80 dBA in the worst acoustic scenario.

The basic data obtained in this study would be useful for sound field simulation in various space forms and conditions [24, 25, 26, 27], by considering various source combinations [28, 29] as well as noise disturbance in various sound environments such as different language conditions [30].

Acknowledgements

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