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Behaviour observation of major noise sources in critical care wards

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Abstract

Purpose

To investigate the behaviour patterns of typical noise sources in critical care wards, and relate their patterns to healthcare environment in which the sources adapt themselves in several different forms.

Methods

An effective observation approach was designed for noise behaviour in the critical care environment. Five descriptors have been identified for the behaviour observations, namely *interval, frequency, duration, perceived loudness and location*. Both the single-bed and multiple-bed wards at the selected Critical Care Department were randomly observed for three inconsecutive nights, from 11:30PM to 7:00AM the following morning. The Matlab distribution fitting tool was applied afterwards to plot several types of distributions, and estimate the corresponding parameters.

Results

The lognormal distribution was considered to be the most appropriate statistical distribution for noise behaviours in terms of the interval and duration patterns. The turning of patients by staff was closely related to the increasing occurrences of noises. Among the observed noises, talking was identified with the highest frequency, shortest intervals and the longest durations, followed by monitor alarms. The perceived loudness of talking in the night time wards was classified into 3 levels (raised, normal and low). The majority of people engaged in verbal communication in the single-bed wards occurred around the Entrance Zone, whereas talking in the multiple-bed wards was more likely to be situated in the Staff Work Zone. As expected, more occurrences of noises along with longer duration were observed in multiple-bed wards rather than single-bed wards. 'Monitor plus ventilator alarms' was the most commonly observed combination of multiple noises.

Keywords

Critical care, behaviour observation, noise source, acoustic environment, statistical distribution fitting, night time

1. Introduction

The patients in the critical care wards are often exposed to excessive levels of noises and activities. In particular, they tend to suffer from sleep distance at night, as a common problem [1]. Unfortunately, as shown in previous studies, the noise levels measured in the wards frequently exceeded the WHO (World Health Organization) guideline values by more than 20dBA [2-6]. Behavioural modification and improvement of major noise sources is considered to be an effective noise reduction strategy in the context of hospital acoustic environments [1]. However, very little observational data regarding noise sources in the healthcare environment exists, though there are some studies investigating the human activities related to interruptions on activity performance and communication in hospitals [7, 8]. Similar to the field measurement and simulation works presented in previous papers [9-12] , researchers have measured the noise levels or studied the sound field of various healthcare environments. In general, however, their results simply counted the frequency or number of occurrences of different noises together with the corresponding mean and standard deviation values, and described the possibilities of avoidable noises to provide noise control solutions, after indicating the dominant sources [5, 13, 14]. The necessary statistical analysis for the noise distribution, considering the variability of noise distribution over different time periods, wards, activities and routine procedures, are often ignored. Reliable behavioural observations for essential noise sources are still very limited.

So far, we have investigated the actual acoustic environment of critical care wards in the UK based on long period nocturnal measurements, and measured the sound power levels for the alarms of typical medical equipment [6, 15]. This paper therefore, presents one of the first studies to relate the behaviour patterns of typical noise sources to the healthcare environment in which the sources adapt themselves in several different forms. An effective noise observation method has been developed with five essential types of measure and critical procedure, and applied to the acoustic environment in critical care as the case study. After the preliminary and formal observations, the behaviour patterns of different noise sources were further investigated by statistical distribution analysis, and the parameters of best fitting distribution for the observed noise sources were calculated as the necessary inputs for the behaviour sub-model of the eventual agent-based model [16]. A fragment of the original check sheet result and the observed result for multiple noises are also provided in this paper.

2. Noise observation method

2.1 Observed noise sources, site and time

Noise sources interact both with the healthcare environment and with other noises, and the diversity and functions of their behaviour remain to be well understood. In order to simplify the observation, only major noise sources were selected. Since alarms from medical equipment and people talking have been identified as the two main sources [17], the objects observed in this study were not only hospital personnel, but also the static medical equipment, including ventilators, monitors, syringe drivers or pumps and humidifiers. In other words, the behaviour observation in this paper refers to the interactions between all the inclusive noise sources and the environment, as a broader definition.

The spatial and time scale of behaviour measurements are crucial in reflecting the nature of the acoustic environment. The single-bed and multiple-bed wards at the Critical Care Department of Northern General Hospital in Sheffield were randomly selected for six observation sessions, from a total of four single-bed wards and two four-bed wards as the observation site.

It was unrealistic to record the patterns of typical noises continuously over a 24 hour timeframe, as only one observer was involved. Although sleep timing is commonly disturbed in the critically ill patients, night time was felt to be the most important time for “normal” sleep and therefore its disruption at this time would be very significant. Also the acoustic environment in the hospital wards during night time is more likely to be quieter than day time, with fewer noises and fewer interruptions, and with more potential opportunities for sleep. Therefore, observations were arranged at the same night time period on a daily basis.

2.2 Descriptors for noise behaviours

The noise behaviours can be described in terms of different forms, for instance, the temporal pattern, appearance, movements, spatial position or orientation, and the effects on the environment or other sources. Similar to the frameworks used in urban acoustic studies [18], five basic types of descriptors are yielded for the behavioural observations of noise sources in the hospital, namely *interval, frequency, duration, perceived loudness and location*.

As the three most commonly used descriptors for complementary information, *frequency* refers to the total number of occurrences of a noise with a specific behaviour pattern per unit time, whereas *duration* is the length of time for which a single occurrence of noise lasts, in the units of time such as minute or hour. Another time-relevant measure is *Interval*, presenting the time between one specified source generating a kind of noise and another generating the same noise.

Perceived loudness is the physical quantity related to the noise generation, which in this case, referred to the sound power level of typical noise sources. For the sake of convenience, the perceived loudness can be categorised into groups according to the actual characteristics of noise source, such as 'high', 'normal' and 'low' level, as demonstrated in the relevant standard for speech levels [19]. Obviously, it would be helpful to obtain the necessary sound power data prior to the observation, similar to a previous paper for the sound power levels of medical equipment [15]. The monitor's perceived loudness refers to three levels, 'advisory', 'warning' and 'crisis', with increasing level of urgency. For instance, if no heart beat or a very abnormal heart rhythm is detected by the monitor, the 'crisis' alarm will go off repetitively. The pump's perceived loudness can be classified into 'infusion' and 'hold-on'. The former is simply due to a long idle time, whereas the latter is related to problems preventing the medication supply, such as tube blockage or low levels of fluid remaining. It is noted that the perceived loudness levels of different types of alarms from either monitor or pump vary significantly, according to our measurements [15]. In contrast, the ventilator and humidifier only generate the alarms at one perceived loudness level.

The spatial location is a position or point of noise source being studied in physical space. Ideally, the floor area of hospital wards can be divided into a series of contiguous cells or grids, such as 0.5m*0.5m square cells, as unique identifiers for spatial indexing. It would be too complicated, however, to identify the accurate location of each noise source in practice, particularly for the mobile sources, such as people talking. An alternative approach, therefore, is to divide the space into many functional zones with irregular geometric sizes. As illustrated in Figure 1, single-bed wards are comprised of patient, staff work, equipment, entrance, medical supplies zones, and corners, with respect to the two possible door positions. Apart from more beds and related zones, multiple-bed wards contains a unique central aisle zone, which is absent from single-bed wards.

The location of an observer should ensure a good view of the whole wards, but not cause any interference with general activity and medical equipment. The observer always sat around the corner of the single-bed ward during observation, and also selected the end of the central aisle at the multiple-bed ward, as shown in Figure 1.

2.3 Recording

The observation recording aimed to obtain significant forms of noise behaviour distinguished from the ambient environment. Each occurrence of a given type of noise within the group of sources was recorded, together with detailed information about the involved individual noise sources and the time of occurrence. This continuous recording method is demanding or even restricted by practical concerns in the critical care environment sometimes, but it provides an exact record of the noise behaviour patterns through the accurate measurement of true durations and frequencies.

As the most flexible and commonly used recording medium, a check sheet was chosen to record behavioural observations upon noise sources reliably and with reasonable accuracy. The stopwatch on a mobile phone assisted the recording of precise durations of noises on the check sheet. The check sheet in this observation study was designed in a suitable format with columns signifying the above five types of descriptors for noise behaviour, and rows denoting successive noise intervals. In addition to the categories of noise observation, there is an extra remark column to note down the useful incidental information for the interpretation of noise behaviour. The background information such as date, time, and number of ward was included at the top of the sheet. The design of the check sheet also took into account the convenience in transferring of the recorded data to computer system for subsequent analysis.

2.4 Making observations

The correct selection of descriptors and recording methods greatly depends on the observer's familiarity with the noise sources to be studied. Therefore two periods of preliminary observations were firstly conducted as an essential part of this study. On the other hand, the observer was seldom invisible to people in the hospital from whom some major noises may be generated, and hence the presence of observer may affect the behaviour of noise sources. The period that the observer spent in the hospital wards during the preliminary observation would also help the human subjects become accustomed to the observer's presence, thus minimising the observer's impact.

The first preliminary observation was made inside a single-bed ward for a whole night, in order to become more familiar with the healthcare environment and the basic behaviour patterns of noises, and practise the measurement techniques. The second preliminary observation was carried out in the corridor of the Critical Care Department, to investigate the interactive behaviour between the acoustic environment of wards and corridor, in terms of the number of door openings, from 1PM to 3PM.

There were 18 beds originally designed in the selected Critical Care Department. However, it should be noted that Figure 2 only represents a half part of the Critical Care Department, since only 10 beds were funded due to financial pressures, and the other sections of the unit were not used during the experiment. It can be clearly seen from Figure 2, that two doors formed the boundaries of the L-shaped corridor, covered by the observer situated in the upper left corner at the second preliminary observation. The middle door internally connects the two parts of the unit, and is always open for the convenience of moving equipment or beds. Conversely, the access to the staff door is highly restricted, and only the healthcare team is permitted to swipe in.

After the preliminary observations, the observer carried out the formal behaviour observations of noise sources. Both single-bed wards and multiple-bed wards were observed for three inconsecutive nights, although the wards might not be the same ones for all the observation sessions. Each observation session started from 11:30PM and ended at 7:00AM the following morning. The observer had a two-minute break in the middle of each session to avoid fatigue and loss of concentration.

2.5 Data analysis

Firstly, the means, standard deviations and medians of the descriptors for the noise behaviour were presented after the descriptive analysis. The graphical Distribution Fitting Tool in the Matlab Statistics Toolbox was applied afterwards to fit distributions to observation data, plot distributions with the data, manage several different fits, and evaluate distributions at various points [20].

The data sets were displayed in a probability density function (PDF) plot, using a probability histogram, in which the height of each rectangle is the fraction of the data points that lie in the bin divided by the width of the bin. This makes the sum of the areas of the rectangles equal to one. Then, a large number of distributions were employed to construct the probability plot of the data. The available types of distribution include Exponential, Gamma, Logistic, Lognormal, Normal, Rayleigh and Weibull. The corresponding parameters for the most appropriate distribution were subsequently estimated with standard errors.

3. Results

3.1 Preliminary observation results

3.1.1 Observation in the single-bed ward

Through the practice in the first preliminary observation, the observer was able to adequately and clearly define the category of noise behaviour, and reliably distinguish the individual noise sources, such as various medical equipment and staff putting on different protective clothing, such as plastic aprons. Moreover, the observer had a general idea of the possible relations between the functional zones and certain noises, which made following observations more efficient.

According to the observations, it is suggested that the *duration* of typical noise sources in the hospital is generally very short, less than one minute, although considerable variations might be found among different noises. Thus, the time unit is determined as *second* for all the behaviour observations in this study.

Unlike the sound power levels of medical equipment fully measured in our previous paper [11], the classifications of people's talking levels in the critical care are still unknown in the literature. In accordance with the observation results, a 3-level scheme was introduced for people's voices at night, namely *raised, normal* and an unusual *low* level, as a lot of people normally tend to speak at a lower level during the night in the hospital. According to Beranek's definition, the average sound pressure levels of normal voice effort at 1m in free field is approximately 60 dBA, whereas it's assumed as 66 dBA for raised voice effort [21]. Whilst it is not possible to confirm the sound pressure levels due to speech during the study, Barenek's definition does give a useful indication of typical levels which may be expected.

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3.1.2 Observation in the corridor

On the night of second preliminary observation, in the four single-bed wards, only single-bed Ward 4 shown in Figure 2 was vacant, whereas both of multiple-bed wards (Bay 1 and Bay 2) were occupied by the same number of 3 patients. The occurrences of noises along the unit corridor, mainly from talking, were much less than the noises inside the wards. This is consistent with the known fact that staff spent most of their working time in the wards. The larger bays potentially facilitate conversations between adjacent nurses. However in some units, such as the HDU or in countries with different staffing ratios there may be fewer nurses in a given area. However this may at times actually increase conversation levels, because certain tasks will require nurses to gather at one patient's bed and so they will need to be called together at these times. In this unit the design was such that the corridors were mainly used for transit, rather than being related to a central nursing station, which could itself be a focus for noise and talk. Different ICU design characteristics may influence the distribution of noise, but this study was primarily concerned with looking at multi-patient bays and single occupancy rooms. The latter are becoming much more common for social reasons and importantly as an aid to reducing the spread of infection.

The interactions between the acoustic environment of wards and corridor are triggered by doors' opening and closing. Figure 3 presents the number of door openings in different rooms and doors of the observed critical care unit, for each half hour from 1AM to 3AM. This time period was chosen, because the majority of elective admissions and discharges are complete before this time and this represents a time towards the middle of a shift, so hand-overs are not occurring. It also represents a key time for sleep for patients. Noise at this time is very important and levels or intervals will represent the "best" that a patient is likely to experience. With regard to the two entrance doors, the middle door was more frequently accessed than the staff door as expected. Not surprisingly, in agreement with the number of occupied beds, the total number of door openings in the two multiple-bed wards (Bay 1 and Bay 2) is much bigger than the number in three single-bed wards. The time variation of door opening was not significant. It is interesting to note, however, that the door of Bay 1 was opened almost 20 times more than Bay 2. Meanwhile, the number of door openings at the single-bed Ward 2 was twice as large as the number of other two single-bed wards. A possible reason might be the relative closer distance between single-bed wards and Bay 1, so nurses at the single-bed wards are more likely to visit Bay 1, rather than Bay 2, when they need help from colleagues. Therefore, the number of door opening and closing depends on the location and function of the wards. This is different, even among the same type of wards, suggesting that the layout of a hospital may in fact influence the behaviour of staff, and consequently, the acoustic environment, to a certain extent.

On average, the doors of single-bed wards and multiple-bed wards were opened 14 and 30 times per hour during the observation period, which may be considered a relatively high number, especially at this time of night. Frequently, this was related to requests for assistance between nursing staff and also the disposal of contaminated bedding or fluids. Together with other influencing factors, for instance, the well regulated sound insulation over the unit, and the intelligently designed closing mechanism for all the doors within 10 seconds, it seems that the acoustic environment of wards and corridors can be considered as two isolated systems with little effective interactions. Thus, it is more important to examine the behaviour of noise sources in the wards.

3.2 Formal observation results

3.2.1 Descriptive analysis of five descriptors of observed noise sources

Table 1 provides a typical fragment of the original check sheet result for one noise observation at the multiple-bed ward from 2AM to 3AM, with four types of behaviour descriptors and notes. The names of all the people involved on the ward remain strictly anonymous in Table 1, and are numbered correspondingly for the noise behaviours, generated by staff conversations. In addition to people talking and equipment alarms, the behaviours of some other occasional but significant noises were also recorded such as hand washing and patient coughing, but they were all excluded from the data analysis. According to the notes, at least three nurses worked together to turn over three patients one by one in this multiple-bed ward during the observational period. It was notable that, a large number of different noises were closely associated with the turning of patients within this hour. Another important recorded observation is the simultaneous occurrences of more than two noises, though these were very rare.

Among the five descriptors of noise behaviour, the frequency, interval and duration results of the typical noise sources are presented in Table 2. It shows results of all the formal observations in the single-bed and multiple-bed ICU wards, in terms of means, standard deviations and medians. It is noted that the standard deviations of the behaviour descriptors are greater than the means, suggesting a wide dispersion or variability of the distributions of the observed noise behaviours. Hence, the medians were also analysed as another measure of central tendency for the data distribution.

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The number of occurrences of pump's alarm and humidifier's alarm was much less than that of the other three noises, which were talking, ventilator's alarm and monitor's alarm. As a result, the interval and duration of pump and humidifier were not calculated separately for single-bed and multiple-bed wards, in order to reduce data errors. It can be seen that vocal interaction was observed to be the noise source with the highest frequency (up to 13 per hour); the shortest interval and the longest duration (nearly 1 minute) for either single-bed or multiple-bed wards, followed by the monitor alarms. Unlike people's talking, the duration of the equipment's alarms is generally less than 10 seconds, and this is in agreement with a previous study showing that the median alarm duration was 1.7 seconds [22]. It is likely that different nurse: patient ratios would influence the time that alarms sounded before they were cancelled. This was seen during our observations especially in the larger bays when nurses were out of the unit. It may also apply to cubicles, where at times one nurse looks after two cubicles at once.

Comparing the noise behaviours between single-bed and multiple-bed wards, more occurrences of noises along with longer duration were observed in multiple-bed wards rather than single-bed wards, except for the duration of ventilator's alarm, which tended to last longer in single-bed wards. More specifically, and taking the frequency results as an example, the frequency of noise sources in the observed multiple-bed wards are approximate 3-4 times the frequency of single-bed wards. This interesting finding is in agreement with the fact that the observed multiple-bed wards are often occupied by three or four patients, and the same number of nurses on the basis of 1:1 Nurse/Patient ratio.

For the remaining two behaviour descriptors, perceived loudness and location are not time related; thereby are represented in a more descriptive way. After the cumulative analysis, the statistical percentages of 'low', 'normal' and 'raised' talking levels were given as 30%, 50% and 20% respectively over the observation period. The rather difficult communication between staff and sedated or ventilated patients, as well as the constant alarm interruptions, all contributed to the surprisingly high percentages of 'raised' talking in the night time ICU wards. With respect to the three perceived loudness levels of monitor's alarm, 'advisory', 'warning' and 'crisis' account for 47%, 50% and 3%, as the patient's monitor only alerts staff at the noisiest 'crisis' level under infrequent emergency circumstances. Moreover, the ratio of pump's 'infusion' to 'hold-on' level was calculated as 2:1.

Regarding the noise location results, obviously all the equipment alarms are restricted within the simplified Equipment Zone between the patient's head and the wall next to as illustrated in Figure 1. The location of vocal exchanges or talking is much more difficult to determine due to people's constant movement, and the type of wards must be taken into account. In the single-bed wards, more than 80% of people's talking was located in the Entrance Zone, along with the remaining 20% occurred in the Staff Work Zone and Patient Zone, since the nurses in the single-bed wards often enter and exit when asking for help, and they often communicate with colleagues from other wards around the door.

On the other hand, the various locations of people talking were relatively more varied in the multiple-bed wards, because of the bigger space, as well as the presence of more staff and patients. Apart from the corners and Equipment Zones, talking in the multiple-bed wards is likely to be identified in each listed zone. Different from single-bed wards, there was no physical boundary between the adjacent working areas, such as the Staff Work Zone 1 and 2, as shown in Figure 1, nurses thus tend to gather around the working zones, to discuss care or handover information, and help each other with the healthcare routine as necessary. Therefore, based on the analysis on the observations, approximate 75% of talking in the multiple-bed wards occurred in the Staff Work Zone, followed by Central Aisle Zone (10%), Patient Zone (8%) and Entrance Zone (5%).

Apart from the analysis upon the five descriptors of noise behaviour, some interesting results were also obtained from the observation. Un-sedated patients may generate more alarms, such as moving the arterial lines or tubes, whether intentionally or not. With regard to the staff, the nurses in the single-bed wards tend to speak in lower voices, possibly as a result of the quieter ambient environment, whereas non-clinical staff, such as the cleaners, appeared less aware of the need to be quiet in the patient environment. It is interesting to note that when a nurse joined an ongoing conservation with a relatively low voice, the other nurses were likely to reduce their talking level soon afterwards, even though they may not be aware of this influence by their colleague. Another aspect of behaviour modification is related to the gentle reminders from the senior staff. In the multiple-bed ward, after midnight, nurses are often informed by the sisters to keep their voices down, for promoting a comfortable environment for patients' sleep and rest, and this approach tended to worked well.

3.2.2 Statistical distribution of the interval and duration of typical noises

By means of Matlab Statistics Toolbox, the probability density function for the interval and duration of observed noise sources are plotted. Hence Figures 4 - 6 show the probability of episodes of noise and their separation in time and their duration. As the frequency data can be estimated from the interval distribution, it was excluded from the study of distribution fitting. Clearly, the majority of the obtained data can be categorised as a short period of time for both interval and duration. The frequency of interval and duration data upon the typical noise sources tends to decrease with the increased period of time in the critical care wards. More importantly, a small number of extreme values with rather long time period feature the uniqueness of noise behaviours in the healthcare environment. In addition, the number of rectangles of humidifier's behaviour data is considerably less than any other types of noises. This accurately reflects the rare occurrences of humidifier alarms during the observation.

To understand the underlying pattern of the noise behaviour, the distribution fitting tests were conducted by comparing the frequencies observed in the interval and duration data to the theoretical frequencies of seven different types of statistical distributions, namely Exponential, Gamma, Logistic, Lognormal, Normal, Rayleigh and Weibull, as shown in Figure 7. The lognormal distribution is assumed to be the appropriate statistical distribution with the best fitting effect for the interval and duration of the observed noise sources. In other words, the two most important variables of the noise behaviours tend to be distributed according to the lognormal distribution, for predictive purposes. For the sake of convenience, Figures 8 - 10 only illustrate the fit of lognormal distribution for the interval and duration of typical noises observed. Regarding the different fit of lognormal distribution to different noise sources, it can be seen that the some sources, such as people talking, fit much better than other equipment noises.

By definition, a lognormal distribution is a probability distribution of random variables which have a normally distributed logarithm. The lognormal distribution is widely used in several areas, including the distributions of city sizes, duration of sickness absence, physiological measurement like blood pressure, and biological measures of length, height or weight [23, 24]. The lognormal distribution has the following probability density function:

$$y = f(x|\mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{\frac{-(\ln x - \mu)^2}{2\sigma^2}} \tag{8.1}$$

where μ is the mean of the included Normal;
σ is the standard deviation of the included Normal.

The estimated parameters (*μ, σ*) of lognormal distributions for the interval and duration of observed noise behaviours are given in Table 3. As a statistical parameter, μ is not equal to the real mean of the interval or duration data. These results can be utilised as the essential inputs in the agent-based acoustic modelling as discussed in a previous paper [16], and also form the basis for the behaviour prediction of similar noise sources in other healthcare environment.

3.2.3 Multiple noise sources

As mentioned in the above section, in some instances, people in the healthcare environment might be subject to noise from a number of different sources. Table 4 provides the number of occurrences of multiple noises observed in the single-bed and multiple-bed wards, with the perceived loudness levels for the equipment alarms if necessary. As expected, the total frequency of multiple noises observed in the single-bed wards is much less than that in the multiple-bed wards.

In total, there were nearly 10 varied combinations of multiple noise sources irrespective of the perceived loudness levels. Among those, monitor plus ventilator, and monitor plus monitor were the combinations observed with the most occurrences (6 times), but comparably monitor plus ventilator was more commonly observed despite of the type of wards. The occurrences of the combination of people talking and equipment also exist in the multiple-bed wards. It should be noted that the only combination of 3 multiple noises was recorded on the first night of the multiple-bed ward observation, which may indicate the worst period of acoustic environment in the ward. Furthermore, it is possible that more than three nurses may engage in conversation, but mainly in the multiple-bed wards.

4 Discussions

Potentially the study could have been made over a 24 hour period, which would have put the night time noise data in the context of the whole day. However, noise reduction is much more difficult in day-light hours, as there are many clinical and nursing tasks that must be accomplished and it could be argued that reinforcing a day-time and night-time contrast is an encouragement to maintaining a day-night rhythm that so often breaks down in illness and in hospital. A significant reason why night-time noise is more relevant and has greater impact on patients than daytime noise, is probably due to the potential for disruption of the restorative process of sleep, which is recognised to be an important factor in recovery rates. Therefore, nocturnal measurements have the greater potential to influence practice that impacts on the patients.

If we understand the behaviours or characteristics of typical noise sources clearly, it would greatly help medical staff or acousticians to influence behaviour (for example the effect of location of clinical discussions) or design in the acoustic environment of the critical care wards. The essential information obtained from this study would make a contribution to the enrichment of effective and efficient noise reduction strategies, and the promotion of relevant guidelines. It will also influence the design of studies investigating the impact of various types of noise, and their influence on sleep quality and on patient wellbeing. Moreover, ambient noise may also impact on communication between patients and staff or even between staff.

5 Conclusions

A specific observation method for noise behaviour was designed in this paper with detailed procedures and behaviour descriptors, and applied in the field observation of typical noise sources in the healthcare environment. Considered as the interactions between wards and corridors, the number of door openings and closings in the selected unit was relatively small, and often dependent on the location and function of the wards, suggesting the possible influence of the layout of hospital on the acoustic environment. As a necessary part of routine care in the ICU wards, the turning of unconscious, sedated or weak patients to prevent bed sores or to avoid lung atelectasis was closely related to the increasing occurrences of noises. The noise behaviour might also be influenced or modified by the staff.

Regarding the five descriptors of noise behaviour, the perceived loudness of people’s talking in the night time was classified into 3 levels (raised, normal and low). It is rather surprising, however, that the ‘raised’ talking accounts for a high percentage over the observation period; this is, probably due to the interruptions from the noisy background environment. According to the statistical analysis, there were notable variations upon the distributions of the behaviour descriptors over all the types of noises, especially given the existence of a certain amount of extreme values in terms of time period. As expected, more occurrences of noises along with longer duration were observed in multiple-bed wards than single-bed wards. Among the observed noises, talking was identified with the highest frequency, shortest intervals and the longest durations irrespective of the type of wards, followed by monitor’s alarm. Nevertheless, the duration of the equipment’s alarms was generally less than 10 seconds. The majority of people engaged in verbal communication in the single-bed wards occurred around the

Entrance Zone, whereas talking in the multiple-bed wards was more likely to be situated in the Staff Work Zone.

After the distribution fitting test, the lognormal distribution was considered to be the most appropriate statistical distribution for noise behaviours in terms of the interval and duration patterns. Those distribution results will not only greatly enhance the further explorations on the behaviour of similar noises in various environments, but also contribute to the completion of the agent-based acoustic model as the essential inputs.

In addition, the varied combination of multiple noises was another interesting feature of the noise behaviour patterns in critical care wards. The 'monitor plus ventilator alarms' was the most commonly observed combination.

Competing interests

None declared.

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Figure legends

Figure 1 *Functional zones and observer's locations for typical ICU wards: (a) single-bed ward with door on the right or left side, (b) single-bed ward with door on the top or bottom side, (c) 4-bed ward with a central aisle zone.*

Figure 2 *Floor plan of the observed Critical Care Unit, with middle door, staff door and the observer's location of the second preliminary observation.*

Figure 3 *Number of door openings in different rooms and doors of the observed critical care unit, for every half hour from1AM to 3AM.*

Figure 4 *Probability density function (PDF) plot for the interval and duration (s) of typical noises observed in the ICU wards: (a) interval of people's talking in single-bed wards, (b) duration of people's talking in single-bed wards, (c) interval of ventilator's alarm in single-bed wards, (d) duration of ventilator's alarm in single-bed wards.*

Figure 5 *Probability density function (PDF) plot for the interval and duration (s) of typical noises observed in the ICU wards: (e) interval of monitor's alarm in single-bed wards, (f) duration of monitor's alarm in single-bed wards, (g) interval of people talking in multiple-bed wards, (h) duration of people's talking in multiple-bed wards, (i) interval of ventilator's alarm in multiple-bed wards, (j) duration of ventilator's alarm in multiple-bed wards.*

Figure 6 *Probability density function (PDF) plot for the interval and duration (s) of typical noises observed in the ICU wards: (k) interval of monitor's alarm in multiple-bed wards, (l) duration of monitor's alarm in multiple-bed wards, (m) interval of pump's alarm, (n) duration of pump's alarm, (o) interval of humidifier's alarm, (p) duration of humidifier's alarm.*

Figure 7 *Distribution fitting considering seven types of statistical distributions for: (a) interval of people talking in single-bed wards, (b) duration of people talking in single-bed wards.*

Figure 8 *Fit of lognormal distribution for the interval and duration (s) of typical noises observed in the ICU wards: (a) interval of people talking in single-bed wards, (b) duration of people talking in single-bed wards, (c) interval of ventilator's alarm in single-bed wards, (d) duration of ventilator's alarm in single-bed wards, (e) interval of monitor's alarm in single-bed wards, (f) duration of monitor's alarm in single-bed wards.*

Figure 9 *Fit of lognormal distribution for the interval and duration (s) of typical noises observed in the ICU wards: (g) interval of people's talking in multiple-bed wards, (h) duration of people's talking in multiple-bed wards, (i) interval of ventilator's alarm in multiple-bed wards, (j) duration of ventilator's alarm in multiple-bed wards, (k) interval of monitor's alarm in multiple-bed wards, (l) duration of monitor's alarm in multiple-bed wards.*

Figure 10 *Fit of lognormal distribution for the interval and duration (s) of typical noises observed in the ICU wards: (m) interval of pump's alarm, (n) duration of pump's alarm, (o) interval of humidifier's alarm, (p) duration of humidifier's alarm.*

Table legends

Table 1 *A fragment of the original check sheet for one observation at the multiple-bed ward commenced from 2AM to 3AM, with the notes and four types of descriptors.*

Table 2 *Arithmetic means, standard deviations (in brackets) and medians (in italic) of frequency (per hour), interval (s) and duration (s) for five typical noise sources observed over 6 nights in the single-bed and multiple-bed ICU wards.*

Table 3 *The estimated parameters (μ, σ and the corresponding standard errors in brackets) of lognormal distribution for the interval (s) and duration (s) for five typical noise sources observed over 6 nights in the single-bed and multiple-bed wards.*

Table 4 *The number of occurrences of multiple noises observed over 6 nights in the single-bed and multiple-bed wards, with the relevant perceived loudness level in brackets*

Table 1 *A fragment of the original check sheet for one observation at the multiple-bed ward commenced from 2AM to 3AM, with the notes and four types of descriptors.*

Time	Location	Type of noise	Duration	Perceived loudness	Notes
2:01	Bed 1, Equipment Zone	Ventilator	1.5s		
2:01	Bed 2, Patient Zone	Patient, coughing	2s		
2:01					Nurse 1 back from break, henceforth two nursed in the ward
2:03	Bed 1, Staff Work Zone	Talking (Doctor 1 + Sister 1)	10s	50% Low + 50% Normal	
2:07	Bed 1, Equipment Zone	Ventilator	10s		
2:08	Bed 1, Equipment Zone	Ventilator	4s		
2:07	Bed 3, Staff Work Zone	Talking (Nurse 1 + Nurse 2)	110s	90% Low + 10% Normal	
2:10	Bed 2, Medical Supplies Zone	Nurse 1, arranging items in a drawer	25s		
2:10	Bed 3, Medical Supplies Zone	Nurse 2, arranging items in a drawer	15s		
2:10	Bed 1, Equipment Zone	Ventilator	4s		
2:11	Bed 1, Equipment Zone	Ventilator	12s		
2:13	Bed 1, Equipment Zone	Ventilator	1s		
2:14	Bed 1, Equipment Zone	Ventilator	1s		

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2:12	Bed 1, Central Aisle Zone	Talking (Sister 1 + Nurse 2 + Support worker 1)	15s	Normal	
2:13					Nurse1, Nurse 2, and Support worker 1, starting to turn over Patient 3
2:14	Bed 3, Equipment Zone	Monitor	1s	Advisory	
2:14	Entrance Zone	Talking (Nurse 4 + Sister 1)	10s	Normal	
2:15	Bed 3, Equipment Zone	Monitor	6s	Advisory	
2:16	Bed 3, Medical Supplies Zone	Nurse 2, washing hands	15s		
2:16	Bed 1, Staff Work Zone	Talking (Support work 1 + Sister 1)	40s	25% Normal + 75% Low	Finishing the turning of Patient 3
2:17	Bed 3, Equipment Zone	Ventilator	2s		
2:17					Nurse1, Sister 1, and Support worker 1, starting to turn over Patient 1
2:19	Bed 3, Equipment Zone	Monitor	2s	Advisory	
2:19	Bed 1, Equipment Zone	Monitor	2s	Advisory	
2:20	Bed 1, Equipment Zone	Ventilator	2s		
2:20	Bed 1, Patient Zone	Talking (Nurse 1, Patient 1)	5s	Normal	
2:21	Bed 1, Equipment Zone	Monitor	2s	Advisory	

2:22	Bed 3, Equipment Zone	Monitor	1.8s	Warning	
2:23	Bed 3, Equipment Zone	Monitor	1.2s	Warning	
2:23	Bed 1, Equipment Zone	Monitor	165s	Advisory	The monitors at Bed 1 and Bed 2, setting off alarms at the same time
2:23	Bed1, Staff Work Zone	Talking (Nurse 1, Sister 1, and Support worker 1)	60s	Normal	
2:24	Bed 3, Medical Supplies Zone	Nurse 2, washing hands	10s		
2:28	Bed 2, Equipment Zone	Monitor	45s	Advisory	The monitors at Bed 1 and Bed 2, setting off alarms simultaneously
2:29	Bed1, Staff Work Zone	Talking (Nurse 1)	8s	Raised	
2:31	Bed1, Equipment Zone	Monitor	1.8s	Warning	
2:32	Bed 1, Equipment Zone	Ventilator	6s		
2:32	Bed 2, Patient Zone	Talking (Patient 2)	3s	Raised	
2:33	Bed 1, Equipment Zone	Ventilator	2s		
2:33	Bed 2, Patient Zone	Talking (Patient 2)	20s	Raised	
2:35	Bed 1, Equipment Zone	Ventilator	6s		
2:34					Finishing the turning over of Patient 1
2:37					Nurse1, Sister 1, and Support worker 1, starting to turn over Patient 4

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2:37	Bed 3, Medical Supplies Zone	Nurse 2, washing hands	10s		
2:38	Bed 4, Equipment Zone	Ventilator	4s		
2:38	Bed 4, Equipment Zone	Monitor	3s	Advisory	
2:39	Bed 1, Equipment Zone	Monitor	90s	Advisory	The monitors at Bed 1 and Bed 2, setting off alarms at the same time
2:39	Bed 2, Equipment Zone	Monitor	1.2s	Warning	The monitors at Bed 1 and Bed 2, alarms going off at the same time
2:40	Bed 2, Patient Zone	Talking (Support worker 2, Patient 2)	130s	80% Raised + 20% Normal	
2:41	Bed 4, Medical Supplies Zone	Sister 1, washing hands	8s		
2:41	Bed 3, Equipment Zone	Horizontal pump	3s	Infusion	
2:42	Bed 4, Medical Supplies Zone	Nurse 1, washing hands	10s		
2:42	Bed 2, Medical Supplies Zone	Support worker 1, washing hands	12s		
2:43	Bed 4, Medical Supplies Zone	Sister 1, washing hands	10s		

2:43	Bed 4, Medical Supplies Zone	Talking (Support worker 2, Patient 2)	30s	50% Normal+ 50% Raised	
2:43					Finishing the turning of Patient 4
2:45	Bed 1, Equipment Zone	Ventilator	1s		
	Bed 4, Equipment Zone	Ventilator	4s		
2:46	Bed 4, Staff Work Zone	Talking (Sister 2, Sister 1, Nurse 1, Support worker 1)	60s	Normal	
2:47	Bed 4, Equipment Zone	Ventilator	4s		
2:48	Bed 4, Staff Work Zone	Talking (Nurse 3, Sister 1)	280s	80% Normal+20% Raised	
2:48	Bed 3, Equipment Zone	Vertical pump	8s	Infusion	
2:49	Bed 4, Medical Supplies Zone	Sister 1, washing hands	10s		
2:52	Bed 3, Medical Supplies Zone	Nurse 2, washing hands	8s		
2:53	Bed 2, Medical Supplies Zone	Nurse 1, arranging items in a drawer	18s		
2:57	Bed 3, Staff Work Zone	Talking (Nurse 1, Sister 1)	10s	Low	
2:59	Bed 1, Central Aisle Zone	Talking (Doctor 1, Nurse 2)	8s	Low	

Table 2 *Arithmetic means, standard deviations (in brackets) and medians (in italic) of frequency (per hour), interval (s) and duration (s) for five typical noise sources observed over 6 nights in the single-bed and multiple-bed ICU wards.*

		Frequency (per hour)	**Interval(s)**	**Duration(s)**
Talk	Single	3.36	823.27 (±1378.56) *360*	42.36 (±80.24) *11*
	Multiple	12.85	235.05 (±256.28) *180*	62.98 (±132.16) *15*
Ventilator	Single	2.93	1206.18 (±2265.52) *360*	13.11 (±32.94) *6*
	Multiple	7.08	485.66 (±589.16) *240*	8.38 (±32.07) *2*
Monitor	Single	2.76	990.48 (±1596.48) *330*	7.69 (±10.48) *4*
	Multiple	12.24	307.82 (±463.56) *180*	14.61 (±54.09) *3*
Pump	Single	0.39	3460.49(±6092.98) *660*	7.07 (±15.63) *4*
	Multiple	1.45		
Humidifier	Single	0.13	12435.00 (±10727.24) *10050*	2.60 (±6092.98) *2.8*
	Multiple	0.23		

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Table 3 *The estimated parameters (μ, σ and the corresponding standard errors in brackets) of lognormal distribution for the interval (s) and duration (s) for five typical noise sources observed over 6 nights in the single-bed and multiple-bed wards.*

		Interval		**Duration**	
		μ	σ	μ	σ
Talk	Single	5.94 (±0.15)	1.43 (±0.11)	2.85 (±0.19)	1.36 (±0.14)
	Multiple	4.99 (±0.06)	1.09 (±0.04)	2.91(±0.09)	1.49 (±0.07)
Ventilator	Single	5.74 (±0.23)	1.80 (±0.16)	1.38 (±0.16)	1.29 (±0.12)
	Multiple	5.56 (±0.11)	1.27 (±0.08)	0.83 (±0.09)	1.11 (±0.07)
Monitor	Single	5.88 (±0.17)	1.42 (±0.13)	1.40 (±0.12)	0.98 (±0.09)
	Multiple	4.80 (±0.09)	1.47 (±0.07)	1.19 (±0.08)	1.29 (±0.06)
Pump		6.84 (±0.28)	1.80 (±0.20)	1.38 (±0.14)	0.86 (±0.10)
Humidifier		8.79 (±0.40)	1.40 (±0.31)	0.77 (±0.25)	0.70 (±0.19)

Table 4 *The number of occurrences of multiple noises observed over 6 nights in the single-bed and multiple-bed wards, with the relevant perceived loudness level in brackets*

		1st Night	2nd Night	3rd Night
Single-bed	Ventilator + monitor(advisory)	1		
	Ventilator+ monitor(warning)		3	1
Multiple-bed	Ventilator + monitor(warning)	1		
	Ventilator + monitor(warning) + talk	1		
	Monitor(warning) + monitor(warning)	2		
	Monitor(warning) + monitor(advisory)		3	
	Monitor(advisory) + monitor(advisory)		1	
	Monitor(warning) + talk	1		
	Monitor(advisory) + talk	1		
	Ventilator + talk	1		
	3 or 4 talk together	6		
	Monitor(advisory) + pump(infusion)	1		
	Ventilator + pump(infusion)		1	
	Nasogastric + talk			1

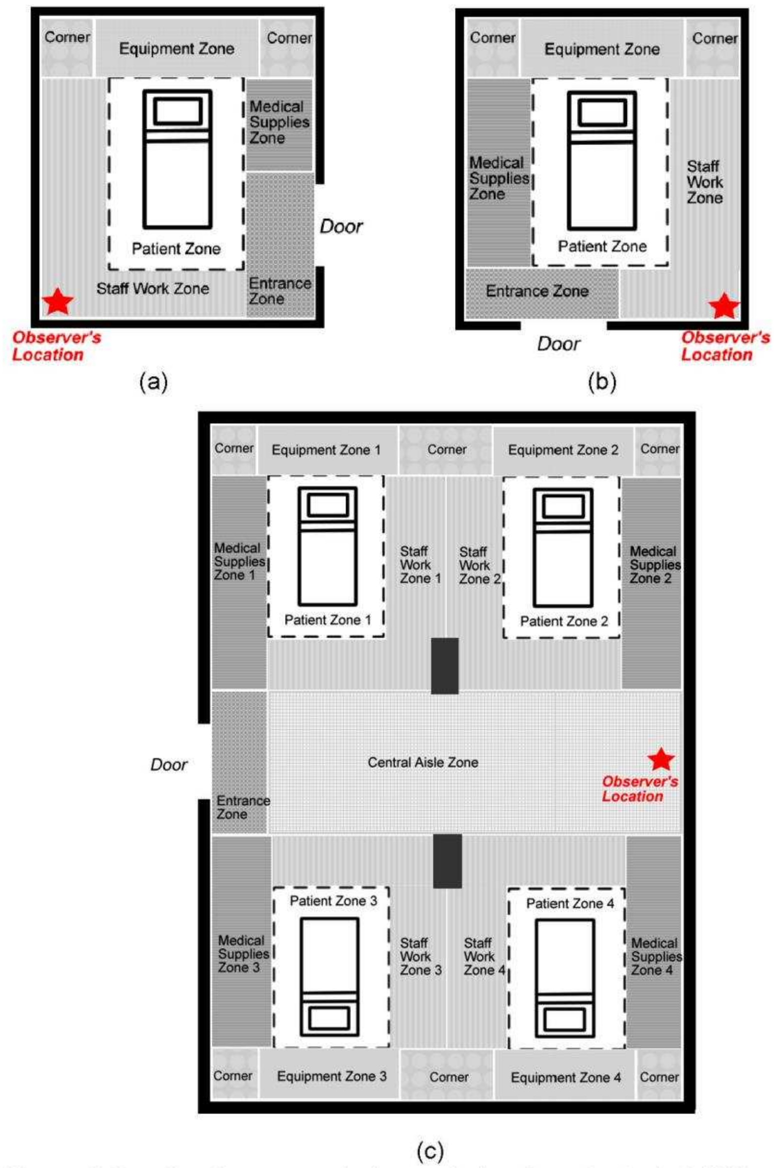
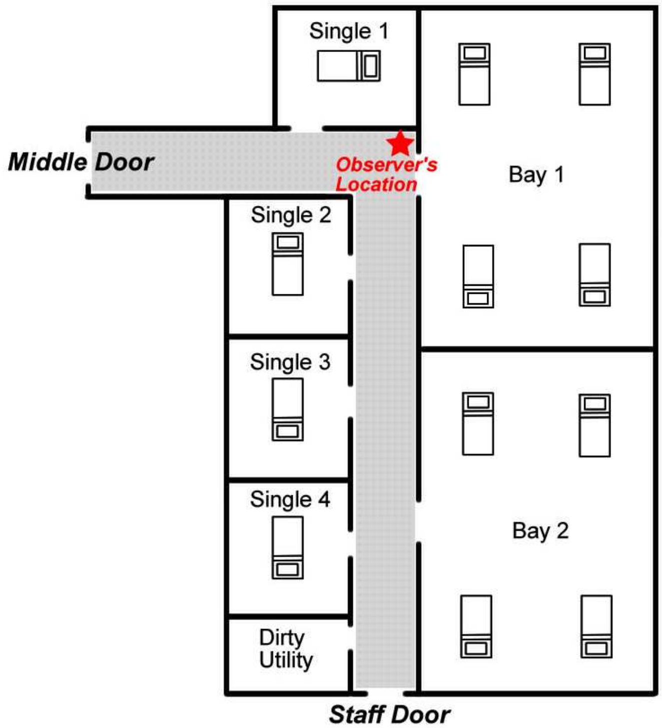


Figure 1 *Functional zones and observer's locations for typical ICU wards: (a) single-bed ward with door on the right or left side, (b) single-bed ward with door on the top or bottom side, (c) 4-bed ward with a central aisle zone.*



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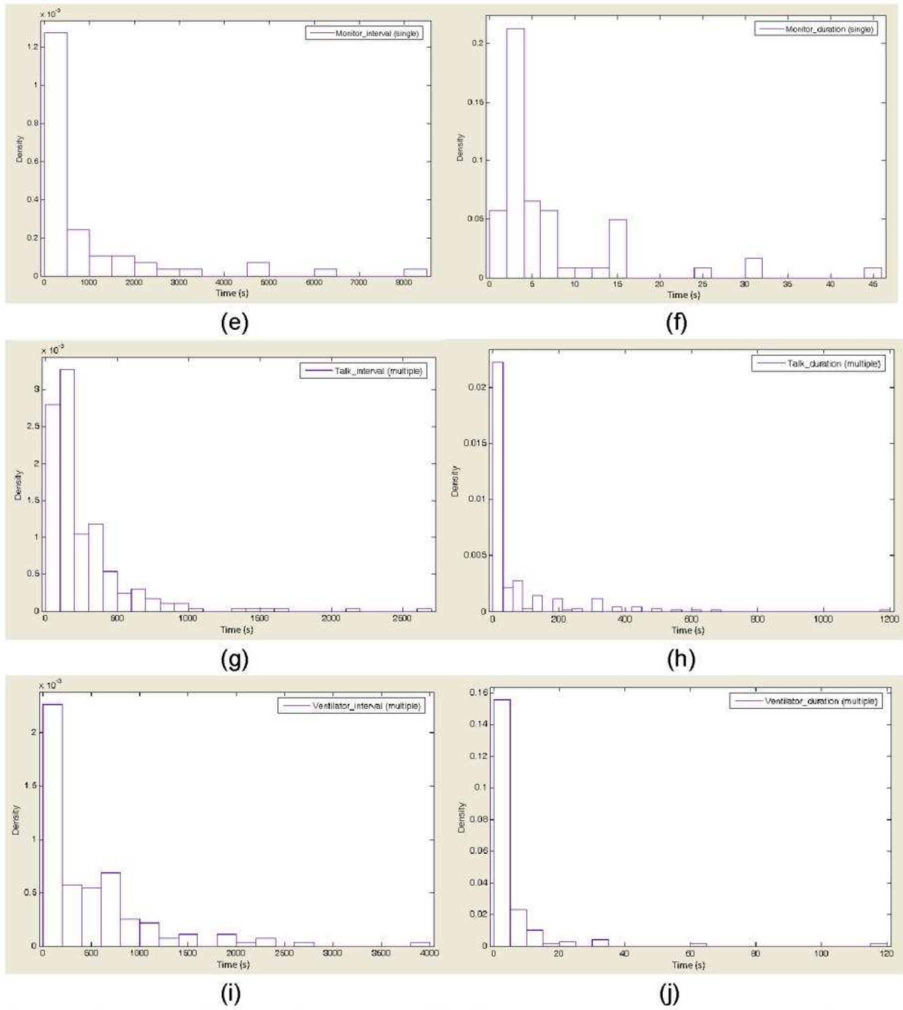

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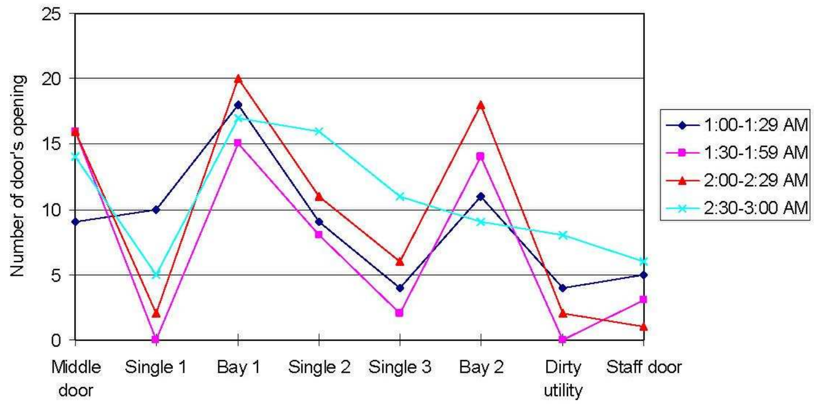

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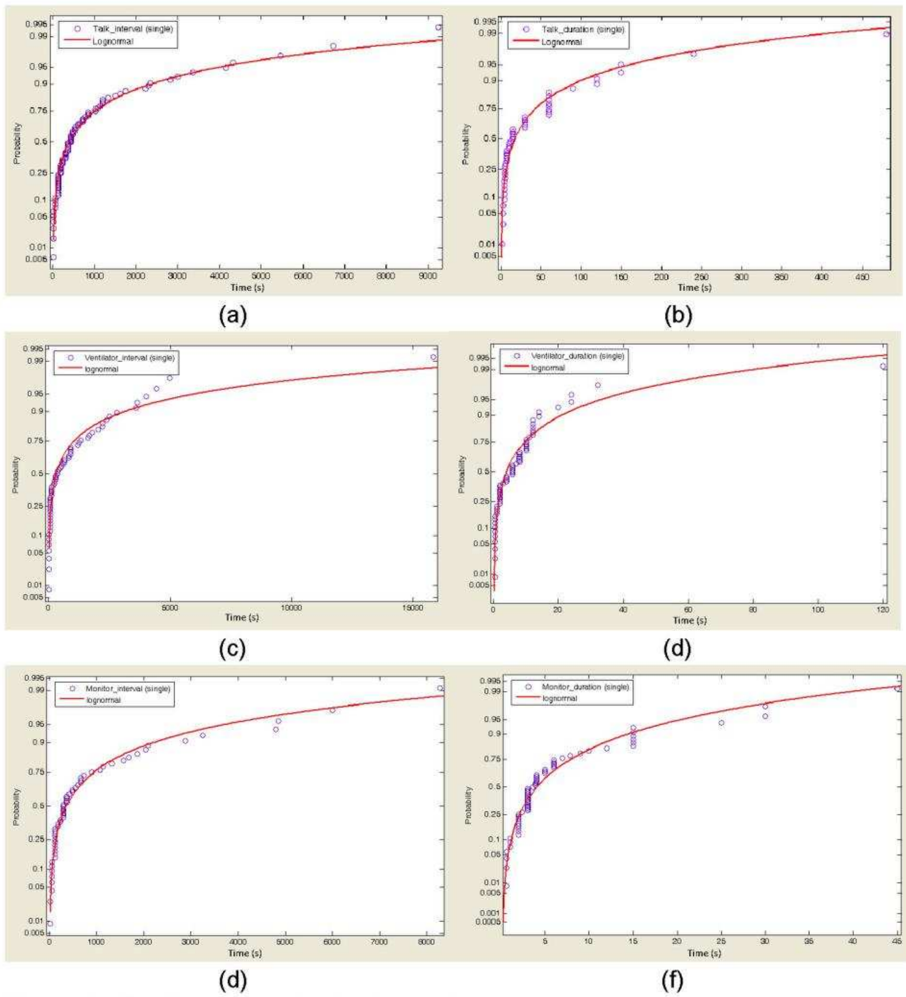

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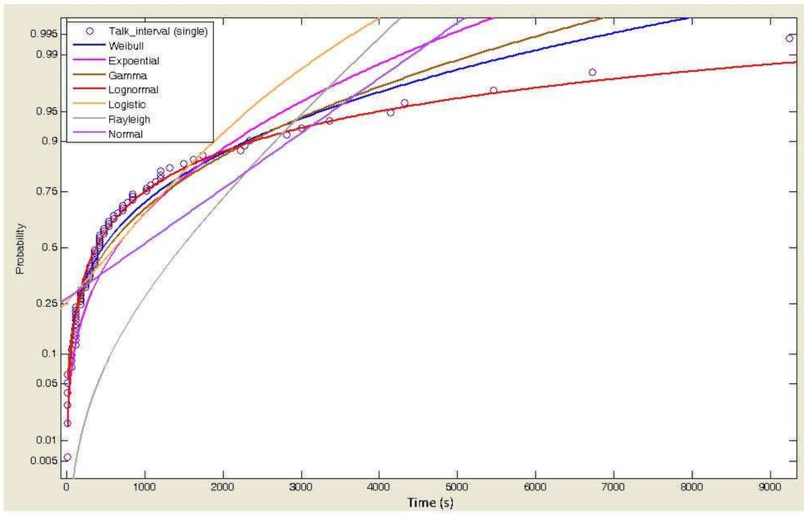
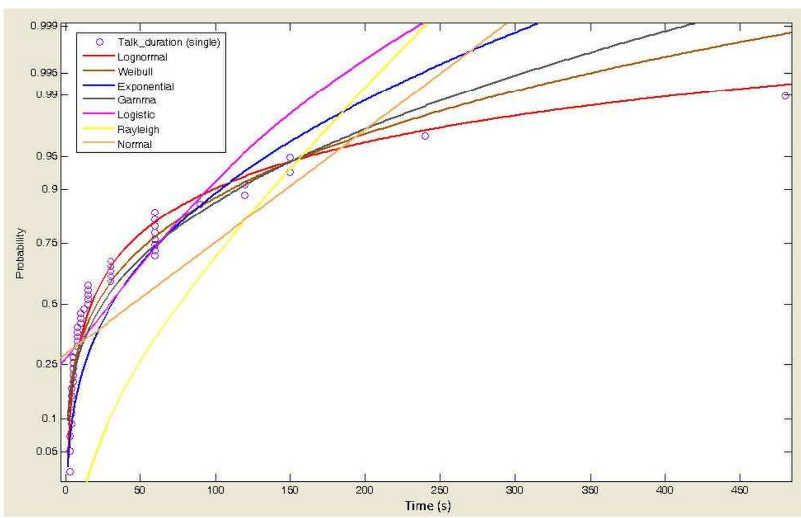


(a)



(b)

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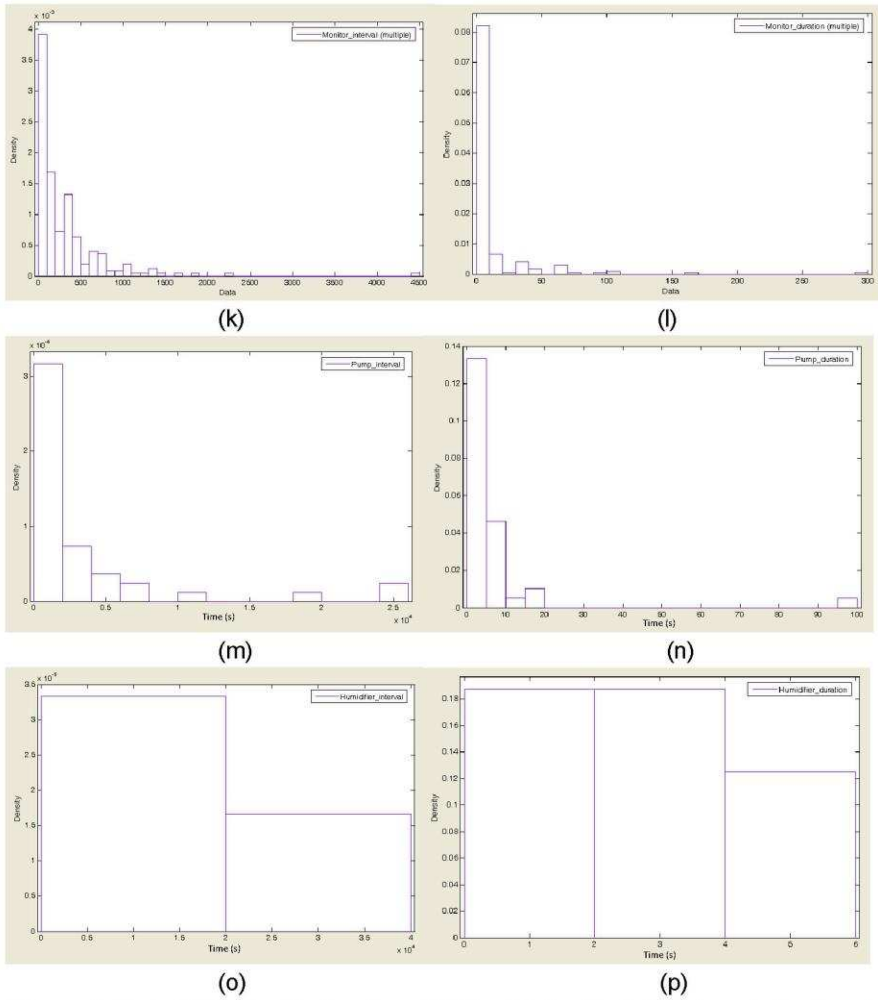

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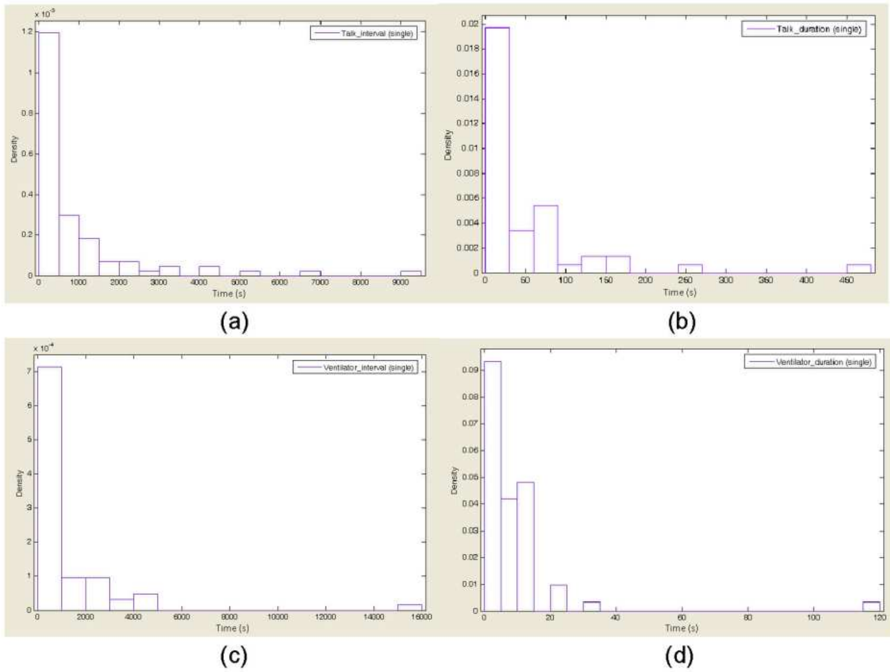

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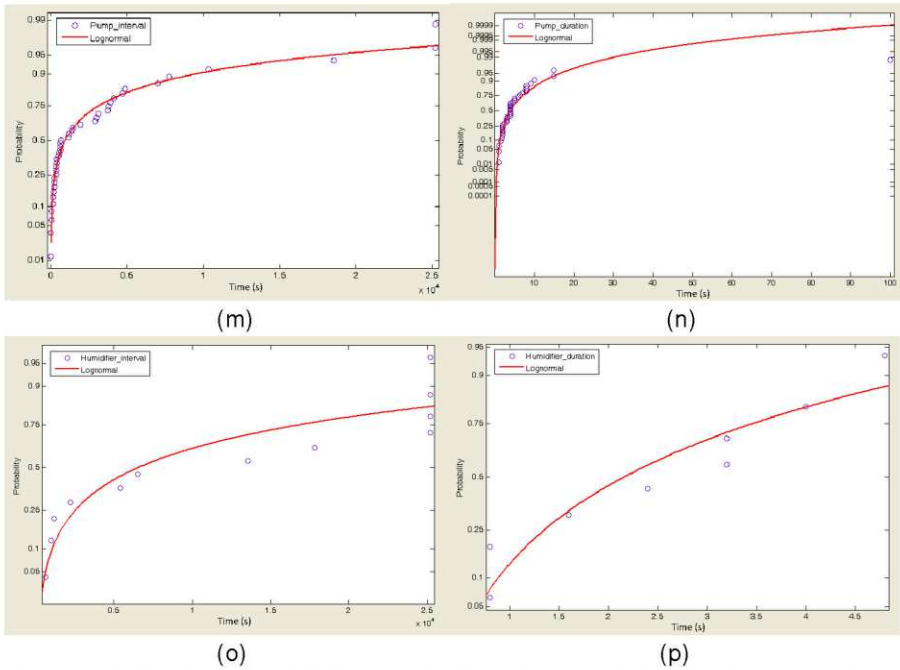
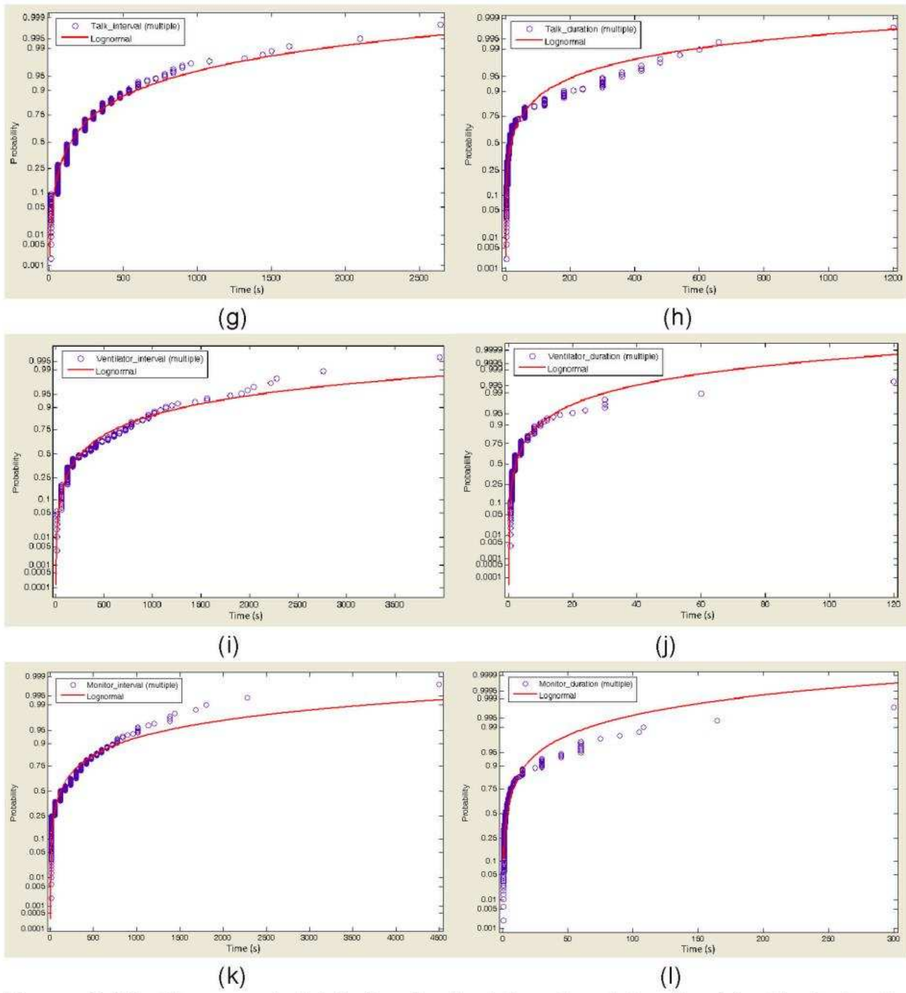


Figure 10 *Fit of lognormal distribution for the interval and duration (s) of typical noises observed in the ICU wards: (m) interval of pump's alarm, (n) duration of pump's alarm, (o) interval of humidifier's alarm, (p) duration of humidifier's alarm.*



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