A study to identify the acoustical characterisation of an adult general intensive care unit

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I hereby declare that this submission is my own work or if not, it is clearly stated and fully acknowledged. To the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except when the acknowledgement has been made in the text.

In memory of my mother
1925-2017

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Abstract

Background: There is a growing body of studies which investigate noise levels in the ICU but few report sound levels longitudinally, in multiple locations and none report data from a mix of single and multiple patient rooms; the common configuration of UK units. There is currently no study that provides a robust description of the noise sources in an ICU or describes sound from the perspective of service users.

Aim: To identify the soundscape of an ICU, utilising a variety of novel research methodologies.

Methods: Preliminary testing provided an understanding of the environment to be studied and piloted a device to collect distributed sound measurements. Three further studies are described. The first utilised the NPL-Minim to collect continuous sound pressure levels from four bed spaces across the GICU. The second, utilised a novel 'Sound in Time' methodology to collect 50hours of observational data to understand the sources of sound originating from these bed spaces. Lastly, sound diaries were completed by 10 each of patients, visitors and nursing staff.

Results: The preliminary study identified the feasibility of, and provided essential parameters to inform a distributed sound measurement study. Following this a total of 271 days of continuous data was successfully measured, which demonstrated an $L_{Aeq271days}$ of 65.4dB, with little variation between day and night. Observational study identified 16784 episodes of disturbance. During the day speech communication was the most common source of sound; at night, alarms became the most prevalent. Patients, visitors and nurses described similar sound sources; however, the individual groups characterised the sources differently.

Conclusion: A variety of methodological techniques, enabled the sound characterisation of an ICU. Concurrent observational and quantitative data collection enabled detailed analysis of the sound environment. Data from the sound diaries will facilitate future study of the perception of sound in this complex clinical environment.

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Chapter One

An Introduction to Sound and Noise

1.1 Introduction

This thesis aims to characterise the acoustic environment of one intensive care unit (ICU) using both quantitative and qualitative methodologies. The studies described utilise three distinct methods including continuous sound pressure level monitoring to identify the noise levels; observational data to identify the key sources of sound disturbance and a sound diary to pilot a method of understanding the perception of sound for patients, visitors and staff. This chapter defines the nouns ‘sound’ and ‘noise’ as used throughout this thesis. It then describes how sound is measured quantitatively, describing the devices available and utilised in various studies described in later chapters and then defines the various terms used to describe sound measurement. The chapter ends with a description of how sound may be described beyond its physical characteristics and how qualitative study augments our understanding of an individual environment, such as an intensive care unit.

1.2 What is sound and what is noise?

Sound pressure is a physical phenomenon and exists whether or not someone is there to hear it. The International Organization for Standardization defines sound pressure as the difference between instantaneous total pressure and static pressure[1]. The tiny variations in pressure that constitute sound are usually only significant because of our sense of hearing. Sound pressure stimulates a mechanical pathway through the ear; the pressure wave is initially funnelled through the outer ear via the pinna and ear canal. It is then conveyed through a series of differentially vibrating structures; the tympanic membrane and in turn, the

three ossicles of the middle ear (malleus, incus and stapes) which amplify the sound wave until it reaches the oval and round windows, the entry to the inner ear, causing mechanical transduction via the thousands of tiny stereocilia in the cochlea. These cause chemical synapses to the auditory nerve fibres. This stimulus is turned into neural information that is initially processed in the auditory cortex and subsequently by other auditory pathways, resulting in hearing.

Amplitude and frequency are two fundamental objective properties of sound. Sound is typically oscillatory in nature and in its most basic form is sinusoidal resulting in a sound known as a pure tone, where the number of waves or cycles per second is termed the frequency. Frequency is measured in hertz (Hz) and relates to our perception of pitch or tonal content of sound. One hertz means an event repeats once per second. For the ear to detect sound there must be at least 20 pressure variations per second and sound becomes inaudible again at 20,000 pressure variations per second[2]. Therefore, the normal range of human hearing is 20-20,000Hz (20kHz), this range however deteriorates with age. Frequency also determines pitch, where a greater frequency results in a higher pitch. Sound is however rarely pure tone, i.e. a single frequency, but made of several frequencies. Industrial noise often contains a wide mix of frequency and is termed broad band noise; whereas white noise is a random signal having equal intensity at different frequencies. The amplitude of the pressure fluctuation is the sound pressure which is measured in Pascals (Pa). The human ear is capable of detecting a wide range of amplitude from 20µPa -200Pa; therefore, a logarithmic scale has been devised in order to describe sound in manageable numbers, this is the decibel (dB) and represents the sound pressure level (SPL). The decibel is not an absolute unit; it is a ratio between a measure in Pa and the agreed reference level of 20µPa, defined as 0dB. For each increase in SPL in Pa by 10, 20dB is added to the dB scale. i.e. 200 µPa is 20dB, 2000 µPa is 40dB, until we reach 200Pa which is

approximately 140dB and considered the pain threshold. More importantly, the decibel scale provides a better approximation to human perception of relative loudness than the Pascal scale. The human ear is not equally sensitive to all frequencies or the full range of amplitude; it is most sensitive to sounds between 2 and 5kHz and low amplitude. The relationship between objective measures of sound and the more subjective perception of sound is complex. Under normal rather than in ideal conditions, the human ear may not perceive a change in sound pressure of <1dB; to perceive a change, an increase of approximately 3dB is required. A 6dB increase represents a of a doubling of sound pressure, an increase of 10dB however, is required for the human ear to perceive a doubling of loudness for SPL above 40dB. For SPL less than 40dB, a doubling of sound requires less of an increment.

Unlike the eye we are unable to close our ears, the auditory channel is permanently open with the brain able to discriminate various sounds even when asleep[3]. Sound can be an annoyance and may not need to be loud to annoy; it is the perception of that sound that causes the annoyance. Any sound may have the potential to cause annoyance, dependant on the perception of the receiver. Noise is therefore unwanted or unpleasant sound and is considered an environmental pollutant resulting in extensive research into the impact of the urban environment on health[4]. Noise can impact on speech intelligibility disabling effective communication, but also has an impact on health including auditory i.e. hearing loss and tinnitus as well as non-auditory effects such as hypertension, stroke, ischaemic heart disease, sleep disturbance, cognitive impairment, longer healing times and an increased requirement for pain relief medication[5].

1.3 Measuring and describing sound

1.3.1 Sound level meters

As described previously, the human ear can detect frequency in the range 20-20,000Hz however the ear is not equally sensitive to all frequencies. To create a metric that correlates with perceived loudness measured in Phons, some weighting of the different parts of the frequency range are necessary. This is best illustrated by the equal loudness contours[6] which are curves in the sound pressure level/frequency plane connecting points whose coordinates represent pure tones judged to be equally loud as shown in figure 1.1.

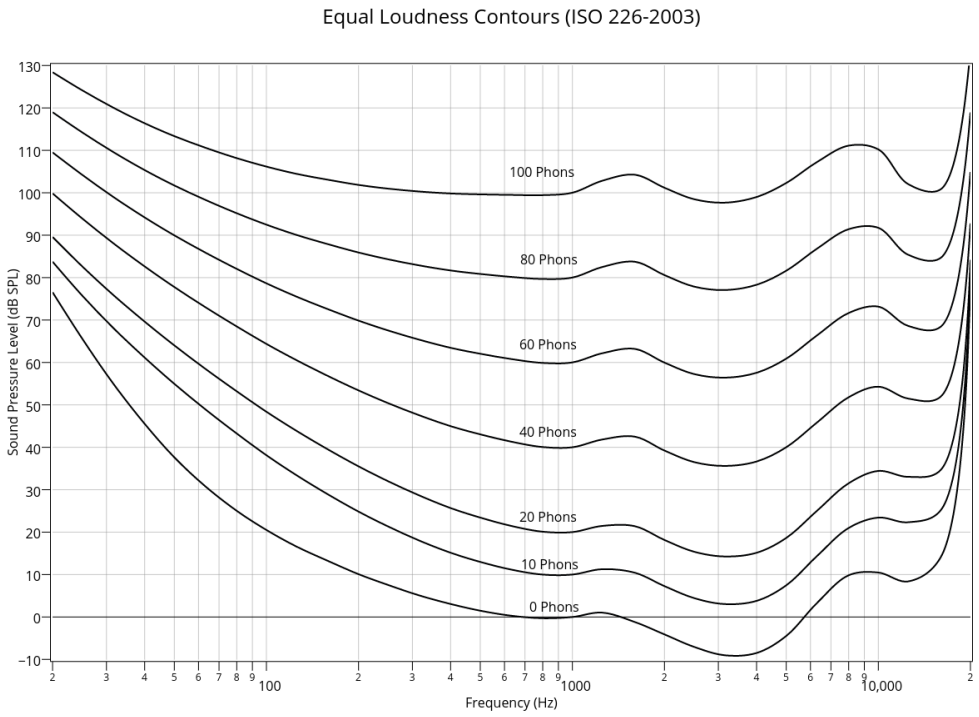


Figure 1.1 Equal Loudness Contours (ISO 226-2003)[6]

Human hearing is frequency selective, requiring the use of frequency weighting filters in sound level meters to correlate the human detection of sound with the objective measurement of sound. These filters or networks "weight" the contributions of the various frequencies to the overall sound level, so that SPL are

reduced or increased as a function of frequency before being combined together to provide an overall level[7]. Three main weightings are commonly reported, A, C and Z. The 'A'-weighting network is the most widely used and modifies the frequency response to approximate the equal loudness contours (figure 1.1) at 40phons[7]. A-weighted measurements correlate well with the perceived loudness at steady state sounds at moderate sound levels, but under represent low frequency sound. C-weighting approximates the equal loudness curves of 100phons and is commonly used for steady sounds at high SPL and impulsive or peak sounds at moderate or high SPL[8]. C-weighting also gives much more emphasis to low frequency sounds. Low frequency noise is associated with increased adverse effects on health[9].

The current international standard that specifies sound level meter functionality and performance is the BS EN 61672-1:2013[10] which mandates the use of A- and C-weighting for all class one (precision) sound level meters. Z or zero weighting is a flat frequency response in the range of 10 Hz to 20 kHz, it was introduced to replace the previous Flat or Linear Filters[8]. A sound level meter is commonly a hand-held instrument that provides objective, reproducible measurement of sound pressure level. The device consists of a microphone, a processing section including a pre-amplifier, weighting network, filters, amplifier, RMS detector (root-mean-square = the square root of the mean of the squares) and a read-out unit[2]. The diaphragm of the microphone responds to changes in air pressure caused by sound waves and converts the pressure signal to an electrical signal. To maintain stability, these devices require regular in situ calibration. The advent of the mobile phone provided a driver for the development of a robust, small, low cost microphone, these were constructed on silicon chips and called micro-electrical-mechanical systems (MEMS) microphones[11]. These microphones provide a cost-effective measurement system for simultaneous, long-term deployment of a large

number of spatially distributed devices which could therefore develop a noise map of an area[12]. These systems have demonstrated stability over time, removing the need for regular calibration and are effective as an alternative to conventional monitoring in the outdoor environment[13].

1.3.2 Energy parameters

Sound pressure levels are reported in dB, annotated with the weighting, type of measurement, for example equivalent (eq), maximum (max), minimum (min) and finally the duration of measurement e.g. minute (min) or hour (hr). The most common method of reporting is the equivalent continuous sound level (L_{eq}), this is an average of the total amount of sound energy measured over a specified period of time. As with any average, the L_{eq} may capture one short loud sound or a series of quieter sounds, therefore to help describe the differences between these two environments L_{max}, L_{min} and percentile levels, known commonly as statistical parameters are utilised and may be measured using either A or C-weighting scales. L_{peak} is used to describe the true peak of sound and is measured only using the C-weighting scale. L_{max} and L_{min} describe the highest and lowest SPL recorded in the measuring period, they do not however, identify the duration of that sound. Statistical parameters such as $L_{0.1}$, L_1 or $L_{90,}$ describe, as a percentage of the overall duration under consideration, how long a particular SPL was exceeded and are therefore useful to identify a single loud noise from a series of noises or the background noise. For example, for L_{90} we would identify the SPL that was exceeded for 90% of the time, this is commonly used to describe the background noise as it would discount any loud noise that might occur in the 10% of time excluded. Whereas an L_1 or $L_{0.1}$ would describe the SPL that was exceeded for just 1% or 0.1% of the time and can therefore describe a loud noise of short or very short duration. To identify the duration of a measurement, a time scale such

as ‘min’ or ‘hr’ is attached to the SPL descriptor, for example a one-hour measurement of the equivalent continuous sound level corrected with A-weighting would read $L_{Aeq1hr.}$ Alternatively internationally accepted abbreviations may be used to described day (07.00-19.00hrs) L_{day}, evening (19.00-23.00hrs) $L_{evening}$ and night (23.00-07.00hrs) $L_{night,}$ which may be abbreviated to L_{DEN} (day, evening, night combined) with different weighting factors applied to the discrete periods to reflect our changing sensitivity to noise at varying times of the day.

1.3.3 Bandwidth and time weighting

Sound may be described as ‘steady state’ which is sound where the level does not change by more than 5dB for a given place and time, for example the sound of a waterfall. Most sounds however, fluctuate by more than 5dB, additionally there may be sounds that are impulsive, individual sound impulses of up to 200ms or a series of impulses following each other in intervals longer than 10ms.To measure this complex sound the frequency range can be divided into bands of either one octave or one third octaves, this is compatible with the physiological processing of the human ear. An octave is a bandwidth where the highest frequency is twice the lowest frequency, the recording will then reject all sound with frequencies outside the set bandwidth, this enables frequency analysis from which the results are presented in a spectrogram.

The sound level meter uses a rolling averaging process, time weightings determine how sensitive to rapid changes in sound level a sound meter is. At any instant the reading is displayed as an average of past readings extending back for a given time period. The meter also applies an exponentially decaying weighting to the past measurements, so that the reading is dominated by the most recent levels and levels beyond a certain time contribute nothing. The time weighting determines the rate of decay of this exponential weighting. Sound pressure meters

have ‘SLOW’ or ‘FAST’ settings with most measurements made with the setting on ‘FAST’. Using the ‘FAST’ response the decay is 0.125s which means that after 0.125s the past reading contributes only 1/e = 37% of its value to the overall weighted mean. Whereas in ‘SLOW’, this level of attenuation is reached at 1s, therefore past values make a stronger contribution to the rolling average and the indicated result is subjected to a degree of smoothing which may provide a better indication of the average noise level in an environment where it is constantly changing.

Two other commonly used descriptors of an indoor sound field are reverberation time and speech intelligibility. Reverberation time is an objective measure of the time required for the sound pressure level to decrease by 60dB after the sound source has stopped. Speech intelligibility is a subjective measure of how comprehensible speech is in given conditions. There are many objective measures which aim to predict speech intelligibility, these include the Speech Transmission Index (STI) and the Speech Intelligibility Index (SII). The STI is a measure based on the generation and analysis of an artificial test signal that replaces the speech signal, this results in an index that ranges from 0 to 1[14]. The SII is a calculated measure, that represents the intelligibility of speech under a variety of adverse listening conditions[15]. Several factors may impact speech intelligibility and its measurement including background noise, the acoustical properties of the environment where speech is transmitted, the receivers hearing and the operator’s clarity. It is suggested that for complex messages the sound level of speech needs to be at least 15dB above the background noise[16]. Noise rating curves are commonly used to measure or specify background noise levels in an unoccupied room, they can however also be applied to noise levels for a particular environment (figure 1.2). The noise rating curve was developed by the

Maximum Noise Rating Level	Application
NR 25	Concert halls, broadcasting and recording studios, churches
NR 30	Private dwellings, hospitals, theaters, cinemas, conference rooms
NR 35	Libraries, museums, court rooms, schools, hospitals operating theaters and wards, flats, hotels, executive offices
NR 40	Halls, corridors, cloakrooms, restaurants, night clubs, offices, shops
NR 45	Department stores, supermarkets, canteens, general offices
NR 50	Typing pools, offices with business machines
NR 60	Light engineering works
NR 70	Foundries, heavy engineering works

Figure 1.2 Noise ratings for various indoor environments – ISO 1973[17]

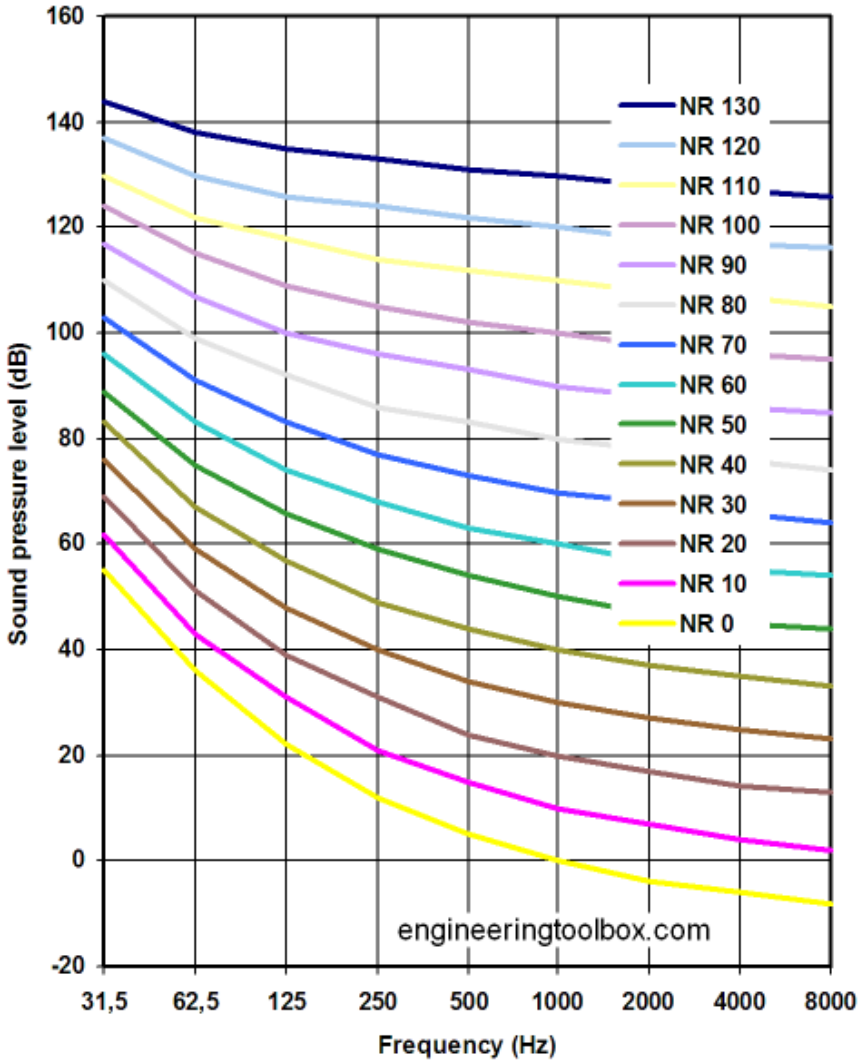


Figure 1.3 Noise rating curves[17]

International Organization for Standardization (ISO 1973) to determine the acceptable indoor environment for hearing preservation, speech communication and annoyance[17]. The noise rating is derived by comparing the noise spectrum in a room with a standardised set of curves as demonstrated in figure 1.3. The lowest curve not to be cut by the actual noise spectrum, when the spectrum and the noise rating curves are plotted in the same scale, is the rating for that space.

1.3.4 Soundscape

The parameters and metrics described above are objective in that they can be defined and measured in an unambiguous, systematic way. However, our perception of the sound that can be so described, is subjective, in that our perception of that sound will change depending on the environment, time of day, mood and a host of other factors. In 2014, the International Organization for Standardization provided a working definition of a soundscape as the '*acoustic environment as perceived or experienced and/or understood by a person or people, in context.*'[18]. Our temporal and spatial awareness of sound are largely processed by different hemispheres of the brain and different individuals will react differently to the same sound[19]. Soundscape research attempts to bridge the gap between objective measurement and subjective human perception. A soundscape is the auditory equivalent to a landscape[20] and describes a combination of sounds that define an environment that most members of that community can relate to. Often this incorporates a number of keynote sounds described as background sounds that typify a space[21], they may not always be heard consciously, but they '*outline the character of the people living there*'[22]. Signals are described as foreground sounds which are listened to consciously, for example an alarm, and sound marks, the term derived from the term landmark, are described as culturally important sounds[21] which make the acoustic life of a community unique. For example, in very broad terms a rural soundscape might consist of bird song and

the gentle flow of water, compared with an urban area with traffic noise. Each of these soundscapes may enable general description of the area but to an individual or community the keynote sounds, signals and sound marks may precisely locate it. As often demonstrated by television drama, the soundscape of an intensive care environment can be easily invoked by the regular beep of an electrocardiogram (ECG) or the assertive emergence of a monitor alarm. The understanding of a soundscape augments our knowledge by capturing the multi-dimensional relationship between the sound source, physical environment and the perceptual interaction with the physical sound[23,24].

Perception describes how individuals feel about the sound rather than simply the physical aspects of that sound[25]. It is often thought that lowering noise levels will lead to a more positive perception of an environment, however intensity is only a part of the mix of parameters that determine our subjective reaction[26] and perhaps quietness may be associated with a lack of annoying sound rather than the absence of sound[27]. Generally, to understand perception it is necessary to measure the level of annoyance or disturbance, this best describes the attitude of an individual or community to the sounds to which they are exposed. There are several methods of describing soundscapes and measuring annoyance such as written or acoustic sound diaries, questionnaires, semantic differential technique[28] and Q methodology[29,30].

The semantic differential technique utilises bi-polar paired adjectives such as ‘quiet -loud’, ‘pleasant -unpleasant’ and ‘comfortable-uncomfortable’ which can be arranged at either end of a 5- or 7-point psychometric rating, such as a Likert type scale and considered as a continuous variable. This test is frequently used to examine the urban soundscape[23] and has the potential to enable soundscape description in the hospital environment[31]. Q methodology combines the strengths

of both qualitative and quantitative methods[32]. Participants are presented with a series of statements and are requested to rank-order the statements from their personal perspective. These rankings are then subjected to factor analysis which enables correlation between similar viewpoints to develop an understanding of the perspective of a group[28]. Sound diaries[33] and questionnaires[34] provide methods of capturing a unique soundscape vocabulary that can be utilised for the semantic differential technique or the Q methodology. Data for sound diaries may be collected using a small recording device to record sounds that may describe the soundscape, a log book can then enable the individual to record factual and emotional information about the recorded sound[33].

Studies using these techniques have identified that sound perception is directly related to the many non-auditory effects highlighted previously. An understanding of the context, source, distance, temporariness and control over noise may be more helpful when attempting to change the soundscape rather than just managing its reducing physical properties[35]. Previously study in hospital environments have demonstrated that patients provided with sound source information become more tolerant of the noise around them, suggesting when these sounds are understood, accepted and habituated, then the perception of the sound environment becomes more acceptable[36]. The healthcare sound environment should be more than acceptable, it should support the well-being and healing of patients[37]. There is however very little study into soundscapes in hospitals and none to the authors knowledge in intensive care units. By attempting a more comprehensive approach to the study of the sound environment in an intensive care unit, the author aims to understand the potential for controlling the impact of noise and moving the philosophy of the intensive care unit from a place of physical healing to a place that also embraces the well-being of patients, visitors and staff alike.

1.4 Conclusion

Amplitude and frequency are two fundamentals properties of sound; amplitude is measured in decibels and frequency in hertz. Human hearing is frequency selective, therefore to achieve a measure of sound as perceived by the human ear, frequency weighting filters are required in sound level meters. Three main weightings are commonly reported, A, C and Z. A-weighted measurements correlate well with the perceived loudness at steady state sounds at moderate sound levels, but under represent low frequency sound. C-weighting is commonly used for steady sounds at high SPL and impulsive sounds at moderate or high SPL. C-weighting also provides emphasis to low frequency sounds. Low frequency noise is associated with increased adverse effects on health. Noise is an environmental pollutant, impacting on both auditory and non-auditory health. Sound becomes noise when the receiver's perception is that of unwelcome or unpleasant sound. Objective measurement may quantify sound but does not describe sound as experienced by the receiver. A soundscape describes sound qualitatively, it portrays the multi-dimensional relationship between the source, the environment and the perceptual interaction within that sound environment. Measuring sound using a range of methods enables the description of a soundscape and provides the tools to understand the impact of noise on the individual and community. Understanding the impact of noise is the key to adjusting or manipulating the soundscape to make the environment more harmonious for those within it.

Chapter Two

Literature Review

2.1 Introduction

The previous chapter identified how sound is described and measured. This chapter identifies the pertinent literature related to this thesis. It reports the relevant regulatory standards for acoustics required in hospital and specifically the intensive care unit. It highlights the historical perspective of noise as a problem in hospitals and identifies previous campaigns in the United Kingdom (UK) to address this problem. A large part of this review identifies and details the literature related to noise measurement and source identification in the intensive care unit, providing a critique of the methods utilised and the limitations of the reported studies. The review then moves to the impact of noise in the intensive care on patients and staff. It finishes with a review of a new method of understanding how noise impacts sleep and rest in the critically ill patient.

2.2 Acoustic standards for hospitals

Several guidance documents make recommendations or set standards for the management of noise in hospitals. British guidance is commonly based on European guidance or Internationally agreed standards where these are available, however much of the information for intensive care is extrapolated from environmental noise guidance and therefore the recommendations are not uniformly applied.

The Control of Noise at Work Regulations 2005 No. 1643[38] is based on the European Directive 2003/10/EC. This identifies daily or weekly personal exposure values for the prevention of hearing loss in employees exposed regularly and

continually to excessive noise i.e. >80dBA. Although it is unlikely that intensive care units would meet this as a continuous equivalent sound pressure level, it contains useful guidance to reduce noise exposure, equally applicable to any workplace or in-patient healthcare facility including:

- choice of appropriate work equipment emitting the least possible noise
- the design and layout of workplaces, work stations and rest facilities
- suitable and sufficient information and training for employees, such that work equipment may be used correctly
- reduction of noise by technical means
- appropriate maintenance programmes for work equipment, the workplace and workplace systems
- limitation of the duration and intensity of exposure to noise
- appropriate work schedules with adequate rest periods.

The Health Building Note (HBN) 04-02:2013 Critical Care Units[39] is national and specific guidance for the intensive care environment, but not specifically for the management of the acoustic environment. It however states three pieces of guidance, although does not specify sound levels or define the terms 'reasonable', 'control', 'reduce' or 'improve'. These are:

- 4.15 '*All bed spaces should be capable of providing visual privacy and reasonable auditory privacy, …'* page 9
- 6.3 '*each base should be partially enclosed to control noise transfer'* page 11
- 6.13 *'the density of the curtains should reduce the level of general noise transmitted and also improve the level of auditory privacy in the bed space'* page 14

It is unlikely that the disposable paper curtains commonly utilised in an intensive care unit would provide any level of noise abatement or auditory privacy. Additionally, there is no reference to acoustic absorption including ceiling tiles or how glass partitions may limit the ability to reduce noise, bed space layout to improve the acoustical environment for the patient or staff caring for them or the level or number of equipment alarms. To some extent this information is provided by the Specialist Services Health Technical Memorandum (HTM) 08-01:2013 Acoustics[40], which is not specific to critical care. The first paragraph identifies the purpose of the HTM as *'to provide comprehensive advice and guidance on the design, installation and operation of specialised buildings and engineering technology used in the delivery of healthcare'* (page iii). The document identifies that this guidance is applicable to new and existing sites and that good acoustical conditions improve patient welfare and staff comfort. It provides recommended criteria for noise intrusion from external (figure 2.1) and internal sources (figure 2.2), it however excludes medical equipment and does provide clear boundaries for noise intrusion.

Room type	Example	Criteria for noise intrusion to be met inside the spaces from external sources (dB)
Ward – single person	Single-bed ward, single-bed recovery areas and on-call room, relatives' overnight stay	40 $L_{Aeq,\ 1hr}$ daytime 35 $L_{Aeq,\ 1hr}$ night 45 $L_{Amax,\ f}$ night
Ward – multi-bed	Multi-bed wards, recovery areas	45 $L_{Aeq,\ 1hr}$ daytime 35 $L_{Aeq,\ 1hr}$ night 45 $L_{Amax,\ f}$ night

Figure 2.1 Criteria for noise intrusion from external sources for ward areas (table 1, page 3 HTM 08:01[40]) Night time defined as 23.00-07.00hrs

Area type	Example	Noise from mechanical and electrical services
Ward areas, sleeping areas	Single-bed ward, multi-bed ward, on-call rooms, relatives' overnight stay Recovery rooms	NR 30 NR 35
Small office-type spaces	Private offices, treatment rooms, interview rooms, consulting rooms	NR 35

Figure 2.2 Criteria for internal noise for areas from mechanical and electrical services (table 2, page 4 HTM 08:01[40])

This guidance recommends the sound insulation characteristics for various clinical areas, highlighting whether that room is considered an area where privacy is required. It suggests that where rooms are adjacent, the potential for noise ingress should be considered (para 2.50). Figure 2.3 identifies the required sound insulating characteristics for hospital rooms, some of which are applicable to an intensive care unit, figure 2.4 identifies the sound insulation ratings for these rooms, please see accompanying notes within the figure.

Room	Privacy requirements for source room	Noise generation of the source room	Noise sensitivity of receiving room
Clinical areas			
Single-bed/on-call room	Confidential	Typical	Medium
Multi-bed room	Moderate	Typical	Medium
Children & older people (single bed)	Private	High	Medium
Children & older people (multi-bed)	Moderate	High	Medium
Consulting room	Confidential	Typical	Medium
Examination room	Confidential	Typical	Medium
Treatment room	Confidential	Typical	Medium
Counselling/bereavement room	Confidential	High	Medium
Interview room	Confidential	Typical	Medium
Operating theatre suite	Private	Typical	Sensitive
Nurseries	Moderate	Very high	Medium
Birthing room	Private	Very high	Medium
Laboratories	Moderate	Typical	Medium
Dirty utility/sluice	Not Private	High	Not sensitive
Clean utility	Not Private	Low	Not sensitive

Figure 2.3 Sound insulation parameters of rooms (Table 3, page 7, HTM 08:01[40])

Privacy requirement for source room	Noise generation of the source room	Noise sensitivity of receiving room		
		Not sensitive	Medium sensitivity	Sensitive
Confidential	Very high	47	52	★
	High	47	47	52
	Typical	47	47	47
	Low	42	42	47
Private	Very high	47	52	★
	High	42	47	52
	Typical	42	42	47
	Low	37	42	42
Moderate	Very high	47	52	★
	High	37	42	47
	Typical	37	37	42
	Low	No rating	No rating	37
Not private	Very high	47	52	★
	High	No rating	42	47
	Typical	No rating	No rating	42
	Low	No rating	No rating	37

Notes:
★ = These adjacencies should be avoided by layout planning. Where this is not possible, $D_{nT,w}$ 57 dB needs to be achieved as a minimum. In practice this is extremely difficult, as it would need very wide partitions and place onerous demands on the building structure to control flanking noise sufficiently.

Note that for:
Confidential – raised speech would be audible but not intelligible, and normal speech would be inaudible.
Private – normal speech would be audible but not intelligible.
Moderate – normal speech would be audible and intelligible but not intrusive.
Not private – normal speech would be clearly audible and intelligible.
Sensitive – room cannot accommodate any noticeable noise from rooms next door.
Medium sensitivity – room generally needs to be free from noise of other rooms.
Not sensitive – noise from other rooms does not affect the use of the receiving room.

Figure 2.4 Sound insulation ratings (dBnT,w) to be achieved on site (table 4, page 9, HTM 08:01[40])

Para.2.26 (page 5) highlights that *'the noise from medical equipment should be considered when it is selected. Ideally it should be chosen so that it does not adversely affect the use of its surrounding space'* and that '*quiet equipment should be chosen'*, going on to note that '*In sleeping areas, intermittent noise or increased background noise levels can disturb sleep*'. This guidance is designed to assess the buildings functionality rather than acceptable operational acoustical parameters. It is written from the perspective of the whole hospital and is not specific to intensive care units. Despite identifying that it applies to existing sites, it is unlikely to be applied retrospectively, only being applied to the areas where

any major refurbishment work is undertaken, therefore many hospitals and intensive care units will not be working to these specifications.

The Guidelines for Community Noise published in April 1999[16] is the most frequently referenced guidance in studies of noise in the ICU and hospitals in general. In part, it has been superseded by more recent documents, (e.g. the Environmental Noise Guidelines for the European Region 2018[41]), which provides one of the clearer definitions of noise limits for hospitals. It defines community noise '*as noise emitted from all sources except noise at the industrial workplace'* and appears to be the only available document that defines average and maximum operational acoustical levels for hospitals outside of the United States (US). It suggests that as patients have less ability to cope with stress, the L_{Aeq} should not exceed 35dB in most rooms where patients are treated or observed (para.4.3.3, page 44) or using the precautionary principle, the lowest level achievable (section 5a, page 48). It specifically identifies that noise should not exceed 30dB L_{Aeq} at any point in the 24hrs and 40dB L_{Amax} at night, defined as 23.00-07.00hrs (para.4.3.3, page 44, table 4.1). If these are compared with the later HTM 08:03 then there is clear discrepancy between the higher levels set for an empty building and those in the WHO guidance which refer to operational levels of noise. The more recent WHO 2009 Night noise guidelines for Europe[42], identify that the guidance previously stated by Berglund 1999 remains appropriate *'that if negative effects on sleep are to be avoided the equivalent sound pressure level should not exceed 30 dBA (L_{Amax}) indoors for continuous noise*'. The authors of these guidelines produced a useful table highlighting the health effects of noise on the population (figure 2.5). This supports the notion that noise limits in a hospital should be between L_{Aeq} 30-40dB due to the level of vulnerability of the population.

Average night noise level over a year $L_{night,outside}$	Health effects observed in the population
Up to 30 dB	Although individual sensitivities and circumstances may differ, it appears that up to this level no substantial biological effects are observed. $L_{night,outside}$ of 30 dB is equivalent to the NOEL for night noise.
30 to 40 dB	A number of effects on sleep are observed from this range: body movements, awakening, self-reported sleep disturbance, arousals. The intensity of the effect depends on the nature of the source and the number of events. Vulnerable groups (for example children, the chronically ill and the elderly) are more susceptible. However, even in the worst cases the effects seem modest. $L_{night,outside}$ of 40 dB is equivalent to the LOAEL for night noise.
40 to 55 dB	Adverse health effects are observed among the exposed population. Many people have to adapt their lives to cope with the noise at night. Vulnerable groups are more severely affected.
Above 55 dB	The situation is considered increasingly dangerous for public health. Adverse health effects occur frequently, a sizeable proportion of the population is highly annoyed and sleep-disturbed. There is evidence that the risk of cardiovascular disease increases.

[1] "Article 8:1. Everyone has the right to respect for his private and family life, his home and his correspondence." Although in the case against the United Kingdom the Court ruled that the United Kingdom Government was not guilty of the charges, the right to undisturbed sleep was recognized (the Court's consideration 96).

[2] $L_{night,outside}$ in Table 5.4 and 5.5 is the night-time noise indicator (L_{night}) of Directive 2002/49/EC of 25 June 2002: the A-weighted long-term average sound level as defined in ISO 1996-2: 1987, determined over all the night periods of a year; in which: the night is eight hours (usually 23.00 – 07.00 local time), a year is a relevant year as regards the emission of sound and an average year as regards the meteorological circumstances, the incident sound is considered, the assessment point is the same as for L_{den}. See *Official Journal of the European Communities*, 18.7.2002, for more details.

Figure 2.5 Effects of different levels of night noise on the population's health (Table 5.4 page 108. WHO 2009 Night noise guidelines for Europe[42])

The latest WHO guidance is the Environmental Noise Guidelines for the European Region[41] published in late 2018. This provides recommendations for protecting human health from exposure to environmental noise originating from various sources rather than locations, therefore hospital noise is not addressed. Example noise limits are however provided for various sources including rail, aircraft, road and wind turbine with a range for these various continuous equivalent various noise levels of 40- 45$L_{eqnight}$ and 45- 54 dB $L_{eqDEN.}$ These limits, if thought harmful to healthy individuals in the general population, must intuitively be considered

similarly in the hospital and intensive care setting. The US Environmental Protection Agency published in 1974 '*Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety*'[43]. This guidance is also commonly cited and suggests that noise should not exceed $45L_{eqDN}$. Although this is similar to other guidance, it is now over forty years old and does not appear to have been superseded in the US, with the exception of the three various WHO documents which were all published subsequent to this guidance.

2.3 Noise in hospitals

Noise is not a new problem for hospitals, in her seminal book '*Notes on Nursing: What it is, and what it is no*t'[44] Florence Nightingale suggests in 1859 that *'Unnecessary noise, then, is the most cruel absence of care which can be inflicted on either sick or well'* p.33. She goes on to highlight the negative impact on patients of individuals thoughtlessly conversing either in corridors outside a patient's room or worse still whispering at the bedside and the soothing nature of music [wind instruments and human voice].

A century later the Kings Fund in 1958 published a report *'Noise control in hospitals*'[45]. The report was based on the findings of surveys distributed to more than 2,000 patients in English hospitals and was repeated in follow-up surveys carried out in 1960 and 1973. These reports highlight both the problem of noise in hospitals but also the changing social attitudes to noise, as various annoyances become daily phenomena, such as road noise. They highlight familiar themes such as hospital equipment, squeaking trolley wheels, slamming hospital doors, vacuum cleaners and dripping taps being common complaints. In an effort to highlight how '*small fixes*' might address many of these issues, the King's Fund commissioned the cartoonist, Fougasse, (Figure 2.6) to produce a series of

informative posters aimed at hospital staff and used the phrase '*Clatter does matter'* [46]

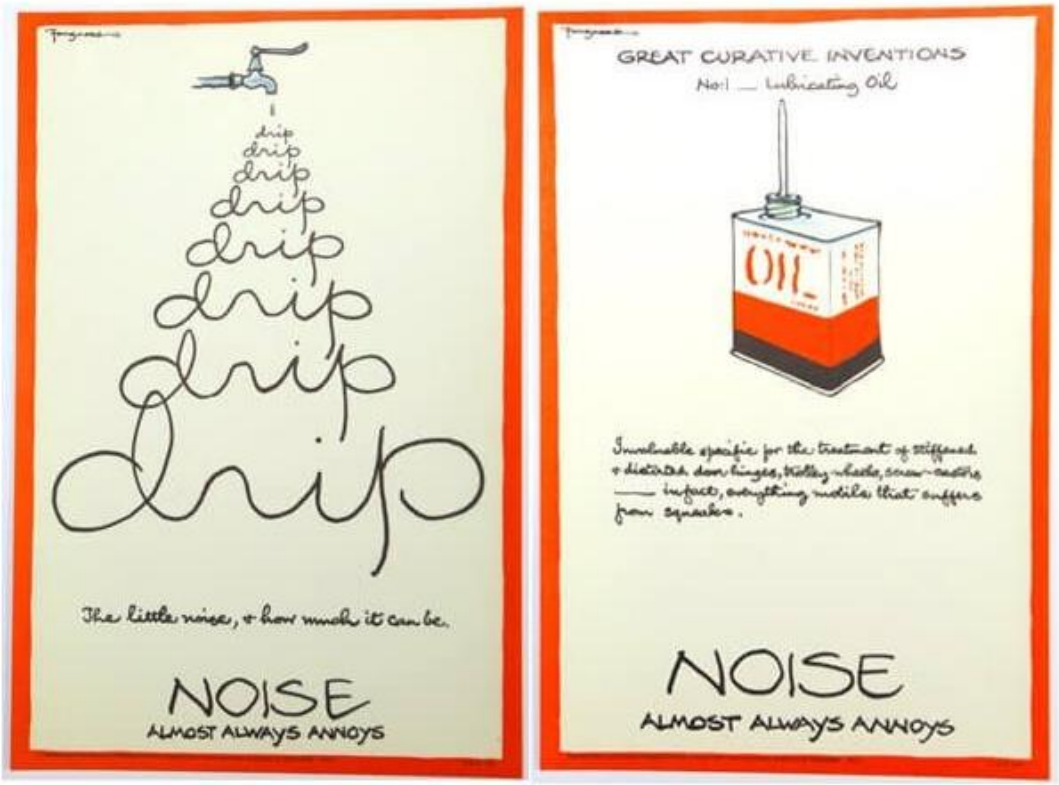


Figure 2.6 Examples of Fougasse Posters[46]

Fifty years later, the Care Quality Commission in-patient survey for 2017[47] noted that the NHS 'Friends and Family Test' has highlighted noise at night contributes to poor patient experience. The in-patient survey reported that 40% respondents were bothered by noise made at night by other patients and 20% of patients were bothered by noise at night from hospital staff. These annual measures demonstrated no or minimal improvement on the 2016 data. In 2017, NHS Improvement[48] published guidance and a case study on how to reduce noise at night and disruption, highlighting that the most effective methods need joint effort from patients and staff. To assist this, methods such as 'quiet time' posters, drawing blinds and diming lights were suggested to promote better sleep quality.

Perhaps this suggests that '*If history repeats itself, and the unexpected always happens, how incapable must Man be of learning from experience*' p243 George Bernard Shaw[49].

Patient experience is supported by studies of noise in the general wards and in specialist areas such as the ICU. A review of studies from various hospitals over 45 years from the 1960's -2005 identified that there was a clear trend for A-weighted equivalent sound pressure levels increasing annually in a linear fashion by approximately 0.38dBA during the day and 0.42dBA at night[50]. Daytime levels increased from 57dBA in the 1960's to 72dBA in 2005, likewise night-time levels from 42dBA to 60dBA, not one study included in the analysis complied with the World Health Organization's 1999 guidance; averaging 20-40 dBA higher than these recommendations[50]. Similar to WHO 1999 Guidance, this is a widely quoted study and the results of this analysis may appear intuitively correct to any clinician working in an intensive care unit, however the inconsistencies in methods and poor reporting of the included studies, require the reader to question the conclusion. Studies of ward areas are more limited than those in the ICU, however SPL appear similar across studies, with a trend as identified in Busch-Vishniac[50] to increase over time. Christensen[51] reports average L_{Aeq} of 42.3dB in a general surgical ward in the UK and in a general medical ward in the US levels were reported to be $L_{Aeq24hr}$ 48.0dB with L_{Amax} 80.3dB, night time levels reduced to L_{Aeq8hr} to 38.0dB[52]. Richardson and colleagues[53] in a pre/post noise reduction study intervention across surgical, medical and orthopaedic wards in the UK, identified sound levels of $L_{Aeq24hr}$ 46.87dB pre-noise reduction intervention and $L_{Aeq24hr}$ 49.67dB post. Interestingly, L_{Apk} (definition as reported in the study) was reduced significantly across all three wards after the intervention, suggesting that although overall noise levels had not decreased the incidence of peak sounds had reduced. A more recent study of five general wards with a mix of orthopaedic, surgical and

medical specialities across two hospitals reports $L_{Aeq24hr}$ between 52.0dB and 55.9dB, with L_{Aeq8hr} between 44.1dB and 49.4dB at night[54].

2.4 Noise in the intensive care unit

Noise in the intensive care unit is considered an ergonomic disaster being a by-product of the ad hoc development of critical care[55]. There is a growing body of studies spanning forty years and originating from fifteen countries that measure noise levels in the adult ICU[24,56-94]. As previously described[50], all report sound levels to be higher than is currently recommended, ranging from L_{Aeq} 39.8-70.0dB with maximum levels of >100dBA, dependant on time of day, occupied beds and methods used. It is however, extremely concerning that despite the number of reports from a broad representation of countries, over a long period of time, little has been achieved in improving our understanding of noise and its impact in the intensive care unit. The majority of studies are too poorly reported to enable replication of individual study or comparison between studies, resulting in an unreliable body of evidence on which to base change and thus improve the acoustical environment for patients and staff alike. It appears that there has been limited collaboration between intensive care clinicians and acousticians to ensure both relevant and correct methodology and acoustically and clinically reliable reporting.

The majority of the studies mentioned above measure SPL alone, however fifteen include a measure of the sources of noise[60-62,64,68,70,71,73,77,79,82,85,86,88,89], three further papers investigate noise sources as the primary purpose of the study[95-97]. Most studies are observational, six report results of interventional studies describing pre and post behavioural and environmental interventions[60, 64,81,82,93,94]. All but three[62,69,78], report the method of measuring sound, most of these used conventional sound level meters, one, our pilot study (chapter five) reported using

MicroElectrical-Mechanical System (MEMS) microphones[80], two utilised a mobile phone application (app)[87,90] and two utilise a device known as a SoundEar™[93,94]. Twenty-one of the studies report placement of the sound level meter near the patient's head to record sound as the patient might experience it [56,58-60,63,67,70,71,74-79,83,88,89-92,97]. Fourteen studies report data measuring SPL continuously for greater than 24hours[61,63,65-67,72,80,82,83,86,91,92,94,89,97] (Table 2.1), three of these studies report limited source data[61,82,86], one reports source as its main focus but due to limited SPL reporting is not included in the table below[97] and three report SPL in multiple simultaneous locations[86,91,92].

By measuring for more than 24hrs, these studies are the most likely to provide representative data to enable an understanding of the sound levels in an ICU. They are however not without problems, the methodology and outcome reporting varied widely, as can be seen in table 2.1. Data were measured in both single[61,63,65-67,72,80,82,83] and multiple[86,91,92] locations; of these, four provide very limited information of the instrumentation, sampling rates and position of the microphone[61,65,82,94]. Sound pressure levels varied between studies, with the highest L_{Aeq} reported during day time hours being 64.8dBA (16.00hrs)[80], the lowest measure reported being 52.8dBA a median value, during daytime (not defined)[91], the highest night time (not defined) L_{Aeq} 62.7dBA[61] and the lowest 43.03dBA (03.00hrs)[86]. Interestingly, it appears there is a tendency for the single/two bed rooms being slightly quieter, although the different methods of reporting make this difficult to determine objectively[63,72,67,86,91,92] and many other factors may have impacted on these results. It can be seen from these examples that objective comparison between studies is extremely difficult.

	Day time L_{Aeq}	Night time L_{Aeq}	24hrs L_{Aeq}	Microphone position	Beds	Year	Country	Unit
Memoli et al,.[80]	64.8 (16.00)	57.8 (03.00)	NR	Staff base	Open bay	2014	UK	GICU
Garrido Galindo et al,.[83]	63.47+-2.13 (12.30)	57.40+-1.14 (01.30)	NR	NR	NR	2016	Colombo	GICU
Kol et al,.[82]	pre 67.6/ post 56 (08.00-16.00)	pre 59.1/post 53.8 (24-08)	NR	Between two beds	Open bay	2015	Turkey	SICU
Tsiou et al,.[61]	61.3-67.4	60.3-62.7	60.3-67.4	NR	NR	1998	Greece	GICU
Guisasola-Rabes et al.,.[94]	60.63 (am)/59.33(pm)	54.98	58.32	NR	Open bay	2019	Spain	SICU
Christensen[65]	60.62 +- 6.66 (08.00-14.00)	50 (night)	56.42+-5.22	Centre of ICU	Open bay	2007	UK	GICU
Tsara at al,.[66]	60.62+-1.76	57.34+-1.47	NR	NR	Mixed	2008	Greece	GICU
Freedman et al ,.[63]	59.1+-6.1	56.8+-4.9	NR	Above patient's head	Single	2001	US	MICU
Salandin et al,.[72]	59	55	NR	NR	Two bed room	2011	Germany	GICU
Ryherd et al,.[67]	NR	NR	53-58	Above patient's head	Two bed room	2008	Sweden	GICU
Ryan et al ,.[86]	54.38 (09.00)-58.9 (17.00)	43.03 (03.00)-49.73 (04.00)	NR	Near patient bed	Single	2017	US	CCU
Park et al,.[92]	54.2	51.1	53.1	Above patient's head	Single	2015	Netherlands	GICU
Danielson et al ,.[91]	52.8 (median)	47.9 (median)	49.4-53.1	Above patient's head	Single	2018	US	MICU

Table 2.1 A comparison of studies reporting SPL for >24hrs

Three studies report on continuous, multiple location SPL measurement, providing excellent information about the tools and methods used, although reporting limited results[86,91,92]. Ryan and colleagues[86] report on a study measuring SPL in two patient rooms and at the nurses' station in a coronary care unit, over a one-month period. The devices were placed seven feet above the floor and as close to the

patient's head as possible. Data were reported as the average highest and the lowest hours $L_{Aeq;}$ and also, the periods at night where SPL was >45dBA. Results demonstrated that room one was generally quieter than room seven where the highest L_{Aeq} 54.38dB was at 09.00hrs and lowest of 43.03dB at 03.00hrs; room seven the highest L_{Aeq} was 58.9dB at 17.00hrs and lowest of 49.73dB at 16.00hrs. The study demonstrated that in room one 55.25% of night time noise was >45dBA whereas in room seven this was 99.61%. The nurse's station was noisier than either room, the highest L_{Aeq} being 65.0dB at 14.00hrs and lowest of 49.98dB at 04.00hrs.

Danielson and collegues[91] report on a study in a medical ICU comprising of 26 single rooms, arranged in pods of four each with their own nursing station. Data were collected for a period of 72hrs, this process was repeated for seven periods of 72hrs resulting in a total of 21days of SPL data. Median SPL were 52.8dBA (50.6, 55.8dBA) during the day (not defined) and 47.9dBA (45.0, 51.3dBA) at night (not defined) (p=0.0009 day vs. night). The longest period of measurement was reported in Park and colleagues[92], who successfully measured SPL in eight rooms continuously for three months. Data was analysed for the 24hr period, day (07.00-21.00hrs) and night (21.00-07.00hrs) for both periods when the rooms were occupied and when they were not. Average noise levels for the entire measurement period was 53.1dB $L_{Aeq336.8days}$ when a room was occupied and 44.2dB $L_{Aeq336.8days}$ when empty, day time averages for occupied rooms were 54.2dBA and night time 51.1dBA. The different methods of reporting make comparison between these and other studies problematic, however all demonstrated quieter units than the majority of other studies and a difference between SPL at night and during the day, more pronounced in Ryan and colleagues than the other two studies, this may be due to the studies being in units with single rooms. Ryan also demonstrated a variance between noise in different

rooms, which may be due to room acoustics including room design or location in the unit.

A recent addition to the literature is a sound mapping study[98], this reports on a novel study utilising four arrays of 16 microphones that measured SPL and location on 248 days for the five loudest sounds above 35dB in each time point (between 2 and 4 seconds) and for each 1cm^2. This identified the noisiest areas of the four bedded bay which were the head of the patient's bed, the areas where the telephones were located and outside the door of a side room.

2.5 Source data

Analysis of the sound pressure levels identify that intensive care units are unacceptably noisy; therefore, an examination of noise sources is important to understand why and how this noise is produced. Of the studies that report sound pressure levels measurement many also report the sources of sound[60-62,64,68,70,71,73,75,79,82,85,86,88,89] in most cases this is as part of a discussion rather than as part of the study methodology. Three further papers investigate the sources of noise[95-97]. These studies collectively identify staff conversation, communication devices such as the telephone, intercoms and door bells, equipment alarms, intravenous pumps as the most prevalent sources of noise. Within these studies fifty-six different descriptors of noise are identified including basins, trollies, bin lids, radios, patient interventions, clinical rounds and shift handover as part of the sound environment of an ICU. These sources are not however mutually exclusive, with some studies reporting equipment alarms and others reporting each individual piece of equipment and its alarm separately. Some studies identify various measures of prevalence e.g. duration of time the sound source was identifiable or number of minutes the sound source appeared in the data[96,97], however many only report a source or the sound pressure level, measured variously as $L_{Aeq,}$ L_{Amax} or

not reported, of an individual source. As with SPL this makes comparison and replication difficult.

Other initiatives to understand and address sources of sound include a quality improvement initiative[64] and a qualitative follow up of post ICU patients[73]. As part of a quality improvement initiative in a thoracic intermediate care area in the US, various modifiable sources of sound were identified to form the basis of a behaviour modification programme. This identified a number of relatively simple changes that might alleviate the nose burden including changing from a roll of towel to folded towel dispensers, eliminating overhead paging and deliveries, and reducing housekeeping at night, covering the amplifier when programming the intravenous pumps, removing, where possible, staff conversation from the bedside, closing patient doors, enabling nurses to change the alarm volumes on the patient monitors, padding the pneumatic tube system to muffle sound as cannisters arrived and padding the bottom of patient chart holders[64]. Johansson and colleagues[73] interviewed patients 2-35 days after their ICU stay to understand the patient's perspective of the ICU sound environment. This identified specific sounds similar to those reported in the key studies, but also more of a psychological perspective on sound where a sound could be both disturbing and comforting dependant on the circumstance, that patients had no possibility of escaping the sound, including the problem of being an involuntary listener and sounds which might have formed the basis of dreams.

Three studies specifically set out to identify the sources of sound in an ICU[95-97]. The earliest paper reported on a quality improvement project to reduce noise levels in an Australian ICU that had recently been relocated to increase capacity[95]. A survey completed by staff, relatives and patients to highlight events that impact noise identified that 79% participants believed there was a problem with noise on the ICU. Staff shouting and talking were highlighted to be significant factors

contributing to the noise. Staff indicated that the telephone, the Continuous Positive Airway Pressure (CPAP) device, ventilator and humidifier alarms were particularly noisy. Measurement of various devices demonstrated high SPL including bin lids shutting (78-85dBA) X-Ray machine (85dBA), intravenous pump alarms (73-78dBA), telephones (72-77dBA) and humidifier alarms (72-77dBA). Outcomes included the installation of sound absorbing tiles, removal of the bin lids, replacing the acoustic ring with a light on the telephone and adjustment of the equipment alarm levels.

Sources of overnight noise were observed in a study in the UK[96]. Six periods of night-time (23.30-07.00hrs) observation took place, using a tool that identified location, type, loudness and duration of sound sources in both single and multiple bed rooms. Five key noise sources were identified, described as talk, ventilator alarm, monitor alarm, pump alarm and humidifier, each source was more frequent in a multiple bed bay than in a single room, this was also true for duration, with the exception of ventilator alarms. Interestingly often this was 3-4 times the incidence, which may be related to occupancy which for the multiple bed rooms in this study, was 3-4 patients. Loudness was assessed for conversation and alarms. Staff conversation was assessed as either low, normal or raised resulting in 30%, 50% and 20% respectively. The monitor alarms were classified as advisory, warning and crisis as is usual[99], this accounted for 47%, 50% and 3% of the alarms respectively.

The most technical study of noise sources in an ICU, utilised calibrated audio recording over three days in an ICU[97] During the three days recording, one 24hr period during weekdays was annotated retrospectively by six non-clinical research assistants to analysis of the sound events using a system called Praat[100], this process took approximately 350 hours. 28 sources and six categories were defined as patient, staff verbal, staff activity, alarms, medical devices and

unidentified. A detailed analysis of the sound sources included the number and total duration of the annotated time intervals, from which the average duration of each sound source was derived, which enabled investigation of concurrent sound sources and whether one source was coincident with another. The source data reported 27412 sound events, the five most common were remote alarm (n=3622/13%), unintelligible speech (n=3342/12%), unidentified thump (n=3278 /12%), nearby alarm (n= 2755/10%) and non-metallic object (n= 2160/8%), however this hierarchy varied if duration was considered, unintelligible speech (239mins/17%), unavoidable speech (124mins/9%), remote alarm (110mins/8%), footsteps (102 mins/7%), and respiratory equipment (98mins/7%) suggesting that some frequently occurring noise sources happened only for a short duration[97]. The authors suggest that the major sources of sound are human interaction and alarms, both of which may be improved by behavioural interventions assisted by technical solutions. Limitations of this study include retrospective analysis of the data by non-clinical researchers, the lack of specificity in the description of the sources and the data being derived from one patient episode over a 24hr period. The technical methodology and analysis however were strengths of the paper, these should be applied to a longer duration study involving a greater number of patient episodes.

2.6 Impact of noise on staff

Healthcare and critical care in particular are considered stressful occupations[101]. Occupational noise has been linked negatively to stress, satisfaction and psychosocial wellbeing and is recognised to amplify the impact of a stressful job[102]. Staff working in noisy workplaces react by becoming less interpersonally engaged, less caring and less reflective[103]. The ICU has been identified as an aurally demanding work environment[104], however despite the large number of studies

related to the noise in an ICU environment there are relatively few studies that identify the impact of noise on staff.

Of the studies that report the impact of noise on nursing staff[67,104] these suggest noise negatively impacts work, causes stress and may lead to burnout in this staff group. Ryherd and colleagues[67] surveyed nursing staff working on a neurological ICU. Their results suggested that noise negatively impacted work (43%), with many staff reporting irritation (66%), fatigue (66%), problems concentrating (43%), tension headaches (40%) and impact on their sleep (38%). In a study looking at stress and burnout in nurses working on two intensive care units[104], nurses reported being (moderately/extremely) disturbed by the noise of telephones (63%/14%), equipment alarms (75%/22%) and patient monitors (84%/30%). In the same study nurses also identified noise caused by construction, personnel shouting, combative or abusive patients, chatter among staff in a foreign language and pill crushing as distressing noises. Burnout was described in this study as emotional exhaustion, depersonalisation and decreased personal accomplishment, this study suggests that a greater degree of noise induced stress is associated with greater burnout. Similarly, a small study of eleven nurses in a paediatric ICU[105] identified that noise level correlated with several measures of stress including tachycardia and annoyance ratings, in this study the average daytime sound level was 61dB(A) and night-time 59dB(A). Higher average sound levels significantly predicted higher heart rates ($p = .014$), greater subjective stress ($p = .021$) and annoyance ($p = .016$). In a mixed methods study, noise was found to be the most highly scored performance obstacle in an ICU, 46% nurses (n=124) reported high noise levels from equipment alarms, telephones ringing, conversation during the day shift and handover in the workspace rather than away from the bedside as a problem[106].

The environment and work practices have been found to impact noise[24,107,108]. Okcu and collegues[24] compared the sound environment of a newly built neurological ICU with a 1980's built medical/surgical ICU. They found that despite L_{Aeq} SPL being similar across the two units, levels of L_{Cpk}, and L_{Amax} were higher in the older unit, mainly due to increased time at the higher levels of noise. The older medical /surgical unit was also perceived by nursing staff as noisier, more annoying, impacting on work negatively and more anxiety provoking than the newer neurological unit. Blomkvist and colleagues[107] report on a study in an eight-bed coronary care unit where, 6-7 patients were admitted daily, resulting in a high patient turnover and the unit was perceived to be a noisy and turbulent environment. The study was designed to understand if improving workplace acoustics might improve the psychosocial environment. The study was divided into three phases; the first baseline data collection (21 days), then the ceiling tiles in the patient rooms were changed for sound reverberant tiles (20 days) and lastly exchanged for sound absorbing tiles (22 days). L_{Aeq} for one week, reverberation time (RT), speech intelligibility and a psychosocial survey were measured for each phase. The improved acoustic conditions conferred by the sound absorbing tiles reduced work demands, pressure and strain for the afternoon shifts. Similarly, a ward in the John Hopkins Hospital in the US, installed sound absorbing panels which reduced the A-weighted equivalent sound pressure levels by 5dBA and reduced reverberation time by a factor of two[108]. Staff and patients completed pre and post intervention questionnaires which demonstrated an improvement in the perception of the noise levels. A complete acoustic redesign of a patient room in an ICU, including installing an acoustic absorbing ceiling, sound proofing equipment, removing alarms from inside the room alongside some behavioural interventions demonstrated improvement in L_{Aeq} of 3dB and L_{AFmax} 10dB[109]. Compared to previously discussed studies this is a disappointing level of improvement, however the results of the few studies looking at environmental

improvement are generally positive and demonstrate that they are at least a part of the solution.

Poor acoustic design and high noise levels are implicated as a cause of medications errors. Medication errors have been shown to increase as interruptions increase[110,111], environmental characteristics such as high noise levels were identified by 56.6% nurses as problematic when preparing or administering drugs[112], in particular noise impacted more commonly on the administration of medicines rather than the preparation[113]. These studies suggest that noise impacts staff negatively, it is possible that reducing workplace stress caused by noisy workplace environments by improved acoustics, may improve patient safety and reduce staff turnover.

2.7 Alarms and alarm fatigue

Many studies highlight equipment alarms as a source of noise in the intensive care unit[62,64,68,70,71,73,75,79,82,84,85,86,88,89,95-97]. Alarms were mandated to increase patient safety but with little consideration of the detrimental effects on patients and staff[55], the impact of human factors[114] or the potential for expansion of monitoring and therefore the associated alarms[115]. The voluntary, but comprehensive International Electrotechnical Commission (IEC 60601-1-8) standard[99] specifies various alarm conditions to guide manufacturers when developing medical devices. This includes a three-stage priority, high, medium and low for various potential conditions, for example a life-threatening condition would require a high priority alarm. The guidance does not identify sound level requirements, but does state that there should be a 3-6dB difference between each priority. In addition, there should be additional warning sounds if a technical fault is detected and to remind users if they have silenced an alarm when the condition triggering the alarm has not yet been resolved. There is also guidance on the characteristics of

an alarm and the suggestion that the use of melodies might be more distinguishable between different pieces of equipment than beeps. Alarms however, are only effective if they activate only when a serious problem occurs. Current alarms systems are simplistic with high sensitivity, but low specificity, operating on the basis of thresholds i.e. an upper and/or lower limit, this may miss crucial information of relevant abnormalities[116,117]. Siebig and colleagues[117] analysed the data from 68 patient episodes identifying whether the alarms were technical valid and clinically relevant, only 14.9% of alarms were identified as clinically relevant, while Drew and colleagues[118] identified an audible alarm burden of 187 alarms/bed/day, 88.8% of which were false. Other studies support these results and suggest that as many 99% of alarms that sound, occur when there is no threat to the patient[119-122], leading to alarm fatigue and thus alarms counter intuitively may disturb patient care[121] diminish patient safety[114-116,123-125] and in extreme cases lead to patient death[114,126-128]. Moreover, medical device alarms appear to have no relationship between the clinical urgency of the alarm and the psychoacoustic properties[129]. An early study suggested that only 50% of alarms were correctly recognised as critical, recognition was impacted by profession and years of experience[130].

The Emergency Care Research Institute highlights alarms and alarm fatigue as one of their top risks[131]. Alarm fatigue occurs when staff are desensitised to alarms by continuous exposure, many of these alarms are false or clinically irrelevant[118]. Alarm fatigue is clearly described in three surveys of nurses' knowledge and practices in alarm management[125,132,133]. These surveys demonstrated that nurses tend to change monitor parameters in response to increased alarms rather than proactively[125], that perhaps their knowledge of alarms and the complexity of changing parameters led to a culture where alarms limits were not changed[132,133] or alarms attended to[132]. Drew and colleagues[118] suggest that despite nurses

utilising default settings as a norm rather than alarms limits being individualised, manufacturers had a responsibility to make monitors more helpful, interactive and intuitive. Nurses commonly describe dissonance between the alarm and the clinical urgency, the noise pollution, the need for nurses have authority to change alarm settings and also to be accountable as part of a team for managing alarms[128].

Better alarm management by nurses may reduce false alarms, however, improvements to the systems may be a more sustainable way to reduce alarm fatigue. A study observing the response and the trigger for an alarm concluded that increasing the alarm delay to 19 seconds from the usual 10 seconds would remove 67% of ignored and ineffective alarms without harming patients[120], this combined with better alarm limit management may prove both effective in reducing alarm fatigue and noise in the ICU, but also without any financial impact. A further improvement would be to combine modification of alarm delays with a model of severity, such that as severity increases alarm delay reduces and vice versa[116].

There is much potential to improve specificity by utilising technologies such as real time signal filters[124] or automated vigilance technologies[134] such as Bayesian probability models, fuzzy logic and neural networks to develop clinical decision algorithms[135,136] which have been shown to reduce false alarms[137]. Several authors discuss the potential use of non-acoustic alarms such as vibrotactile devices[115,138-140], which may improve clinician reaction times[140,141] and reduce noise annoyance. A study by MacFarlane and colleagues[134] highlights the potential of a metacognitive attention aid to assist in the early identification of an alarm and enable remote alarm muting, in the intensive care unit this type of device may provide the ability to remove the acoustic alarm by sending the alarm signal with collateral information directly to the nurse. To date, however there is little evidence

that these alternatives are in clinical practice or making rapid progress to market and there is a need for academic, industry and clinical partnership to evaluate new alarm technology in the clinical setting[141]. Therefore, current best practice is to develop and enforce clear alarm guidance[123] and to review the multiplicity of causes for non-actionable alarms including consumables, configuration, environment, workflow, infrastructure and human resource[142].

2.8 Impact of noise on patients

Patients remember noise as a prominent and sometimes distressing feature of their ICU admission. Several studies investigating the patient's perception of the ICU environment[143-149,151-153] report noise as a stressor. Five of these studies[143, 144, 146-148] utilise the 42 item Intensive Care Unit Environmental Stressor Scale (ICUESS)[141] that identified 'not being able to sleep' as a highly ranked stressor. For the noise related items there was marked inconsistency in the ranking and the score attributed to each potential stressor. This may reflect patients varying perceptions to noise and annoyance, which will be impacted by length of stay, time of data collection, unit geography, case mix and cultural factors and likely influenced by sample size and modifications to the tool (see table 2.2).

Item	Rank Cochran and Ganong (n=165)	Rank Novaes et al,. (n=50)	Rank So and Chan (n=50)	Rank Hweidi et al,. (n=20)	Rank Yava et al (n=155)	Mean Cochran and Ganong[141]	Mean/SD Novaes et al,.[138]	Mean/SD So and Chan[142]	Mean/SD Hweidi et al,.[139]	Mean/SD Yava et al,.[143]
Not being able to sleep	4	2	3	3	4	2.42	3.34 (0.98)	1.48 (1.40)	3.34 (0.68)	2.88 (0.82)
Nurses and doctors talking too loudly	28	15	37	15	22	1.44	2.54 (1.15)	0.58 (0.86)	2.61 (1.26)	1.83 (0.87)
Hearing other patients cry out	13	18	38	20	6	1.93	2.46 (1.23)	0.54 (1.05)	2.41 (1.23)	2.77 (1.35)
Unfamiliar and unusual noises	32	22	23	7	27	1.37	2.40 (1.11)	1.04 (1.07)	3.08 (0.96)	1.64 (1.16)
Hearing the heart monitor go off	26	25	18	13	16	1.58	2.26 (1.16)	1.18 (0.87)	2.81 (1.14)	2.27 (1.32)
Hearing buzzers and alarms from machinery	14	32	4	4	12	1.89	2.02 (0.91)	1.44 (0.93)	3.43 (0.73)	2.35 (0.87)
Hearing the telephone ring	7	35	35	38	28	1.26	1.92 (1.12)	0.62 (0.70)	2.11 (1.08)	1.61 (0.85)

Table 2.2 A comparison of noise related stressors from five studies using the ICUEES

An interview study of 13 patients, 2-35 days post ICU, seeking information about the sound environment in the ICU reported both positive and negative sound experiences[149.] Sound was generally perceived more positively if the patients understood the sound. When this was not the case, the recollection of that sound could lead to adverse stress reactions and was also linked to unreal experiences, perhaps providing some explanation of noise being linked with delirium[149]. A very recent study utilising the Intensive Care Experience (ICE) questionnaire[150] identified that frightening experiences and equipment noise were the most strongly correlated $r=0.534$; $p<0.01$[151]. It is possible that patients may not always recall noise as a stressor, however if they do recall this, it may be because it is particularly pertinent to their individual memory of the intensive care experience.

These studies are based on surveys or interviews that ask specifically about noise; it may be that studies where recollection of noise is not prompted, may provide a more valuable insight into patient perception[69,145,152]. Merilainen and colleagues[69] utilise an innovative qualitative methodology of visually recording four patients, this identifies that on average patients are disturbed by noise on 35 occasions per day. A large study of patients followed up six months post-ICU through self-reported questionnaires (n=212) and structured interviews (n=86)[152] identified noise as one of the main psychological problems faced by patients after ICU. Patients reported '*crashing and banging'*, 'a *man making animal noises'*, '*screaming for hours'*, '*alarms*', '*the noise the staff make…joking, laughing*'. A similarly designed study by Hofhuis and colleagues[145] also revealed noise as a theme. In the survey (n=50) sleep disturbance (48%) and noise (40%) were the most common complaints. Of the patients who complained of disturbed sleep 54% attributed this to noise. These studies suggest that noise in the ICU is a significant stressor for patients, given that these findings span 30 years, they suggest that despite knowledge of the poor sound environment, any change in practice, equipment or environment is

not improving the patient experience. This may be due to poor staff knowledge and lack of inclusion in developing new working environments and practices that might mitigate the impact[153].

2.9 Sleep

Sleep is a complex process influenced by many physiological and environmental factors. Lack of sleep is associated with a host of adverse outcomes[154] including stroke, coronary heart disease, diabetes mellitus, metabolic dysregulation, cancer[155, 156] obesity, stress, decreased immunity and socio-economic status[155]. Numerous studies over the last fifty years have identified that a sleep duration of about seven hours is associated with the lowest all-cause mortality risk; with a U-shaped association with sleep duration either side of this time period[155, 156]. More recently concern has been raised that sleep deprivation may impact on delirium in ICU patients and therefore improved sleep may reduce this clinical syndrome associated with increased ICU morbidity and mortality[157].

Normal sleep architecture includes two distinct stages, non-rapid eye movement (NREM) and REM. NREM is comprised of three stages, the first two stages are light sleep and the third, deep slow wave sleep, which is believed to be the most restorative stage of sleep for physiological repair. REM is considered to be necessary for memory consolidation[158,159]. Normal sleep consists of four to six approximately 90-minute cycles of NREM and REM cycled sleep[159]. Measuring sleep in the ICU is difficult. Sleep and wakefulness are regulated by Circadian Rhythm for wakefulness and homeostatic sleep processes for sleep[159,] many of the processes are affected by the use of sedation in ICU patients[154].

The gold standard measure of sleep is polysomnography (PSG), which requires technical expertise to apply the electrodes and interpret the data, it is expensive and has a time lag between collecting the data and receiving a report[160]. In addition, PSG studies have been difficult to interpret in ICU patients due to hepatic and renal failure and the dysregulation caused by sepsis and shock, alongside the impact of many of the common medications impacting sleep architecture[158,159] see figure 2.7. Other measures such as actigraphy have a tendency to overestimate sleep in ICU patients, as it relies on movement to judge wakefulness, and the bi-spectral index has not yet proved effective in sleep studies[159]. Several survey instruments have been reported to assess patient and/or nurse subjective assessment of sleep; however, the majority lack effective validity and reliability testing[160]. These authors identify the Richards Campbell Sleep Questionnaire (RCSQ) as the most valid and reliable tool currently available, although it requires patients to be awake and cognitively able, therefore its use in the ICU population may be limited[160]. Recently however, a study of 381 self-reports in 120 patients, 43 mechanically ventilated for a part of the study, demonstrated that self-reporting sleep using the RCSQ was feasible and acceptable. Sleep quality was reported as poor 34.4±5.60, with sedative agents, gender, noise, daytime sleepiness and mechanical ventilation being the main disruptive factors[161].

Sleep abnormalities, including sleep deprivation, abnormal sleep architecture and sleep disturbance are common in ICU[162], these may persist or develop after the critical illness[154,163], the relationship between poor sleep and long-term outcomes is unknown[154,158]. Studies utilising polysomnography demonstrate that some ICU patients are quantitatively sleep deprived, however more are commonly qualitatively deprived with 40- 50% sleep taking place during the day[63,154,158,159,164]. Sleep is fragmented with increased arousals, increased sleep latency, decreased sleep efficiency, most studies suggest there is an increase in stages 1& 2 NREM

and a decrease or absence of stage three NREM and REM[62,154,158,159,164,165] although one study suggested that stage 2 NREM sleep was also decreased[63]. Some patients may suffer poor sleep before admission to an ICU[166], which may continue whilst critically ill, however the majority of patients are likely impacted by the numerous environmental and pathophysiological factors (figure 2.7) and the medications commonly utilised in care (figure 2.8) impacting the regulation of sleep[167].

Environmental noise does not appear to be significant in PSG studies with only 10-30% arousals or awakenings in critically ill patients attributed to noise[62,63,164]. However, when healthy subjects slept in an ICU, noise more commonly caused arousals and awakenings[62]. This suggests that perhaps as patients recover, sleep may be more disrupted by noise and that during the acute phase of their illness that other elements of the environment or treatment may be more disruptive[60]. Two systematic reviews[168,169] suggest that the heterogeneity between studies makes it impossible to quantify the extent that noise contributes to sleep disruption in critically ill patients and thus the potential benefit of noise reduction is unclear. Horsten and colleagues[169] suggest that the majority of disturbances remain unexplained, requiring a focus on more intrinsic sleep disrupting factors in the ICU. Despite this, patients perceive noise to be an important factor in sleep disruption[166,170,171] and describe sleep quality as poor and worse than their sleep at home, reinforced by a perceived improvement once they are discharged from the ICU[166]. Patients and visitors remember noise as a prominent and a sometimes-distressing feature of ICU[147,148,152,172]. Nevertheless, not all sound is perceived in the same way by patients. Some patients have no recollection of the sound environment, whereas others may interpret sound both as disturbing but also as comforting[36,73]. Patients suggest closing doors, pulling down blinds at night, sleeping medication (although this study found no correlation between sleep

and sleeping medication), reducing interruptions, dimming the lights, removal of alarms and reported better sleep when sedated intravenously[166]. Nurses subjective assessment of patient sleep is often an overestimate and differs greatly from the patient's assessment[173]. To date only one study has demonstrated a link between the negative impact of noise and positive impact of increased restorative periods and subjective sleep quality[174].

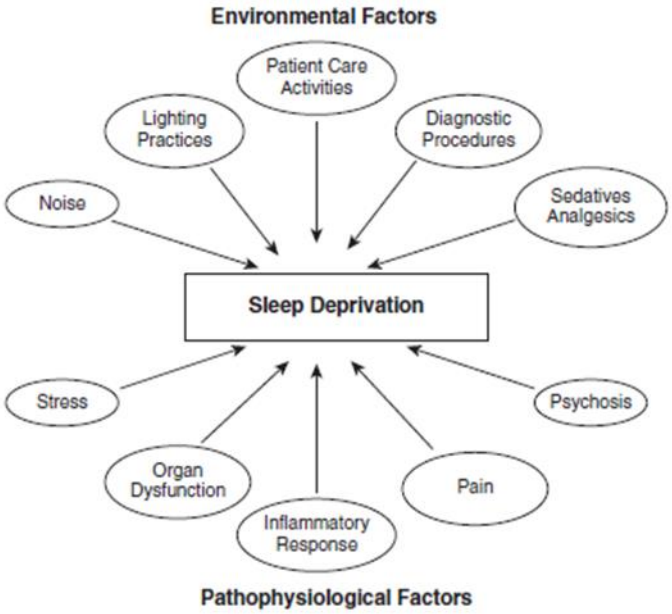


Figure 2.7 Factors associated in sleep disturbance in the ICU from Pisani et al, 2015[154]

Despite many years of study describing sleep abnormalities in ICU, few units have changed practice[175,176]. ICU staff recognise both the importance of sleep and the presence of sleep disruption during an ICU stay however routine use of objective tools to measure sleep and the use of sleep bundles/protocols is infrequent[175,176], although sleep assessment appears to be more common in units where nurses influence sleep strategies[176]. There is also considerable variation in interventions to promote sleep across countries, including noise reduction, dimming lights,

reducing nurse interventions, keeping patients awake during the day, although few units use ear plugs or reduce alarm volumes[176].

Drug Class	Examples of Drugs	Effect on Sleep Architecture	Potential Mechanism
CNS			
AED	Phenobarbital, carbamazepine, phenytoin	Very sedating. AEDs tend to ↑ TST, ↓ sleep latency. May ↑ SWS	Action on neuronal sodium influx in glutamate channels or GABA type A
TCA	Amitriptyline, imipramine, nortriptyline, desipramine, doxepin, clomipramine	Very sedating; suppresses REM sleep, ↑ TST, ↑ stage 2 sleep	Antimuscarinic activity, α_1-receptor stimulation
Anxiolytic BzRA	Alprazolam, lorazepam, diazepam, oxazepam, propofol	Very sedating; ↑ TST, ↓ sleep latency, ↓ SWS duration, ↓ REM, ↑ stage 2 sleep same	GABA type A receptor stimulation; may also affect endocannabinoid
SSRI	Sedating: paroxetine, fluvoxamine; "activating": fluoxetine, sertraline, citalopram	In general, SSRIs tend to ↑ TST; less sedating than TCAs and MAOIs; ↓ REM, ↓ SWS ↑ TST, ↓ SE	↑ 5HT activity
SNRI	Venlafaxine	TST	↑ 5HT and NE activity
Mood stabilizer	Lithium	↑ TST, ↑ SWS, ↑ stage 2 sleep, ↓ REM, ↓ REM latency	Neuronal sodium channels
Anti-Parkinson	Bromocriptine, levodopa	Sedating; nightmares, ↓ SWS	Dopamine
Cardiovascular			
Stimulant	Norepinephrine, epinephrine dopamine	Activating; ↓ REM, ↓ SWS	α_1-, α_2-, $\beta-$Receptor stimulation; D_2 α_1-receptor stimulation
Lipophilic β-blocker	Propranolol, pindolol, metoprolol, timolol	Activating; ↑ awakenings, ↑ TWT, ↓ REM, nightmares	CNS β-blockade
α_2-Receptor agonist	Clonidine, DEX	↑ Stage 1, ↓ REM, nightmares	α_2-Receptor stimulation
α_1-Receptor blocker	Doxazosin, prazosin, terazosin	↑ TST	α_1-Receptor inhibition
Analgesic			
Opioid	Codeine, morphine, hydrocodone	Sedating; ↓ SWS, ↓ REM	μ-Receptor stimulation
NSAID	Ibuprofen, indomethacin, celecoxib	↓ TST, ↓ SE	Prostaglandin synthesis inhibition
Other			
Methylxanthine	Theophylline	Activating; ↓ TST, ↓ SE, ↑ stage 1, ↓ REM	Inhibits adenosine
Antihistamine	Diphenhydramine, promethazine	Sedating	Histamine 1 receptor blockade and can have Ach effect
Corticosteroid	Dexamethasone, prednisone	Activating; ↓ REM, ↓ SWS, nightmares	↓ Melatonin secretion

Ach = acetylcholine; AED = antiepileptic drug; BzRA = benzodiazepine; DOPA = dopamine; 5HT = serotonin, serotonergic; MAOI = monoamine oxidase inhibitor; NE = norepinephrine; NSAID = nonsteroidal antiinflammatory drug; SE = sleep efficiency; SNRI = serotonin norepinephrine reuptake inhibitor; TCA = tricyclic and tetracyclic antidepressant; ↓ = decrease or reduce; ↑ = increase.

Figure 2.8 Common drugs in ICU patients and effects on sleep architecture from Hardin 2009[158]

Earplugs and eye masks have been shown to improve sleep quality and quantity in healthy subjects exposed to ICU noise and light suggesting they may be useful in ICU patients[177]. Studies in ICU patients however have shown a varying rate of compliance with the devices[178-183], but in those patients who tolerate them, NREM stage 3 sleep is increased and long awakenings are reduced[177,181], patients report better sleep duration[177,180] and that they are a helpful aid to sleep[178]. Earplugs have been shown to reduce or delay symptoms of delirium or confusion[180,183] and improve patient reported sleep[182,183].

Many studies have measured the impact of programmes to reduce noise at night and improve sleep in the ICU with generally disappointing results. Several studies have demonstrated statistically significant improvements in noise levels at night following the implementation of a night time sound reduction protocol, however the level of reduction was clinically irrelevant and did not improve patient reported quality of sleep[60,81,93,94,184,185]. One study demonstrated a non-significant reduction in background levels as measured by L_{90} and a reduction in some aspects of the Toft adapted sound disturbance scales[188] completed by both staff and patients on the intervention unit, however the authors were unable to show any statistical significance in overall measures[187]. Likewise, a study employing quantitative measures of sleep was also unable to show an improvement in sleep quality or quantity nor reduction in noise[188].

Two studies have shown positive results[189,190]. A study in Taiwan employed a night time protocol of decreased patient interventions and noise reduction that significantly reduced quantitative and qualitative measures of sound, the number of patient interventions and subjective measures of sleep improved. Protocol adherence was reported to be 98.6%[189]. The second study employed a multicomponent and multidisciplinary bundle of measures to reduce noise, light and patient interventions, this demonstrated good compliance with a reduction in noise, light and interventions, as well as an improvement in qualitative sleep measures resulting in a reduction in delirium in a group of elective surgical patients[190]. A further study utilising measures of delirium demonstrated a reduction in delirium but, but did not demonstrate improved sleep or adequately report a reduction in night time sound levels[191]. Results are awaited from the UNDERPIN-ICU study[192] which aims to reduce delirium using a multicomponent programme including noise reduction.

Alternative methods of reducing noise in the ICU include the introduction of music or noise cancelling headphones. Noise cancelling headphones have been shown to be effective on models in reducing the noise level by nearly 7dB in an ICU environment[193] while caregivers in paediatric and adult intensive care units suggested they improved the noise environment and were acceptably comfortable[194]. Two studies suggest that patients requiring mechanical ventilation required less sedation[195,196], demonstrated a reduction in blood cortisol and prolactin levels[196] or a reduction in anxiety[195] after music intervention. One study also utilised a noise cancellation device which was not as effective as the personalised music intervention[195]. Similarly, another study in Taiwan demonstrated an improvement in sleep quality and quantity in patients receiving sleep inducing music and eye shields compared with patients wearing only ear plugs and eye shields[197]. A feasibility study to decrease delirium through music using a three-arm study protocol of personalised music, non-personalised music i.e. music selected for its potential for relaxation or attention control i.e. audiobooks is currently in progress[198].

2.10 Restorative periods

Restorative periods were first described by Ryherd and colleagues[67] who noted that there were periods of the day or night-time when the noise was generally quieter and more stable. They hypothesised that these levels of SPL over a five-minute period might be restorative to patients, as the background sound was less fluctuant and the foreground produced less impulsive noise. These periods were thought to represent episodes when patients were less likely to be disturbed and may reduce awakenings from sleep. These periods were more common at night but were described as restorative if they occurred at any time of the day or night. They described these levels as times when the noise stabilised to L_{Aeq} 47-48dB, L_{AFmax} 52-53dB and L_{Cpk} to 71-72dB, but did not necessarily reduce to the levels

recommended by WHO[16,41,42] or the US Environmental Protection Agency[43]. Ryherd and colleagues identified 109 periods of time when L_{Aeq} fell below 50dB for ≥five minutes, the mean duration of these restorative periods was day time (9 mins) and night time (13 mins) with maximum day time length (19 mins) and night time (50 mins). Two further studies report restorative periods or time[75,97], but utilise differing sound levels, weighting and measures sound. Tegnestedt and colleagues[77] defined restorative time as a minimum of 5 minutes with L_{ASmax} below 55dB as well as L_{cpk} below 75dB, using SLOW weighting, which may have missed peaks of sound. They also described cumulative restorative time defined as the cumulative period of time for a shift or room type. Cumulative restorative time increased at night and in the evening, compared with day shift ($p<0.001$) and despite no difference in L_{ASeq} between room types, multi-bed vs. single room, there was a trend towards longer cumulative restorative time in a single room compared with a three-bed room $p=.074$. Park and colleagues[97] utilised Ryherd and colleagues[67] description of restorative periods, demonstrating shorter duration of restorative time during the day but similar at night. They however refined the definition by considering previous evidence that suggested patient disturbance causing arousals and awakenings from sleep required an increase in peak sounds from background sound[63] rather than being a definitive level of peak sound causing the disturbance. Therefore, they proposed an additional definition of restorative periods of <17.7dB relative to background (L_{R2B}). using this new definition, a greater duration restorative time was seen for both day and night-time[97]. Utilising restorative periods provides researchers with a potentially objective measure to understand the relationship between objective measures of sound and sound as perceived by the users of the environment.

2.11 Conclusion

Several guidance documents are available to guide standards for the management of noise in hospitals. Generally, this guidance is designed to assess the buildings functionality rather than acceptable operational acoustical parameters. It is written from the perspective of the whole hospital and is not specific to intensive care units. The World Health Organization has published a series of guidelines for community noise which suggest acceptable operational acoustical parameters for a wide range of environments and identify noise levels for the intensive care unit. This suggests noise limits of L_{Aeq} 30-40dB for an intensive care unit based on the vulnerability of the population.

Noise in hospitals is not a new problem, this was originally highlighted by Florence Nightingale over 160 years ago. Various campaigns aimed at reducing noise levels in hospitals appear to have been universally unsuccessful as noise levels appear to increase linearly year on year. Within the intensive care unit there is a growing body of studies reporting the sound levels to be higher than is currently recommended. There is considerable variation in the methods and reporting of studies measuring sound in ICU's, making replication and comparison difficult. This includes limited reporting of methods and wide variability in the recording of sound pressure levels, the time period for recording, the reported energy levels; including maximum and/or mean continuous and/or maximum peak levels; and the positioning of the microphone. Few studies report sounds levels longitudinally in multiple locations and none of these report data from a mix of single and multiple bed rooms as is common in the UK. Many of the studies include data on the sources of noise, however most include this as part of the discussion and not as a part of the study methodology. The three studies that set out to measure source data, achieved this through very different methodologies, one utilised a survey as a part of a quality improvement project, the second limited the sources they

included and the third used recorded data which resulted in poor differentiation of the noise sources. There is currently no study that provides a robust description of the noise sources in an ICU and none that report qualitative sound scaping data.

Noise impacts patients, visitors and staff alike. The ICU has been identified as an aurally demanding work environment which negatively impacts work, increases error, causes stress and may lead to staff burnout. Improved acoustic conditions have been shown to decrease noise levels and reduce work demands, pressure and strain and may improve patient safety. Alarms are a common source of noise, with evidence that the majority of alarms are not critical or false, leading to alarm fatigue. Despite this the current guidance focuses on the clinical urgency rather than the quantity and sound level. Suggested solutions are better alarm management by nurses rather than utilising technology to reduce the false alarm rate. Patients and visitors remember noise as a prominent and sometimes distressing feature of ICU admission. They often link noise with impaired sleep, yet environmental noise does not appear to be significant in awakenings and arousals from sleep when measured using polysomnography. Researchers have tried to better understand this phenomenon and suggest that patient disturbance is caused more by fluctuant noise than a definitive level of peak sound and hypothesise that restorative periods as times when patients may gain rest even if the background sound level remains greater than the WHO recommended levels for sleep.

There is little evidence that noise can be controlled effectively by implementing behavioural change. The majority of the studies are small, and as with many other noise reports for ICU, poorly designed and reported. Interventions that rely on behavioural intervention have neither been shown to make a sufficient difference nor deliver sustainability. These studies frequently follow the medical model where

success is reported based on statistical significance, often chasing a number, in this case the WHO guidance of 35dB$L_{Aeq.}$ This demonstrates a poor understanding of acoustical research, where patient focused outcomes and acoustical significance are of greater relevance. More recently however, the patient, rather than just their disease has come to the fore. It is likely that this refocusing on a broader set of survival outcomes will support better, study of the intensive care environment, including all noise sources, ways of working and the design of an ICU. To this end, there is some early evidence that manipulating the environment may improve patient experience, reassuringly there are some promising studies using music to change the sound environment, reduce stress and therefore perhaps promote sleep.

Chapter Three

Aims, Objectives and Hypotheses

3.1 Aims

The overall aim of this PhD thesis is to describe the acoustic environment of the General Intensive Care Unit (GICU) of St George's Hospital, London. Novel methods for sound measurement, source identification and perception of sound by users of the GICU are presented. Specific aims are:

1. To complete preliminary testing of the National Physical Laboratory (NPL) Minim utilising an Electrical-Mechanical- System (MEMS) microphone within the GICU environment. To ensure an understanding of the environment to be studied and the impact of the environment on the sound monitoring equipment (Study 1).
2. To complete longitudinal, distributed, continuous sound pressure level monitoring across the GICU (Study 2).
3. To identify the key sources of sound disturbance in the GICU using a novel method of data collection (Study 3).
4. To pilot a method of understanding the acoustic environment as perceived, experienced and/or understood by the patients, visitors and staff (Study 4).

3.2 Objectives

1. To record continuous sound pressure level monitoring at 1-minute intervals, using nine acoustical indicators (L_{Aeq}, L_{Ceq}, L_{Amax}, L_5, L_{10}, L_{25}, L_{50}, L_{75}, L_{90}) across multiple bed spaces in a GICU.
2. To construct and pilot a data collection tool to identify the key sources and prevalence of sound disturbance in the general intensive care unit.

3. To undertake observational data collection of the sources of sound at multiple bed spaces, during concurrent continuous sound pressure level measurement.
4. To understand if there is a relationship between sound pressure levels, the prevalence of sound sources and user perception, experience and/or understanding of the acoustic environment.
5. To pilot a method to collect patient, visitor and nursing staff perception, experience and/or understanding of the acoustic environment. This data will identify the keynote sounds, signals and sound marks required to develop individual descriptors of the acoustic environment of the GICU for use in a later sound scaping study.

3.3 Hypotheses

1. Longitudinal, distributed, continuous sound pressure level monitoring using 1-minute averaging, sound pressure levels will exceed the current published guidance of 35dB (L_{Aeq}) during the day and 30dB (L_{Aeq}) at night.
2. Longitudinal, distributed, continuous sound pressure level monitoring using 1-minute averaging, individual sound events will exceed the current published guidance of 40dB (L_{Amax}) or 45dB (L_{Aeq}) during the day and 35dB (L_{Aeq}) at night.
3. Minimum 1-minute average sound pressure levels will exceed the current published guidance of 35dB (L_{Aeq}) during the day and 30dB (L_{Aeq}) at night.
4. Sound pressure levels will not be significantly different at night (23.00-07.00hrs) compared with the day (07.00-23.00hrs).
5. Sound pressure levels in multi bed areas will be significantly higher than in single side rooms.
6. The key sources of noise will result from communication, clinical equipment and procedures.

7. Episodes of sound will be less prevalent at night (23.00-07.00hrs) than in the day (07.00-23.00hrs).
8. Patients, visitors and staff will perceive sound differently from each other.

Chapter Four

Setting for the studies

4.1 Introduction

The setting for the studies to be discussed in the following chapters, is an 18-bedded adult, general intensive care unit (GICU) which forms one part of a larger intensive care service. This chapter will highlight the geographical layout of the unit and the bed spaces studied, it will also identify the occupancy and acuity data for the study periods comparing this with annual data for the year (2015) and the year previous to the study (2014). Finally, as the helicopter lands on the roof of St James's Wing, where the GICU is located on the 1st floor, it will highlight the frequency of helicopter landing and take-off during the study period.

4.2 Geographical layout

The GICU consists of two large rooms as shown in figure 4.1, each with a central staff base. The largest area is known as the ICU and contains 10 beds, this is split into two working spaces. One side of the room contains four (beds 2, 3, 4 & 5) and the other of six bed spaces (beds 6, 7, 8, 9, 10, 12). Two single rooms are also located in the area, one on each side (beds 1 &11). The other working area is a six-bedded high dependency (HDU) area (beds 14, 15, 16, 17 18 & 19).

Figure 4.1: A geographical representation of the layout of and approximate measurements in mm of the GICU. The red circles indicate light fittings above each bed and the blue diamonds, where preliminary acoustical measurements were obtained.

Each of the larger rooms is divided by a staff base; an area with computing and printing facilities, telephones, storage for paperwork and desk-space. These are commonly the areas where professional staff congregate to communicate, review investigations and document care. Each bed space is surrounded with various monitoring and supportive equipment. A typical bed space (figure 4.2) contains the following clinical equipment:

- Physiological monitor with integral alarms
- Oxygen flow meters that may be connected to face masks, high flow humidified nasal oxygen, nebulisers, non- invasive ventilation and invasive ventilation Both ventilators have integral alarms
- Suction unit

- Pressure relieving mattress with an alarm
- Active Compression System to enhance the circulation of blood in the deep veins of the legs with integral alarm
- Feeding pump with integral alarm
- Multiple syringe pumps and infusion devices each with integral alarms
- Haemofiltration device with integral alarm.

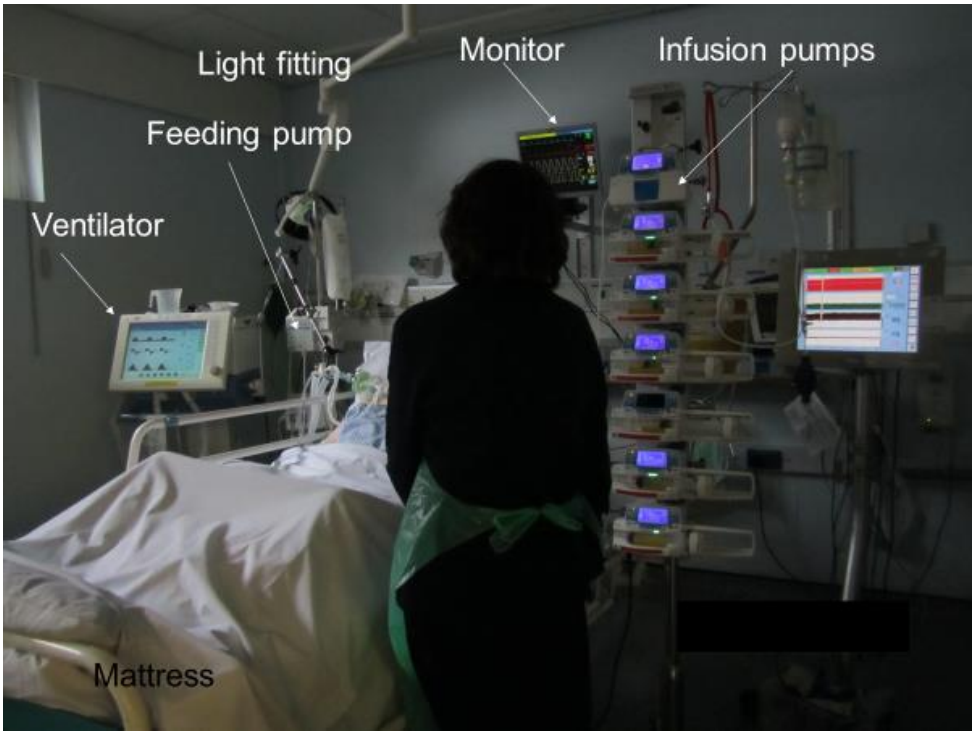


Figure 4.2 GICU bed space (side room 11) with common sources of noise highlighted. Oxygen and suction are located at the back of the head end of the bed.

In addition, each bed space contains or has located in close proximity, two bins (one for clinical and the other domestic waste), a bedside chart table where charts are written and documentation stored often in clip files, chair and a clinical trolley that contains essential pieces consumables such as intravenous and enteral syringes, needles, dressings and hygiene products. Figures 4.3-4.6 provide a schematic layout for each of the observed bed spaces and photographs of bed

spaces 3 & 5 to illustrate the lack of space with only the minimum of equipment in place.

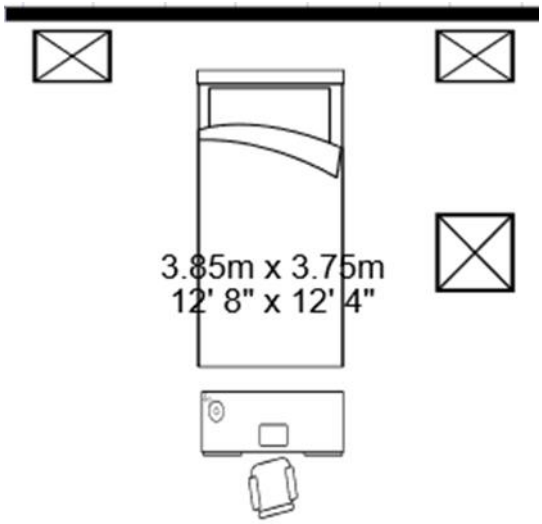


Figure 4.3 Schematic diagram of bed spaces 3 & 9 illustrating a typical floor plan with usual position of bins, chart table and bed. Bed spaces 3 & 9 have a similar bed spaces immediately either side, divided by only curtains. At the foot of these beds is a walk way, with a wash hand basin on a column opposite, behind this sits the staff base (see 4.1)

Figure 4.4 Photograph of bed space 3 (bed space 9 is similar) demonstrating the lack of space and ingress from items at adjacent bed spaces

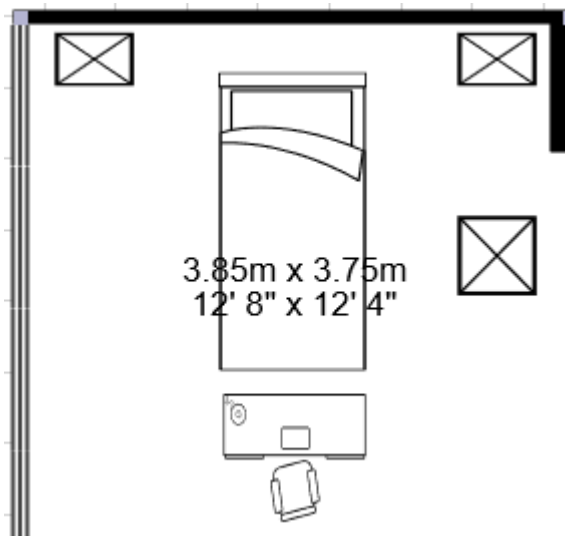


Figure 4.5 Schematic diagram of bed space 5 illustrating a typical floor plan with usual position of bins, chart table and bed. Note this bed space has a glazed wall to its left-hand side and a short solid wall on the right-hand side of the bed. To the right-hand side of the bed is the staff base and, on the wall, adjacent to this side are two wash hand basins. A door to the HDU area is at the foot end of the bed. Diagonally opposite is bed four.

Figure 4.6 Photograph of bed space 5

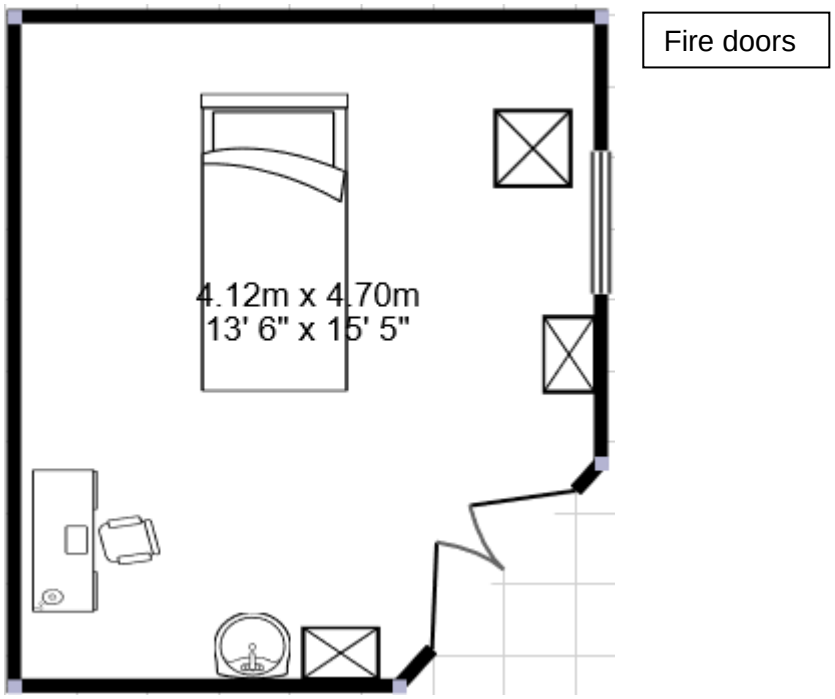


Figure 4.7 Schematic diagram of bed space 11, a side room
Illustrating the usual position of bins, chart table, bed and wash basin. On the right-hand side, at the head of the bed are two fire doors, used regularly to exit the unit with patients

As required, items such as an armchair for the patient, smaller chairs for visitors, bed side table for food or patient possessions are brought into the bed space. Around each bed space with the exception of the side room is a curtain track on which hangs a set of disposable curtains to provide visual privacy. In the near vicinity of each bed space is an apron holder, a wash hand basin for handwashing, above which is a towel dispenser, soap dispenser and below a waste bin. The GICU was purpose built in the early 1980's when the care offered to the ICU patient was far less complex, requiring less bed side equipment, personnel and there was less concern regarding cross infection. The whole unit is tight for space, but it is of note that the bed spaces do not conform to the latest building regulations[39], requiring an individual bed space to be a minimum of 25.5m^2. The bed spaces under study are approximately 14.5m^2, the side room (bed space 11) is a little larger at 17.7m^2, they do not have pendants on which to

place the majority of equipment. They can therefore be tightly packed with equipment which require additional trollies and stands on which to place the equipment, leaving little physical floor space around the bed. The two other adult ICU's at St George's were built in the early 2000's and are more spacious with improved acoustic absorption from more modern building materials such as the flooring. The age and space of intensive care units varies across the UK, with many units working in similar or even older units. There has however been a large amount of new build since the Private Finance Initiative (PFI) commenced in 1992. In these builds the units are more likely to conform with contemporary regulation, they are however owned by a third party and therefore upgrading or changing the layout of one of these units is costly and time-consuming. The age and layout of units worldwide varies enormously; in most first world countries, it is unusual to find patients cared for in multi-bed bays, the norm would be single side rooms or rooms of 2-3 patients only. Likewise, ICU bed availability varies substantially worldwide, ranging from less than 1 to >30 ICU beds per 100,000 population[199], with the UK at the lower end, with a provision of 6.6 beds per 100,000 population[200].

4.3 Case mix

Intensive care units typically care for patients when they are at their sickest, however many patients are admitted for observation in a bid to detect early signs of deterioration and thus to prevent organ failure, therefore not all patients become critically unwell. Patients also improve or deteriorate, requiring greater or less organ support for periods during their stay. Severity of illness scoring systems are commonly used in ICU to recognise how sick a patient is at a point in time and for mortality and morbidity prediction. They are used by clinicians to provide insight into their practice and by regulators to ensure maximal use of resources[201], they are also used to help describe the case mix of a unit or cohort of patients in

research studies. As is common in many intensive care units, the GICU measures APACHE II (Acute Physiology, Age, Chronic Health Evaluation II)[202] within the first 24hrs of admission to describe the individual patient's severity of illness based on the patients acute and chronic physiology. Higher scores correspond to more severe disease and a higher risk of death and perhaps also workload and activity and may therefore correspond to noise levels at a patient's bed side[92]. Additionally, patients are identified by their level of need for organ support or observation using the Intensive Care Society Levels of Critical Care for Adult Patients[203], this classifies patients as in table 4.1. Levels of care are usually monitored daily and therefore help to describe a patient's trajectory of illness during their ICU stay. The majority of patients within an intensive care unit would be either level 2 or 3, however delay in discharge or patient frailty may result in a patient staying on the ICU when at levels 1 or 0.

Level of care	**Descriptor**
Level 3	Patients receiving Advanced Respiratory Support alone or patients receiving a minimum of 2 organs supported
Level 2	Patients receiving single organ support, stepped down from level 3 care or requiring a greater level of observation than can be provided on a ward
Level 1	Patients recently discharged from a higher level of care, patients in need of additional monitoring or clinical interventions, clinical input or advice or patients requiring critical care outreach service support
Level 0	Patients' needs can be met through normal ward care

Table 4.1 Levels of care adapted from ICS 2009[203]

Table 4.2 provides information on both occupancy and acuity for comparison over the study periods and study bed spaces. This demonstrates that the calendar year

2014 was similar in occupancy and acuity for the 18 ICU beds as the calendar year 2015, the year studies 2 and 3 took place. Additionally, reviewing the data for the two periods of study 6/7/15-23/9/15 (study 2) and 12/7/15-12/8/15 (study 3), occupancy and acuity data is again similar, with occupancy a little lower compared with all beds over the year and acuity a little higher. This may reflect the summer period where there is commonly a reduction in admissions, with those admission being more commonly emergency admissions than elective, as demonstrated by a higher APACHE II.

Period	No. patients treated	Total length of stay (days)	Total occupancy (%)	Mean (SD) APACHE II score	L3 days*	L2 days*	L1 days*	L 0 days*
2014	2034	6038	92%	14.1 (8.16)	4336 (52.6%)	3773 (45.8%)	121 (1.5%)	8 (0.1%)
2015	2015	5967	91%	14.2 (8.06)	4413 (53.7%)	3664 (44.6%)	135 (1.64%)	1 (0.%)
6/7/15-23/9/15	425	1243	87%	14.4 (7.79)	1077 (57.4%)	780 (41.5%)	21 (1.1%)	0 (0%)
12/7/15-12/8/15	164	487	87%	14.6 (7.59)	511 (58.7%)	355 (40.8%)	4 (0.5%)	0 (0%)
6/7/15-23/9/15 Beds 3,5,9,11	61	294	93%	15.8 (6.93)	247 (63.5%)	136 (35.0%)	6 (15.0%)	0 (0%)
12/7/15-12/8/15 Beds 3,5,9,11	22	117	94%	17.4 (5.39)	145 (67.4%)	70 (32.6%)	0 (0%)	0 (0%)
2016	1849	6225	95%	13.8 (7.65)	4485 (54.4%)	3623 (44.0%)	129 (1.6%)	2 (0%)
2017	1939	5973	91%	13.7 (8.18)	4126 (51.2%)	3772 (46.8%)	156 (1.9%)	0 (0%)
2018	1980	5893	90%	13.5 (8.33)	4074 (50.8%)	3752 (46.8%)	191 (2.4%)	1 (0%)

Table 4.2 Occupancy and acuity data for the study periods and the years 2014 & 2016 for comparison. Please note columns 5-8 do not equal column 2, as they include whole and part days, part days are counted as a complete day for CCMDS data entry. Rows 1-4 & 7-9 contain data for all beds; rows 5&6 data for beds 3, 5, 9 & 11 only

Table 4.2 demonstrates that the four bed spaces studied, had a higher occupancy and acuity than average during studies two and three in 2015. Although all bed spaces can accommodate both level 2 and level 3 acuity patients, longer stay patients as they recover or post-operative patients may be located/moved to the

HDU area of the unit, increasing the acuity in the beds studied. This demonstrates that the study bed spaces were generally representative of the unit as a whole, but reflect the level of care and acuity of patients usually cared for in those particular bed spaces. For the years 2016-2018 there is a slight decrease in occupancy and acuity over this time period, with more level 2 patients and fewer level 3 patients, this is reflected in the concomitant decrease in APACHE II scores. Data for study four was collected over a prolonged period, (07/2015 -10/2015 and 02/2017- 12/2018) the selection of patients should not have been impacted, it is possible however that the change in acuity may have impacted noise levels and therefore the reported perceptions of these patients. Unfortunately for the latter part of this study sound pressure levels were not available for comparison.

4.4 Helicopter landings

As a major trauma centre, the hospital hosts a helicopter pad. This is situated on the roof of the building in which the general ICU is located and is open from 08.00-20.00hrs daily. The earliest landing during this study was 08:56hrs 2/8/2015 and the latest 20:09hrs 15/8/2015. During the study period 6/7/2015-23/9/2015 the helicopter arrived or departed on 132 occasions, the sound pressure levels during these events were measured on 434 occasions. 20 data points were lost due to the loss of power between 21/8/2015 and 1/9/2015, and the remaining 14 lost due to drop out from the sound devices (NPL Minim). Three of these landings/take off featured in the ‘Sound in Time’ data, reported in Study 3, Chapter 7. Table 4.3 provides the average sound pressure levels of each bed space and for the four bed spaces combined, during a helicopter arrival or departure. On average sound pressure levels increased by 1.2dB during arrival or departure of the helicopter. This was most noticeable at bed space 5 where the increase on average was 1.7dB; bed space 9 = 1.5dB, bed space 11 = 1.0dB and bed space 3 = 0.8dB. Bed five is located next to a window, below the helicopter pad.

Bed space	L_{Aeq}	L_{Ceq}	L_{Amax}	L_5	L_{90}
3	66.5	79.0	77.7	70.6	62.1
5	61.8	64.6	73.7	66.4	55.9
9	66.2	81.1	77.1	70.3	61.7
11	70.0	56.1	82.0	74.9	63.0
Combined	66.6	75.1	78.1	71.1	61.1

Table 4.3 Average SPL for 5 energetic parameters during an arrival or departure of the helicopter for each bed and the four beds combined

4.5 Conclusion

The first section of this chapter identified the layout of the unit, demonstrating where the bed spaces under study were located and a schematic representation of the bed spaces utilised for studies 2 & 3. It has highlighted the array of equipment that may be required to care for a critically ill patient, which must be fitted into these bed spaces, much of which is positioned at the head end of the bed space. It has also highlighted that it is an older unit, no longer compliant with the current building regulations for an ICU. This is likely to impact the noise levels within the unit.

The next section identifies the case mix data for the years 2014-2018. This includes two years, 2014 and 2016 for comparison purposes, when data was not collected and the years 2015, 2017 and 2018 when data collection for studies 2, 3, and 4 occurred. It also highlights similar data for the precise periods of both studies 2 and 3. This demonstrates that the beds under study were occupied for the majority of the time and contained patients with a high acuity, representative of a patient requiring care in an intensive care unit. The data identifies that the study periods were typical of the case mix of this unit. Lastly, a potential external noise annoyance, the arrival and departure of a helicopters from the helipad, is discussed and the impact it had on sound pressure levels at each bed space.

Chapter Five

Study One: Preliminary Investigations

5.1 Aim

To complete preliminary testing to ensure an understanding of the environment to be studied, a pilot of the equipment for such a study and an understanding of the impact of the environment on the sound monitoring equipment.

5.2 Introduction

To understand the acoustical environment of an ICU, a series of preliminary studies were performed in collaboration with the National Physical Laboratory (NPL) in Teddington. Study 1 is comprised investigations 1a-1c designed to describe the sound in the general intensive care unit (GICU) using conventional technology followed by the development of the NPL Minim utilising an Electrical-Mechanical-System (MEMS) microphone to enable continuous, longitudinal, distributed sound pressure measurement in one GICU.

These studies referred to below as studies 1a-1c represent a period of testing to enable the development of a bespoke system of acoustical measurement, the NPL Minim. It represents the foundations for the subsequent pieces of work, ensuring an understanding of the environment to be studied (1a), a pilot of the equipment for such a study (1b) and an understanding of the impact of the environment on the sound monitoring equipment (1c). In reporting these studies, I acknowledge the contributions of the Acoustics Division at the NPL, in particular Dr Gianluca Memoli and Dr Richard Barham. These studies are fully reported in two publications[74, 80], the writing for this chapter is adapted from this work.

5.3 Study settings

The study was set in an 18-bedded adult, general intensive care unit (GICU) as described in chapter 4. During study 1a, data was measured at bed spaces 6, 8 &, 11 (a side room), located within the ICU, bed spaces 16, 17 &18, located in the HDU and the two staff bases, one in the HDU and the other the ICU. Data for study 1b was measured at a single point on the ICU staff base. Study 1c was located in the sound laboratories at the NPL, Teddington.

5.4 Ethical approval

Local research ethical approval was sought but not required for this part of the study (Appendix 1 – Letter dated 16th June 2011). No patient data was required and sound measurement was of sound pressure levels only; which could not identify individual communication from patients, staff or visitors to the unit. Data was recorded directed onto the conventional measurement devices or transmitted in the case of the NPL Minim, via a designated local area network (LAN) cable to a secure password protected NPL website for storage. Sound pressure level data was converted to numerical data and analysed using Excel on password protected PC's at both the National Physical Laboratory and St George's University Hospitals NHS Foundation Trust or by myself on an encrypted laptop with password access.

5.5 Participants

There were no participants involved in the preliminary studies. Human noise was measured, but only in terms of the quality and quantity of sound, not as voice recordings. There are three main user groups who are both part of the soundscape and also impacted on by the noise of the GICU, these are: the patients, their visitors and the staff (permanent and visiting). Each of these groups is likely to experience and engage with the sound environment in diverse ways and thus the impact on each may differ.

5.6 Study 1a: Conventional sound monitoring in GICU

5.6.1 Methods

A total of eight areas were investigated within the GICU on a typical weekday in November 2011, providing 8 sets of 30-minute recordings. These included six bed spaces providing a selection of spaces including ICU, HDU and a side room (beds 6, 8, 11, 16, 17 and 18) and both staff bases (blue diamonds in figure 4.1). These areas were identified as they were available on the day of data collection but also represented a selection of locations around the GICU.

A Norsonic type 121 sound level meter fitted with a ½'' microphone (Norsonic, type 1201/30323) was mounted on an extensible tripod and protected from the air conditioning using a 6cm windshield. The calibration of the system was checked before and after the measurements using a Norsonic 1251 sound calibrator. Each measurement lasted 30-minutes and the instrument was programmed to A weighted sound pressure levels in 1/3-octaves between 8Hz and 20 kHz, with 'FAST' time averaging.

Values of L_{Aeq}, L_{max}, L_{min} were reported at intervals of 15-minutes, 1-minute and 1-second. 15-minute intervals provide broad information of the acoustical properties of an environment, whereas shorter intervals provide greater detail e.g. the possible identification of individual noise sources. The following statistical parameters ($L_{0.1}$, L_5, L_{10}, L_{25}, L_{50}, L_{75}, L_{90}, L_{95}) were automatically available for the 15-minutes intervals and calculated in post-processing for the 1-minute intervals.

The microphone was placed at a height of 1.35 metres from the floor; this reflected the estimated position of the patients' head, of visitors sitting at the side of the bed or staff during patient care. During the measurements, observed noise events were documented (e.g. alarms, staff noise, oxygen, telephones, single loud events),

together with the distances from the positioning of the microphones to the main reflecting boundaries (i.e. the back and side walls closest to each bed space).

5.6.2 Results

The 15-minutes intervals as seen in figure 5.1 show relative consistency in SPL across the various bed spaces and areas measured, with some increase in maximum SPL at bed 18 and the HDU staff base, as L_{90} is not affected this suggests some short but loud bursts of sound at both the bed space and the staff base. Additionally, there is an overall decrease in noise in the side room, bed space 11 compared to the other bed spaces.

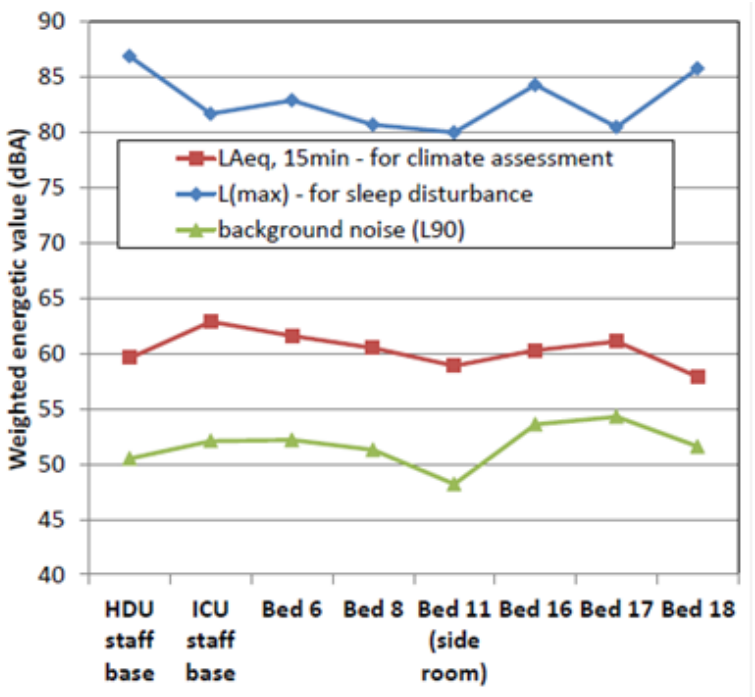


Figure 5.1: 15-minute averages for L_{Aeq}, L_{max} and L_{90} for each of the eight areas measured across GICU

Figure 5.2 demonstrates the statistical parameters, the percentage of time the energy levels were exceeded for a given decibel level at each bed space and also the staff bases. Despite the average L_{Aeq} being similar for the HDU staff base

(59.6dB), ICU staff base (62.9dB) and bed 8 (60.5dB), as identified in figure 5.1; figure 5.3 identifies that bed 8 and the ICU staff base exceed the 60dB level for a greater percentage of time (25%) than the HDU staff base (10%).

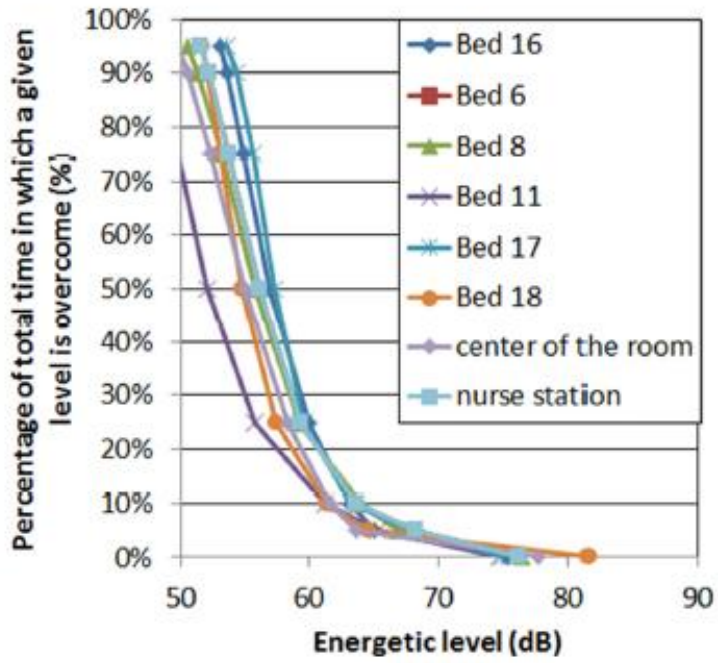


Figure 5.2: 15-minute averages for statistical parameters for each of the eight areas measured overcome across GICU

These figures also identify that measuring L_{90} and L_{Amax} are sufficient to ensure adequate data are recorded at either end of the dB spectrum and no further valuable information would be gained from measuring L_{95} or $L_{0.1}$. 1-minute and 1-second recordings provide more detailed data, however 1-second recordings provide 60 times as much data as 1-minute recordings, which requires large amounts of storage and powerful interpretation algorithms. It is therefore important to identify whether this level of detail is required. Using 'FAST' averaging (125ms) preserves the minimum and maximum values within the 1-minute recording using

L_{Amax} and L_n (where L_n is a statistical parameter); these help us to understand pressure variations of less than one minute.

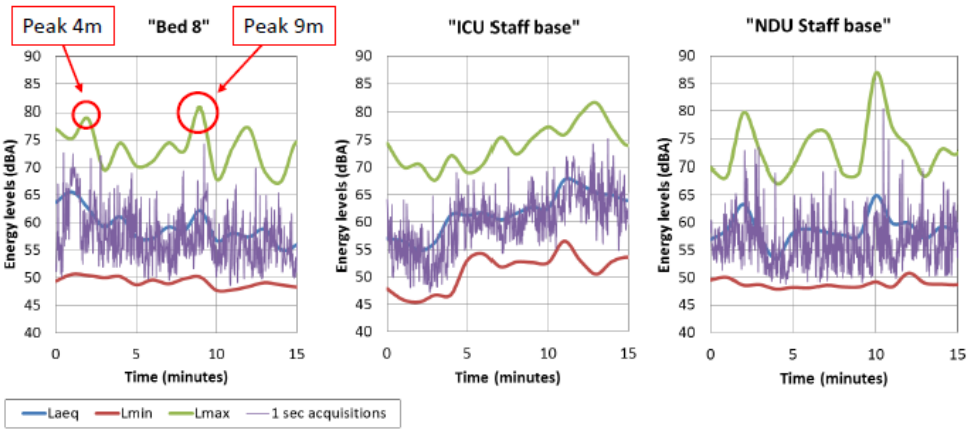


Figure 5.3 1-minute recording of L_{Aeq}, L_{Amin} and L_{Amax} and 1-second recording of L_{Aeq} for bed space 8, ICU staff base and HDU staff base

Figure 5.4 demonstrates that the peak at 4 minutes is likely caused by a number of repeated noises, as the threshold of 70dB was never reached but the peak lasted for longer, whereas the peak at 9 minutes was more likely due to a single loud event as the peak exceeded 70dB.

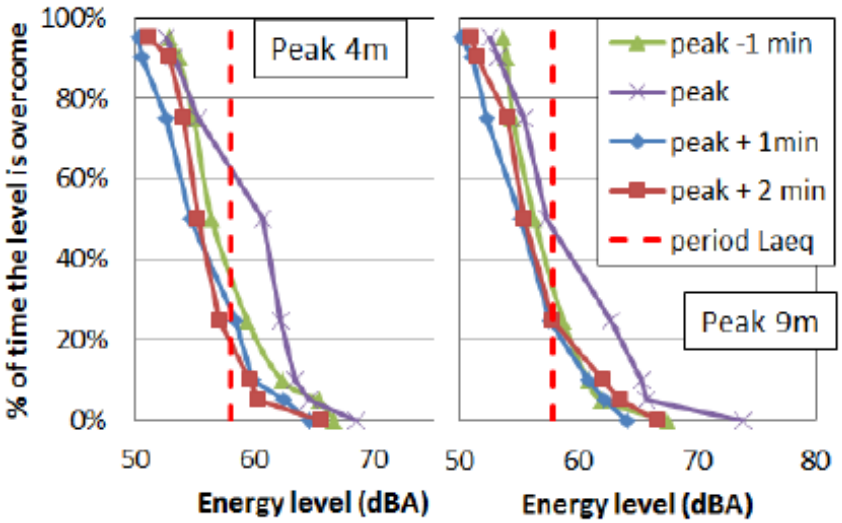


Figure 5.4: 1-minute statistical levels, calculated from sixty L_{Aeq}, 1-second averages, for two peaks from bed space 8 as highlighted in Figure 5.3

5.6.3 Learning

This study demonstrated the utility of conventional sound recording and its limitations, in terms of visibility, obtrusiveness and cost per unit for a distributed, longitudinal study. It identified that the sound pressure levels in these short periods of measurement were in excess of current international recommendations for an intensive care unit. In this study the side room was quieter. Analysis of the statistical parameters demonstrated the ability to isolate and review noise events.

5.7 Study 1b: Continuous sound monitoring in GICU

5.7.1 Methods

Conventional sound monitoring as used in study 1a, is large and expensive. Each device may cost more than £5000 and they require specialist knowledge to operate. The devices are either hand held or require a tripod, which is large and cumbersome. Temporal sampling is limited in duration and spatial sampling requires point by point sequential measurements, necessitating operator presence. To characterise the sound environment of the intensive care unit, both temporal and spatial analysis is required. Conventional devices lack the flexibility required to continuously and simultaneously monitor each bed space in the GICU. As previously described in chapter 1, recent advances have enabled the development of small, relatively inexpensive measurement systems, making them feasible for spatial and permanent deployment in multiple locations, such as the GICU. Previous study has identified the utility and reliability of MEMS technology for distributed sound measurement in the outdoor environment[12,13]. The system therefore required testing to identify its applicability in the indoor setting. This included the choice of an informative set of eight acoustical indicators; the positioning of the units across the unit to achieve the most effective sound recording, the temporal resolution for the acquisition (to obtain the optimum

balance between the amount of data to analyse and the effects to be monitored) and the conflicting needs for the system to be unobtrusive so as not to impact on normal clinical working and at the same time, reflect the patients, visitor and staff experience of noise. The light fittings installed at the head end of each bed were identified as the ideal location for mounting a MEMS microphone.

A prototype device called the NPL-Minim (Crown Copyright NPL) was developed specifically by the Acoustics Division at the NPL for this purpose. The NPL-Minim was developed at the NPL for indoor distributed sound measurement. It is based on a previous design, the Distributed Remote Environmental Array Monitoring System (DREAMSys) developed for outdoor application[12,13]. Concurrently a password protected, web-based database was developed, enabling data to be reviewed in real time and subsequently analysed. Testing of this new system took place in situ on GICU and the NPL in early 2012. The system samples sound continuously at 48kHz to avoid losing high frequency information. Samples are batched into blocks of 1-minute for which eight acoustical parameters identified previously in study 1a, (L_{Aeq}, L_{max}, L_5, L_{10}, L_{25}, L_{50}, L_{75}, L_{90}) were programmed. The NPL-Minim consists of a MEMS microphone with a frequency response conforming to IEC 61672-1 Class 1[10] mounted on a pre-amplifier, a digital acquisition (DAQ) unit to acquire the A and C weighted pre-determined energy levels. The data was downloaded via dedicated LAN connections to a database with data filtering and web-based interfaces for analysing the large amount of data generated by continuous 1-minute recording. For this part of the study, the unit was pragmatically positioned close to an existing mains power source and LAN connection to enable the testing of the device in situ. The device was located for a period of one month in April 2012 on the ICU staff base behind the PC's with the microphone positioned to reduce the impact of co-located devices which might cause reflection (figure 5.5). As there was the potential to need to access the device regularly during

testing it was considered appropriate for the test site to be a staff base rather than a bed space. Therefore, the impact of the microphone mounting device (1c) and the impact of room boundaries (1a) have been considered elsewhere. The NPL-Minim was calibrated immediately before measurements commenced, using a standard hand held calibrator.

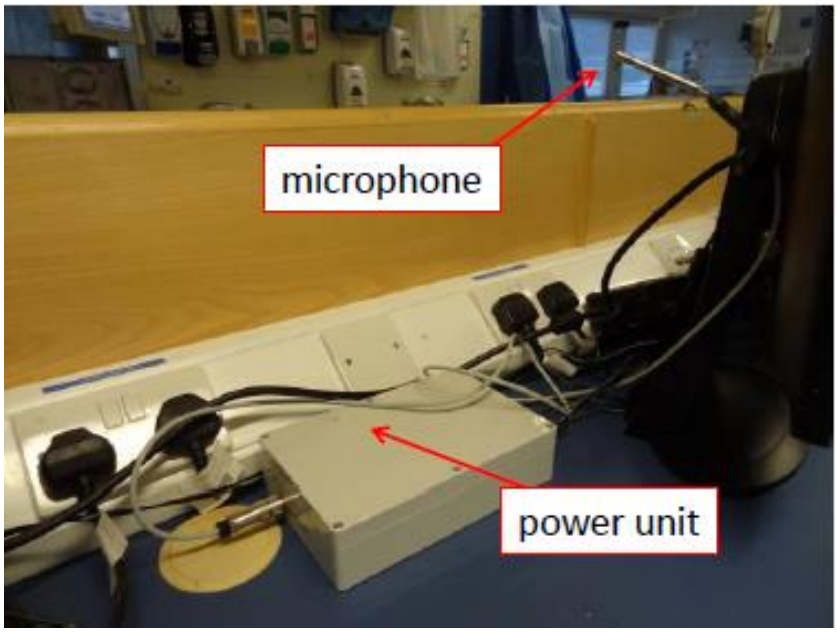


Figure 5.5 Photograph of NPL-Minim in situ in the GICU

5.7.2 Results

Data was analysed for a one-week period from 23rd - 29th April 2012 inclusive. This week was identified as it was thought to represent a typical week with no altered working practices from bank or school holidays or estates work undertaken on the unit. The mean L_{Aeq} demonstrated a diurnal pattern, with the GICU being less noisy from approximately 23.00-05.00hrs with little difference seen between the complete week and weekdays (Figure 5.6). The average L_{Aeq} for two spot measurements taken during the conventional sound recordings in November 2011 compare well with these continuous recordings. Further analysis of statistical

parameters provided information on some regularly occurring noise peaks. L_{90} recording highlighted two 6dB peaks above the background averages; one occurring at 08.00 and another at 20.00hrs, this was consistent with medical and nursing staff changeover times. Combined information from L_{75} and L_{90} levels showed a 3dB increase in noise occurring daily between 17.00 and 18.00hrs, this is most likely when the medical staff are collecting information at the ICU staff base for the evening ward round. The device remained stable over the month and subsequent calibration following installation was not required.

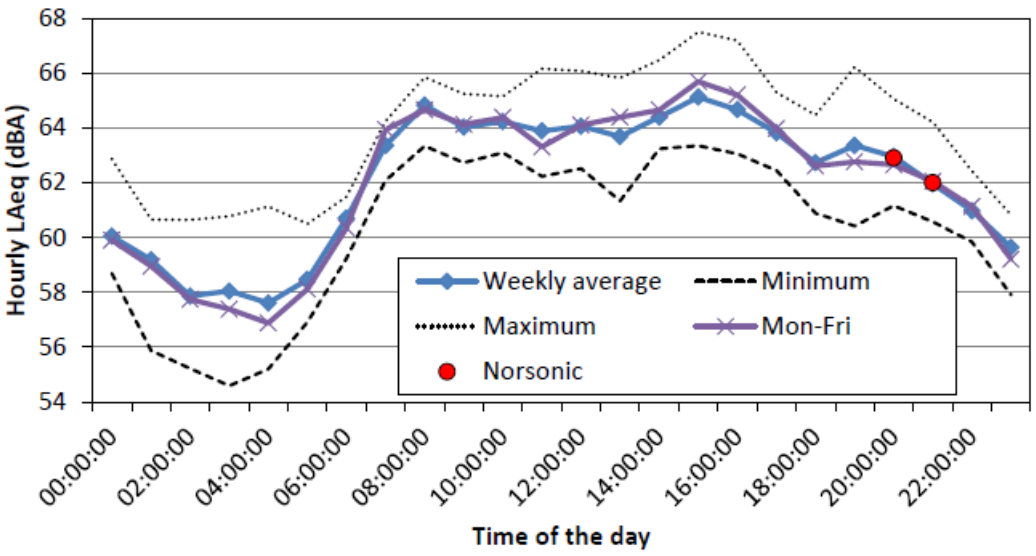


Figure 5.6 Average L_{Aeq} levels recorded continuously over one week at the ICU staff base using a NPL-Minim unit. The red dots indicate 15-minutes "spot" measurements taken during classic sound recording and shown in Figure 5.1

5.7.3 Learning

Study 1b demonstrated the stability and utility of the NPL-Minim in the clinical environment for longitudinal, distributed sound pressure level measurement. The data was consistent with the snapshot recordings, but provided substantially more information including daily trends similar to those seen in other studies. This study suggests the NPL-Minim is suitable for indoor use.

5.8 Study 1c: Microphone testing at NPL and in situ

5.8.1 Methods

To provide distributed sound recording across the GICU and to demonstrate the patient, visitor and staff perspective of noise it was decided to record data from each bed space and above each staff base. To avoid any impact on patient care, a decision was made to locate the microphone above the head of the bed on a light fitting provided at each bed space. Any structures close to the microphone would have the potential to impact on the sound recorded either absorbing or reflecting sound. Due to the nature of the unit, reflection is most likely as there are few sound absorbing materials close to the bed space and many reflective sources. These include the light fitting, the ceiling, surrounding equipment and the indoor environment itself. To provide a correction factor, the impact of these structures was therefore assessed at the NPL under hemi-anechoic and reverberant conditions and then tested in situ.

An anechoic chamber provides a substitute for "free field" conditions, where sound energy travels away from the source with little reflection back. The walls and ceiling are covered with cones, wedges or pyramidal structures made of sound absorbing material, the floor is either of mesh or retracts to enable entry to the chamber. Hemi-anechoic chambers have a solid floor on which to work and are therefore more appropriate for most testing (see figure 5.7). Conversely a reverberant chamber reflects sound back by containing a number of reverberant surfaces sited at differing angles so sound easily travels from one surface to another. These chambers test the impact of the light fitting in two extreme conditions providing the boundaries for the impact expected on the microphone in the environment under investigation.

During November 2011 a series of tests were completed in the reverberant and hemi-anechoic chambers at the NPL. A model was made of the proposed light fitting and placed on the floor of the relevant chamber with the sound source located above it i.e. providing an inverted representation of the final location (figure 5.7). The acoustic influence of the light fitting was identified using a microphone with a nominally flat free-field frequency response (Brüel & Kjær type 4135) mounted on a long pole, positioned in the far field below a descendant facing sound source in a hemi-anechoic chamber. The configuration in figure 5.7 was then used to establish the free-field frequency response of the microphone, using a time selective technique[204]. As can be seen from figure 5.7 the configuration of the experimental set-up the pathway from the source to the microphone to was discernibly shorter than the indirect pathways. The response was measured with a time-selective technique that effectively removes the influence of reflections, leaving the response of the microphone to the direct sound from the source. This is effectively the free-field response of the microphone. The microphone was then attached to the mounting structure and the measurements repeated, but this time without utilising a time selective technique. The influence of the mounting structure was then determined from the ratio of these two responses (or the difference in decibels) and corrected for the change in separation between the sound source and the microphone showing that there are three main components to this correction that need to be isolated: reflections from the wall and from the light fitting post, scattering and corrections due to distance.

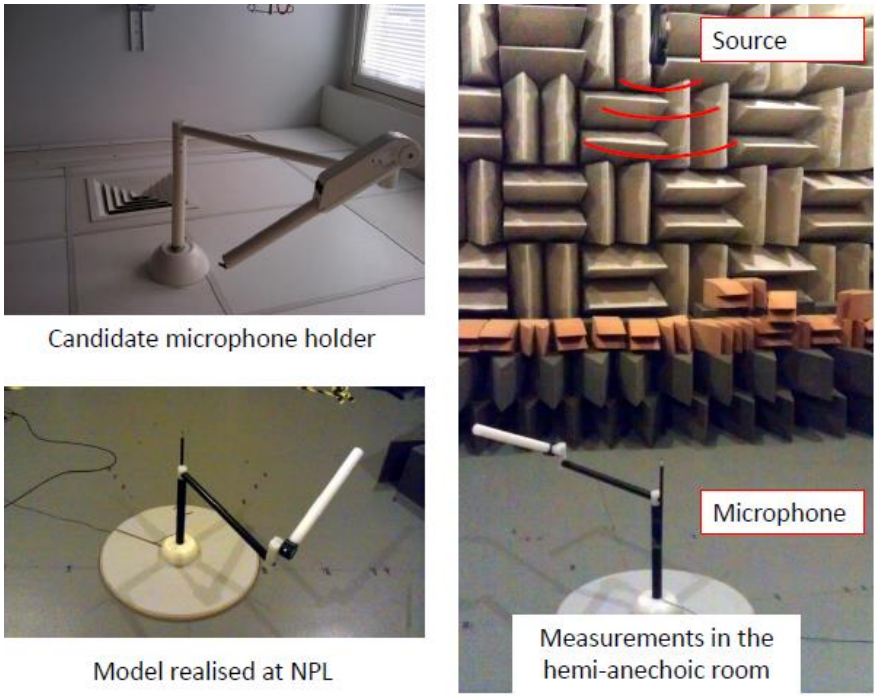


Figure 5.7 Photographs showing top left GICU light fitting; bottom left model made at NPL, right inverted presentation in the hemi-anechoic chamber at NPL

In addition to the influence of the light fitting, it was important to understand the effect of the medical equipment and room acoustics, which cause a series of multiple reflections i.e. a semi-reverberant environment. Estimating the effect of the microphone mounting in these conditions is difficult, as the precise nature of the field (and the amount of reverberation) is unknown. It was therefore decided to explore a controlled scenario, exploring the response of the model system in a fully reverberant environment. The model of the light fitting was placed in the centre of the NPL reverberant room, pointing upwards, as in the semi-anechoic chamber, using the floor to mimic the ceiling. As before a 1/4inch microphone was positioned at a 90º angle at increasing distances from the mounting structure. A reference source of pseudo-random noise was placed two metres from the microphone, in two different positions: Source Location 1(SL1) had the sound source located on

the floor, whilst Source Location 2 (SL2) had the source elevated by approximately 70cm (Figure 5.8).

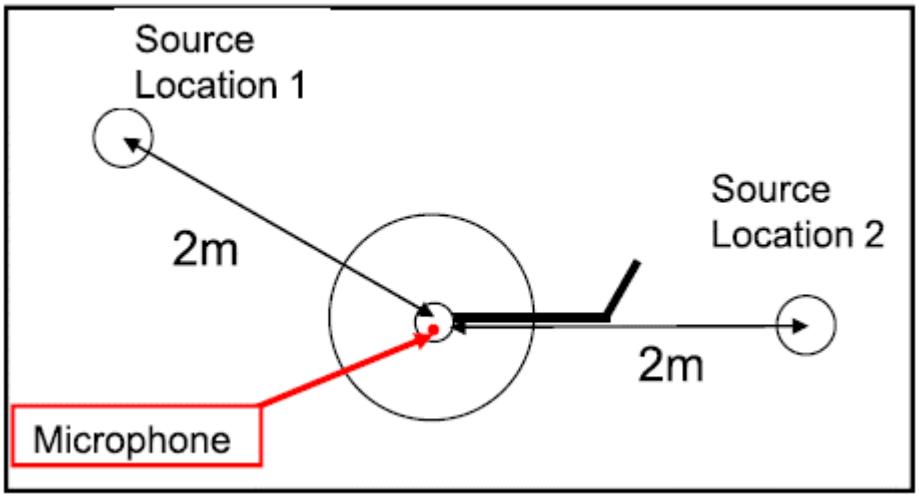


Figure 5.8 Measurement set-up in the NPL reverberant rom, in order to estimate the effects of reverberation on the measurements

A 10-second linear average of the A-weighted sound pressure levels was taken and the levels recorded. The process was repeated four times for each selected distance in the range 0–80cm, where 0cm is directly adjacent to the mounting structure.

In addition to estimating the corrections required in ideal conditions (the hemi-anechoic environment) and fully reverberant conditions, it is necessary to understand how these corrections represent the noise environment as experienced by the patient, visitors and staff in the GICU.

Using an empty bed space (bed space 18 in figure 4.1); 15-minute spot measurements as described in study 1a were conducted at different distances from the light fitting, with a similar background noise for all three measurements. Measurements were also taken near bed space 7 and also in bed space 3, but this time with the bed removed, in order to identify the impact of the bedframe and

mattress. L_{90} was used to determine differences between positions, to remove the intermittent impact of short loud noise. Figure 5.9 a and b shows the most relevant positions for this type of measurements, corresponding to the head of the patient (P1, at 119 cm from the fitting) and the head of visitors (P3) or staff (P2). Measurements were repeated near bed space 7 and, in order to estimate the value of Δloc (local absorption), also at bed space 3 with the bed removed.

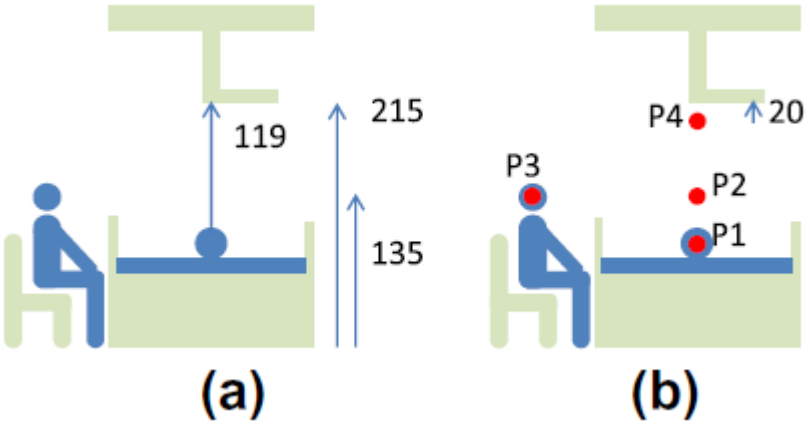


Figure 5.9 In situ assessment of the correction for obtaining the noise at patient and visitor level: (a) geometry involved near beds (distances measured in cm) and (b) relevant receiver positions, P1 represents the head of the patient, P2 staff working at the bed space, P3 the head of visitors sitting by the bed and P4 the position of the microphone

5.8.2 Results

A series of measurements were made with the microphone mounted at different distances from the structure in both hemi-anechoic and reverberant conditions. After a broadband analysis, the effect of the mounting could be estimated as a correction of +1.8 ±0.2 dBA (microphone head at 15 cm from the mock-up fitting) and of +0.65 ±0.1 dBA (microphone at 27.5 cm from the central pole) to the data without it, confirming that the difference is mainly explained by the fitting (Figure 5.10). Based on these results, the microphone should be placed 20–30cm from the

light fitting. Due to practical considerations i.e. to allow the rotation of the horizontal pole, a distance of 20cm seems to be the best option.

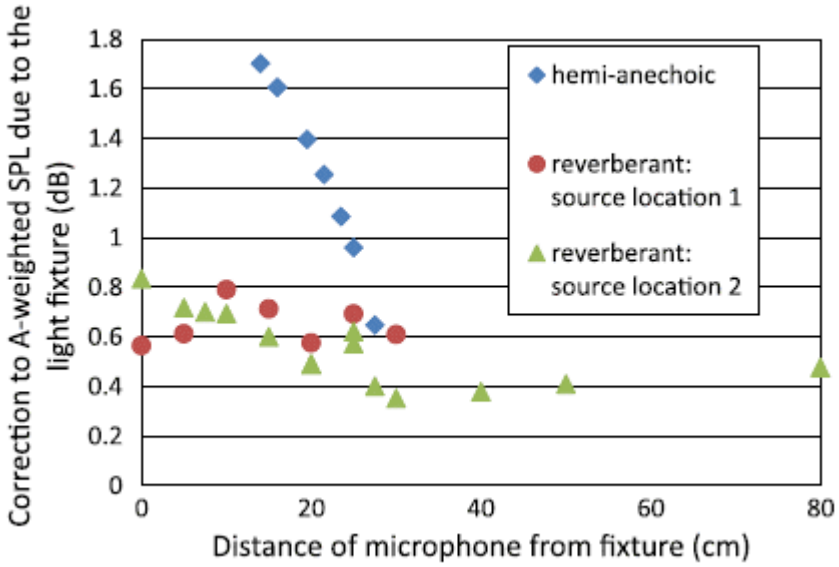


Figure 5.10 Effect of the presence of the mounting structure on the measured level, as observed in a hemi-anechoic and in a fully reverberant environment

Figure 5.11 shows a comparison between the total correction from the microphone studies at the NPL and in the GICU. While the difference measured between position P1 and P4 is compatible with the correction factors estimated at NPL, and all the measurements fall within a band of ±2dB from the reference (in position P4), there is no consistency in the measures taken in GICU. Since the measurements obtained without the bed (bed space 3) follow a similar trend to the ones taken near bed 7 and bed 18, within the ±1dBA uncertainty, these results did not allow determination of local absorption (∆loc).

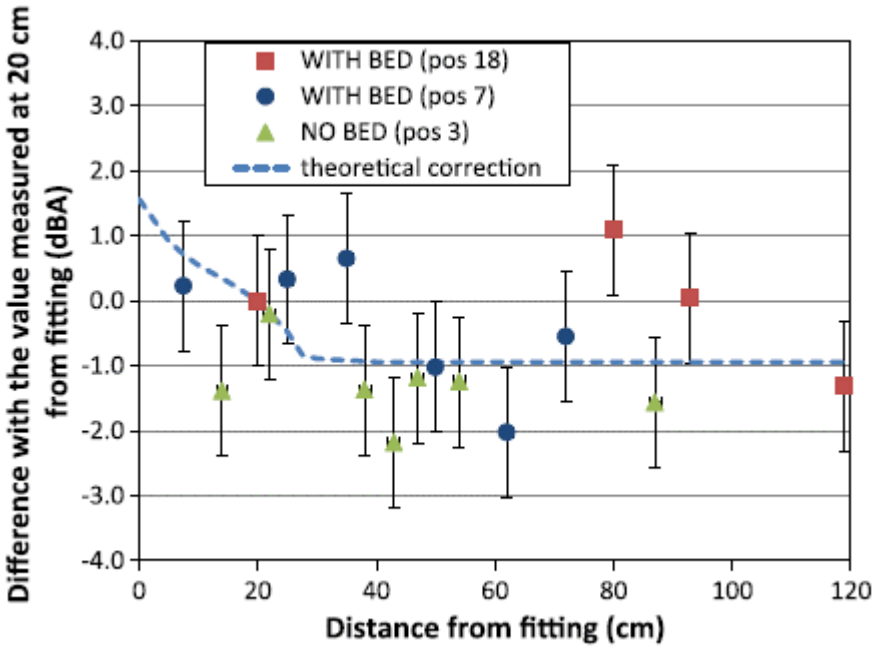


Figure 5.11 Comparison between correction factors measured on GICU and at NPL, in terms of differences from the value measured/expected at 20 cm from the fitting. The dotted line represents $\Delta 1$ when $\Delta 1 \geq \Delta 2$ and $\Delta 2$ otherwise. Error bars represent estimated measurement uncertainty of ±1dB

5.8.3 Learning

Study 1c identified in laboratory conditions, the impact of various structures on the microphone including the pole on which the microphone was to be mounted and the potential impact of the ceiling. In situ testing identified the correction factor to ensure measurement related to the users of the GICU bed spaces, with the intension of ensuring the results were clinically relevant as well as scientifically sound.

5.9 Discussion

Conventional sound meters and continuous sound measurement using the NPL-Minim demonstrate that the sound pressure levels in the GICU measured by L_{Aeq} and L_{max}, consistently exceed those recommended by the World Health Organization[16,41,42] and are consistent with published studies in the ICU[24,56-73,75-

[79,81-94]. At times maximum levels exceed guidance contained in 'The Control of Noise at Work Regulations[38] for safe working, although these levels are not for protracted periods of time, thus not requiring ear protection for the staff in an ICU. Detailed analysis of the statistical parameters recorded with the conventional sound measurement instruments over 30-minute periods identified some interesting features, such as the peaks at bed space eight, that combined with observational data, will identify the sources of sound and may identify potential areas of annoyance for patients or staff. Repeated findings of this type would help to identify those sounds that could be modified to reduce annoyance.

The analysis of the 1-minute data capture suggested that with 'FAST' averaging, 1-second recording is not required, that minute recording with L_{Aeq}, L_{max} and the following statistical parameter values (L_5, L_{10}, L_{25}, L_{50}, L_{75}, L_{90}) will provide the additional data required. This type of snapshot recording, although in this case it was for very short periods, provides data that may however not be reflective of a 24hr period and is a criticism of many previous studies[24,59,60,64,68,75,78,81,84,85,87,88,90,93]. To utilise conventional sound measurement for longer periods of time is inappropriate, it is invasive to patient care, requires regular calibration, would be prohibitively expensive and due to its visibility may bias results. The continuous data provided by the NPL-Minim provided observation of a week; this data is more likely to provide typical rather than atypical data over a 24hr period, although data recording would need to be longer to identify any weekly rather than daily trends. It showed an interesting daily diurnal variation, common to the majority of studies measuring for 24hrs or greater[61,63,65-67,72,82,83,86,91,92], which was retained at the weekend suggesting the pattern of sound is much unchanged at weekends; this is not surprising given the nature of the ICU workload. Both the continuous data collection with NPL-Minim and the snapshot data collection identified the need for observational data to augment SPL data to recognise the sources of noise.

The NPL-Minim demonstrated reliability over a prolonged period of time, but in this pilot study the device was not placed at the bed side and could not therefore provide a representation of sound from the perspective of the patient, visitor or staff. The instrumentation is easily disguised, with the majority of the boxed electronic elements being placed above the false ceiling and only the wire attaching the microphone to the boxed elements and pencil like device containing the microphone visible. This work suggests the NPL-Minim is suitable for indoor use.

Laboratory testing demonstrated that the microphone is minimally affected by the light fitting if it is fixed at a distance of approximately ≥20cm, this requires a +1.3dB correction. Identifying this correction and positioning of the microphone enables the recording to be relevant to the patient, staff and visitor's perspectives. These preliminary studies suggest that a continuous study recording SPL using the NPL-Minim at each bed space and over each staff base, over a prolonged period of time is feasible and will provide greater information to describe the sound environment in an GICU and discover the potentially modifiable sources of noise.

5.10 Conclusion

The literature identifies the need for a distributed, longitudinal study of sound in an ICU. These preliminary studies have identified the feasibility of such a study, with the aim of describing the sound environment of the GICU and to inform future studies regarding required statistical parameters, microphone location and postulate a correction to demonstrate sound from the patient, visitors and staff perception while at the bed space.

Chapter Six

Study Two: Distributed Sound Measurement

6.1 Aim

To complete longitudinal, distributed, continuous sound pressure level monitoring across a general intensive care unit.

6.2 Introduction

Preliminary testing, as described in the previous chapter, identified that the NPL-Minim was suitable and stable for continuous, distributed sound monitoring in an indoor environment. This chapter describes the processes required to enable and deliver a study measuring distributed sound in an ICU. The chapter commences with a description of the installation and testing of the microphone to understand the impact of the light fitting on sound measurement. This additional testing was required due to an unexpected change of light fitting between the preliminary work and this study. It then describes a challenging period of time, experienced when attempting to install in conjunction with the NHS Estates and IT departments, the remaining instrumentation above the ceiling tiles in the ICU and HDU and the compromises made to commence data collection. Lastly it describes the period of data collection, and presents the results of a longitudinal, distributed, continuous sound pressure level monitoring study in the GICU of St George's Hospital, London.

6.3 Methods

6.3.1 Study Setting

The study was set in an 18-bedded adult, general intensive care unit (GICU) as described in chapter 4. During this study, data was measured from four bed spaces (bed spaces 3, 5, 9, 11) located in the ICU, bed space 11, being a side room.

6.3.2 Ethical Approval

Ethical approval was granted by the Office for Research Ethics Committees Northern Ireland REC reference:15/NI/0106 IRAS project ID:128446 on the 2nd June 2015 (Appendix 1 – Letters dated 2nd June 2015 and 8th June 2015). For this phase of the study no patient data was required and sound recording was of sound pressure levels only and could not identify individual communication from patients, staff or visitors to the unit. Data was recorded via a microphone above the individual bed space and immediately transmitted via a designated local area network (LAN) cable to a secure password protected laptop for storage. Sound pressure level (SPL) data was converted to numerical data and analysed using Excel on password protected PC's at both the NPL and St George's University Hospitals NHS Foundation Trust.

6.3.3 Participants

There were no participants involved in this phase of the study. Human interaction was recorded but only in terms of the quality and quantity of sound, not as voice recordings. There are three main user groups who are both part of the soundscape and also impacted on by the noise of the GICU, these are: the patients, their visitors and the staff (permanent and visiting). Each of these groups has differing effects of the impact and experiences from sound.

6.3.4 Installation and testing of the microphones

To ensure that the microphones were appropriately positioned over the beds, a decision was made to connect them to the light fitting above the bed. A simple bracket was developed that could easily fit to the microphone and the light. This bracket ensured the microphone would not accidentally be damaged by the articulation of the horizontal arm of the light fitting, as it sat neatly on the underside of this arm (Figure 6.1).

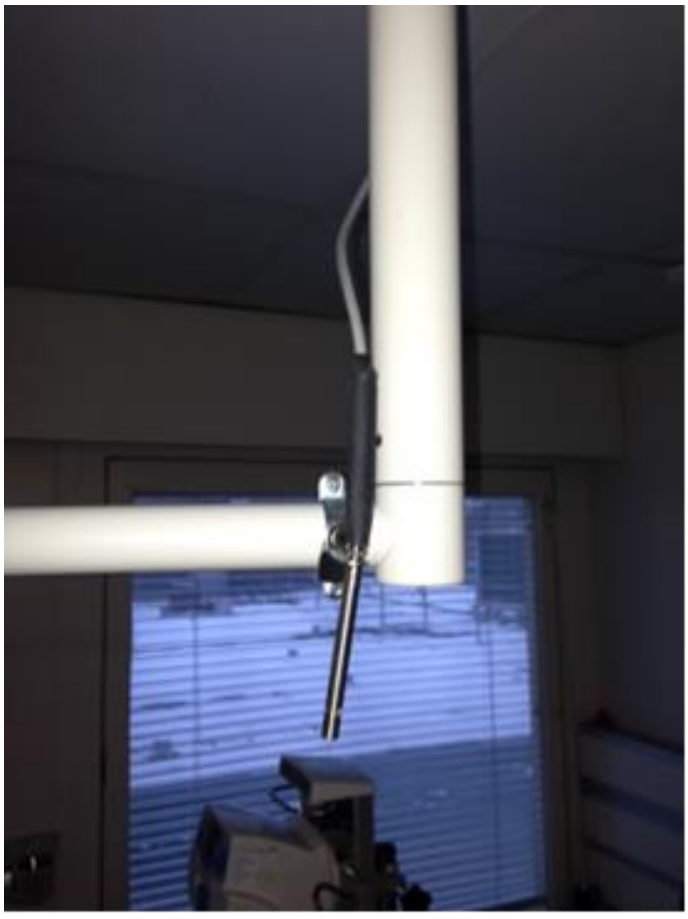


Figure 6.1: Initial proposed installation of the microphone on the original light fittings in the GICU

The microphones were installed in late 2012 in anticipation of the enabling works being completed. Unexpectedly in January 2013, the GICU received funding to

replace the lights above the beds, as a date for the beginning of the study was not yet agreed, it was not possible to delay this work. The new light fitting had an articulated arm at the point where the microphone was to be installed, thus rendering the original brackets and positioning redundant. In addition, during their period of installation, the original brackets had become distorted from continued use of the light and therefore the new lights provided an opportunity to design a more robust bracket. A prototype bracket was forged in metal and connected to the down pole using two jubilee clips. Previously the positioning of the microphone had ensured a relatively clear field around the microphone (figure 6.1). As this was no longer possible, a suitable distance needed to be identified to ensure that the microphone was not impacted by the down pole. Study 1c had previously identified a distance of between 20-30cm as acceptable. To identify the best distance and the impact of this structure on future noise recordings, further testing at NPL was required. Two prototype fittings were made, one extending 32cm (figure 6.2) from the down pole and another 21.5cm (figure 6.3).

Testing took place in July 2013 in the hemi-anechoic chamber at the NPL using an inverted representation of the light fitting and bed space as in chapter five figure 5.8. Each bracket was sited as if above the patient's head, i.e. facing towards the back of the bed space, 31.5cm from the floor, the smallest possible distance to ensure the microphone was clear of the light when moved or rotated but also to reduce impact from the ceiling. Testing identified how closely aligned the arm of the light fitting, which was connected to the down pole, could be to the microphone and fitting without causing impact on the sound measurement, assuming 0° was perfect alignment. Testing of both fittings identified the shorter fitting produced impact between 0-20°, however the longer fitting caused impact at a wider radius (figures 6.4 & 6.5). To confirm this, the brackets were again tested sequentially this time using a broadband signal, more representative of sound in the clinical

Figure 6.2 32cm bracket

Figure 6:3 21.5cm bracket

environment. This confirmed that the 21.5cm bracket caused least interference, the impact of the bracket at 0° being -1.19dB using an A-weighting and -1.59dB without A-weighting (figure 6.6), outside of 20° the impact was negligible.

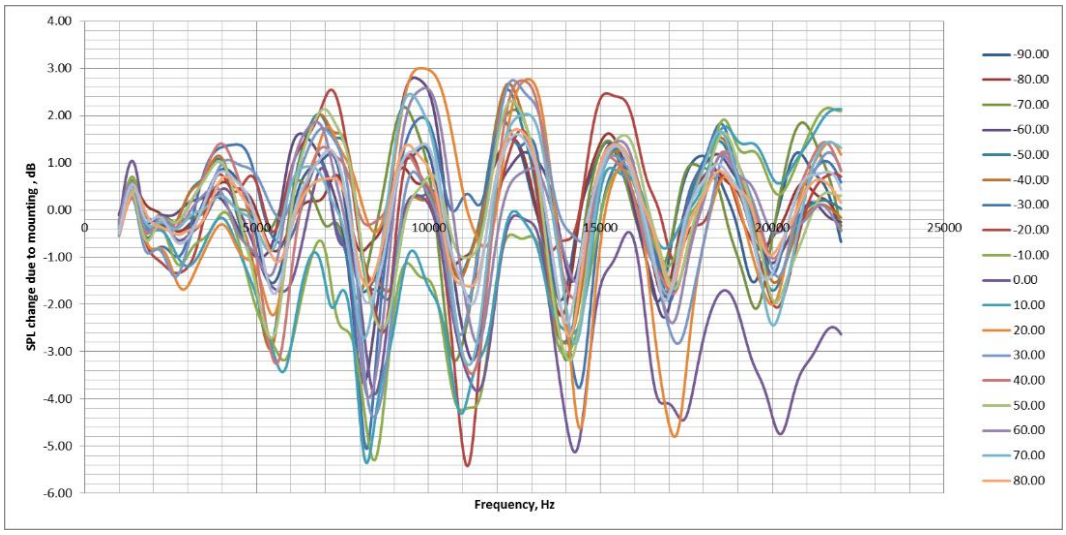


Figure 6.4: Frequency response with the microphone placed on the 21.5cm at 10° intervals away from the microphone

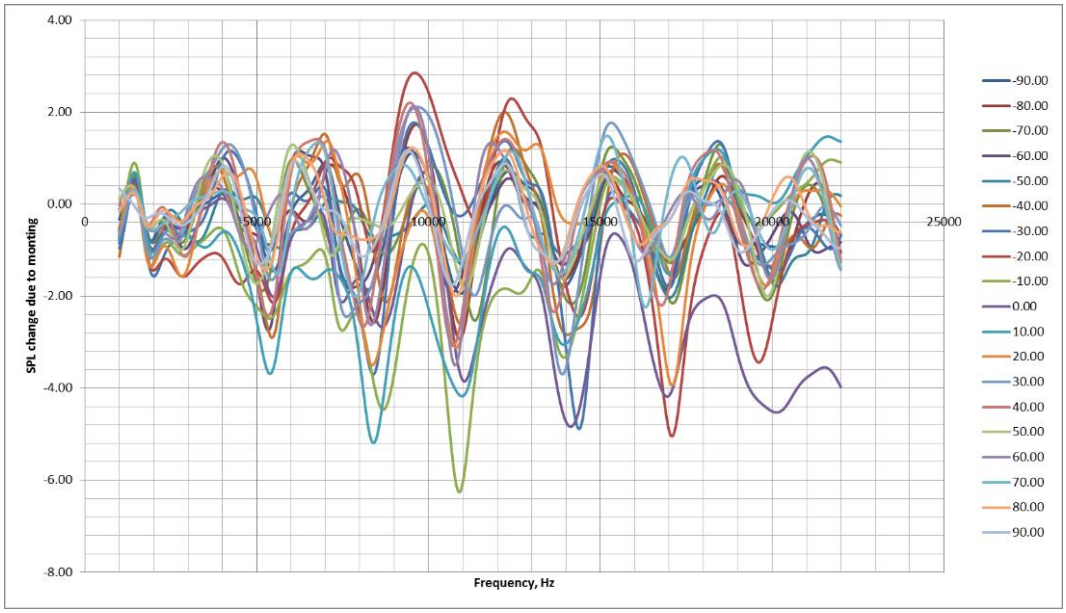


Figure 6.5: Frequency response with the microphone placed on the 32cm bracket at 10° intervals away from the microphone

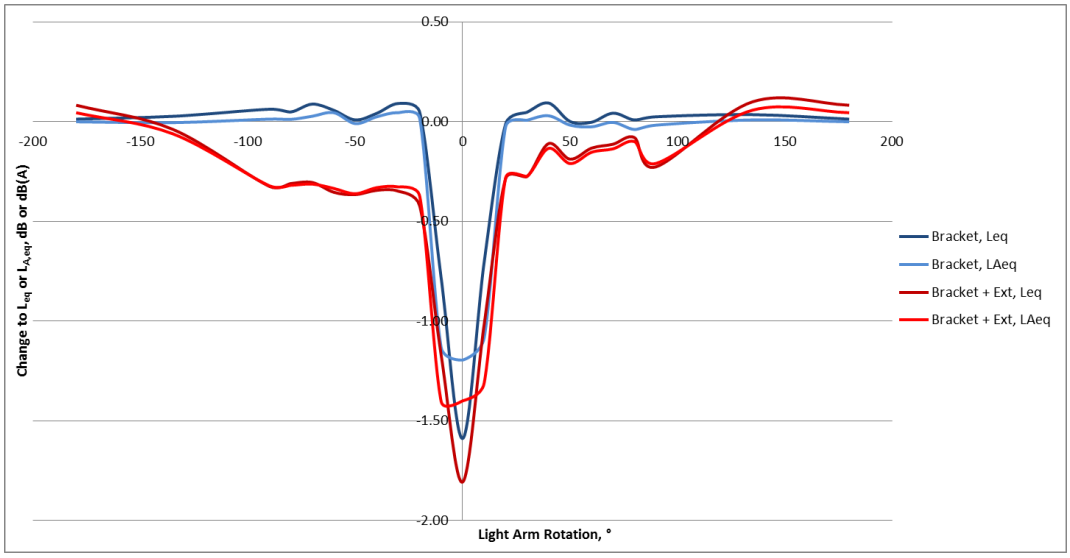


Figure 6.6: Broadband response with and without A-weighting for 21.5 and 32cm brackets

6.3.5 Installation of the remaining instrumentation

In January 2012, discussion commenced with the hospital Estates and IT departments regarding installation of the NPL-Minim, an electrical supply and a LAN connection to each bed space and the two staff bases as indicated in chapter four figure 4.1. Access to the bed spaces for any works to occur, could only be provided when there was no patient in the bed space. Co-ordinating empty bed spaces, estates and IT engineers proved problematic; however electrical power was installed and tested by July 2012. Initially in February 2012, a vacant LAN connection at the back of each bed was made live. At this point the Infection Control department decided that they preferred the instrumentation and wiring to be located above the false ceiling. Therefore, the electrical work to provide a dedicated power supply to each unit was installed above the false ceiling, as requested. This allowed the unit to be concealed in the ceiling, thus reducing the risk of inadvertent disconnection and an infection control risk from the bed space. This now however required cabling from the LAN socket at the back of the bed

space into the ceiling. It was decided to locate new LAN sockets and cabling in the ceiling, requiring a separate installation of 20 LAN sockets.

Due to pressures on the hospital IT department and the difficult bed side access this was not completed until the beginning of June 2013. All units were then tested using the web-based database, however initially only units 3, 4, 15, 18, 19 and 20 were providing a signal. Several attempts were made to resolve this issue, with various electrical and IT problems identified, eventually both departments claimed their individual equipment was working. Therefore, in 2014 all NPL Minim units were removed for testing, this identified a fault in the stability of the units and was corrected. In January 2015, over a period of several weeks, all units were replaced in the ceiling, with the expectation that all units would provide data. Initial testing demonstrated that only six units in bed spaces 1, 3, 5, 7, 9 and 11 provided data and subsequent testing demonstrated that only four units 3, 5, 9 and 11, consistently provided data. As these bed spaces were highly representative of the main ICU and due to the large amount of time taken in attempting and failing to install a system to record across all beds and staff bases, a decision was made to commence the study utilising the four working units. These were calibrated for use in February 2015; however, at this point access to the web-based database was lost. The member of staff at NPL maintaining the website had left, at the time it was not thought possible to replace them in a timely manner to use the website as the data collection point. A decision was made to install a password protected lap top in the GICU and the data was down loaded via the LAN connections directly to this. The disadvantage of this was that data could not be reviewed in real time.

The laptop was connected to the LAN connections on the 30/6/2015 and the devices calibrated with a sound calibrator on the 6/7/2015. This provided a period of time where staff acclimatised to the introduction of the equipment, with the aim

reducing the impact of the equipment on behaviour. The NPL-Minim was programmed to acquire information at one-minute intervals using a 'FAST' detector response for nine acoustical indicators (L_{Aeq}, L_{Ceq}, L_{max}, L_5, L_{10}, L_{25}, L_{50}, L_{75}, L_{90}) over the period of the study. Data collection commenced at midday 6/7/2015 following calibration and was completed at 17.00hrs 23/9/2015. At 18.00hrs 22/9/2015 the signal from the device above bed space 5 was lost; within 24hrs all signals were lost and a decision was made to complete data collection.

6.3.6 Data Analysis

Scripts were developed to extract the raw data from the database to an Excel spreadsheet, taking the opportunity to filter corrupted (non-numeric) or missing (blanks and zero-valued) data resulting from transmission errors in the network, correct and synchronise the time base and calculate selected longer period L_{Aeq} as necessary. For each bed space, post-processing within the spreadsheet was carried out. The data for L_{Aeq}, L_{Ceq}, L_{Amax} and the statistical parameters were averaged from the energy-based averages of the 1-minute values, using a macro to convert logarithmic data for each hour of the day. The data was then collated to provide an average for each week by hour of the day and day of the week. To test for the significance of the difference between variables including bed space, hour of the day, day of the week, day/night and weekday/weekend, one-tailed t-tests were calculated, where alpha =0.05, with the hypothesis that L_{Aeq} for *n* will be higher than the comparator and the null hypothesis that the L_{Aeq} is not higher for *n*. Data for L_{Amax} and L_{90} were extracted to calculate restorative time (RT) utilising Park and colleagues[92] definition <17.7dB L_{Cpk} relative to background i.e. L_{90} (L_{R2B}). As L_{Cpk} was not measured, $L_{Amax1min}$ was used in its place to calculate restorative time relative to background noise.

6.4 Results

6.4.1 Sound pressure levels

Continuous sound pressure levels were successfully measured at four bed spaces, including one side room for a period of eleven weeks, in a busy general ICU without any disruption to clinical care. During the 11-weeks there was loss of data between 21/8/2015 and 2/9/2015 due to a break in the electrical supply and the loss of one bed space (bed space 5) one day earlier at the end of the recording period than the remaining bed spaces. Data was therefore collected at three bed spaces (3, 9 & 11) on 68 days and one (bed space 5) on 67 days, a total of 271days. Not all days were whole days (i.e. complete 24hrs) and there was dropout of individual minutes of data over the entire measurement period, therefore the results include a total of 370,054 minutes of data.

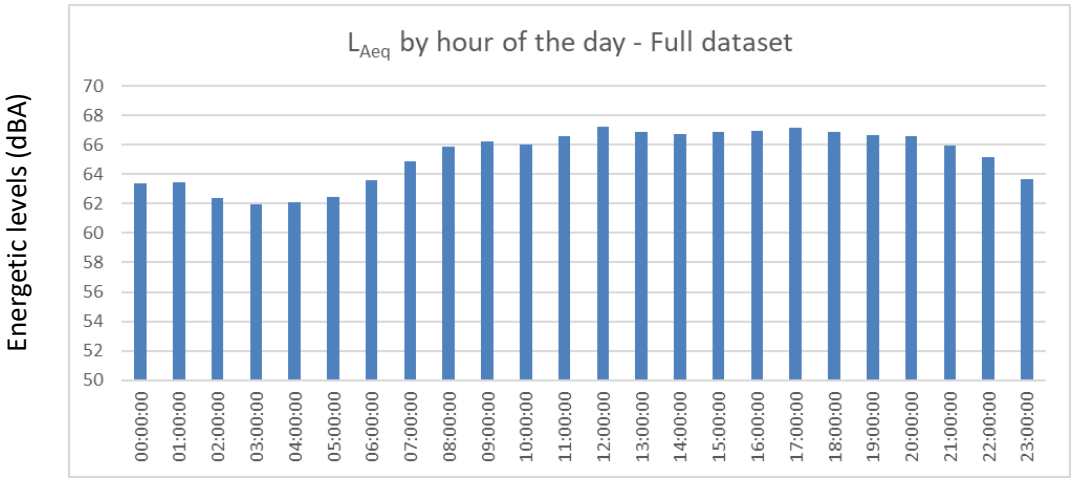


Figure 6.7 Combined average L_{Aeq} for each hour over the 11-weeks of data collection

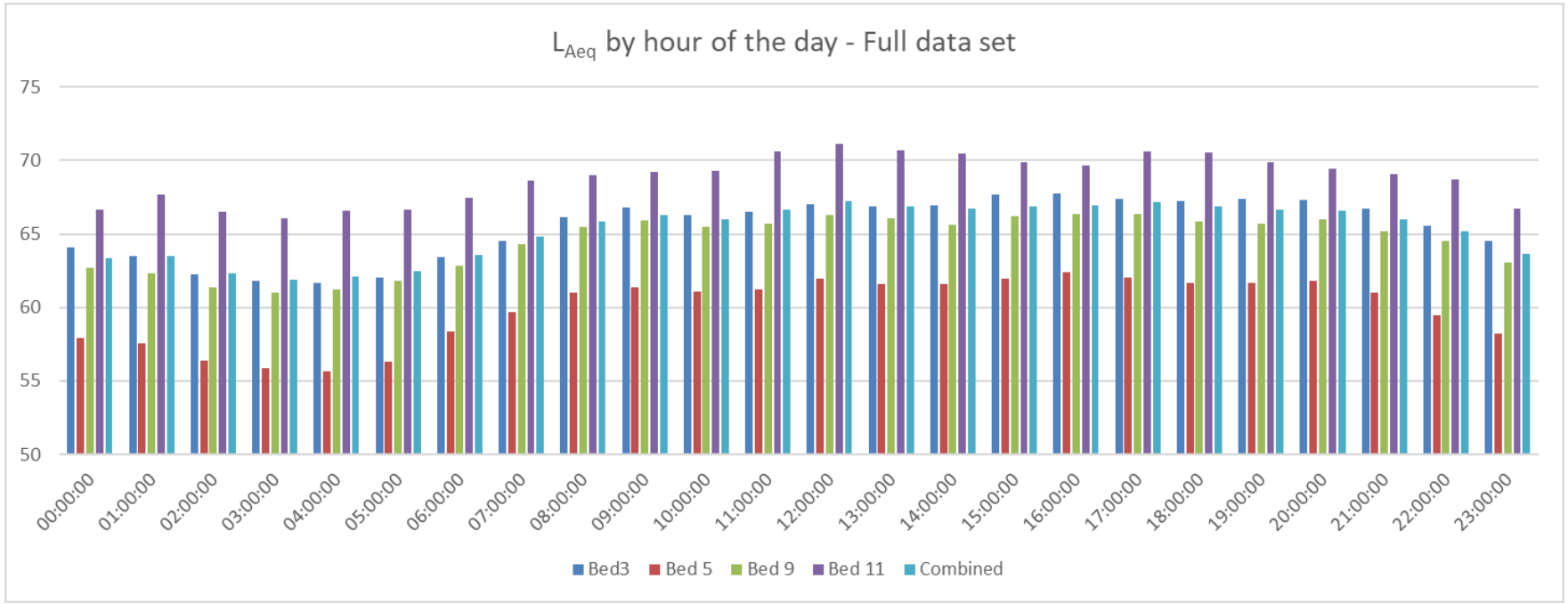


Figure 6.8 Average L_{Aeq} for each hour and each bed space over the 11-weeks of data collection

The average SPL across all units over the period recorded was $L_{Aeq271days}$ 65.4dB (SD 4.64), with little variation between day (07.00-23.00hrs) 66.4dB (SD 4.01) and night (23.00-07.00hrs) 62.9dB (SD 4.71) (t=34.64, df=6327, p<0.05), although there was a small reduction in sound levels to 62.2dB (SD 4.87) between 02.00-06.00hrs (t=4.46, df=3154, p<0.05). The GICU was noisiest at 12.00hrs (67.2dBA, SD 4.17) and 17.00hrs (67.2dBA, SD 4.01) (figures 6.7).

The four bed spaces demonstrated difference in average L_{Aeq}, bed space 5 ($L_{Aeq67days}$60.2dB, SD 3.63) appeared to be consistently the quietest, while bed space 11, a side room the nosiest ($L_{Aeq68days}$68.9dB, SD 4.55); bed space 3 ($L_{Aeq68days}$ 65.7, SD 4.02 and bed space 9 ($L_{Aeq68days}$ 64.7, 3.05) appear similar (figure 6.8). To identify if this was statistically significant, the hour demonstrating the greatest L_{Aeq} variation across the four bed spaces was tested. This assumed that if this hour demonstrated difference then there is a high likelihood that those hours with less variance will also demonstrate the same. The hour with the greatest standard deviation was 04.00hrs (62.1dB, SD 5.11), this demonstrated statistical significance for all combinations with the exception of bed spaces 3 and 9 (table 6.1).

04.00hrs	11 x 3	11 x 5	11 x 9	3 x 5	3 x 9	9 x 5
t-stat	6.39	15.11	6.98	9.68	-0.059796	11.17
df	130	129	130	129	130	129
p value	$1.35x10^{-9}$	$1.27x\ 10^{-30}$	$6.96x10^{-11}$	$2.72x10^{-17}$	0.48	$5.45x10^{-21}$

Table 6.1 One tailed T -tests for each bed combination demonstrating that with the exception of bed spaces 3 and 9, all other combinations of bed spaces were significantly noisier than the other at 04.00hrs.

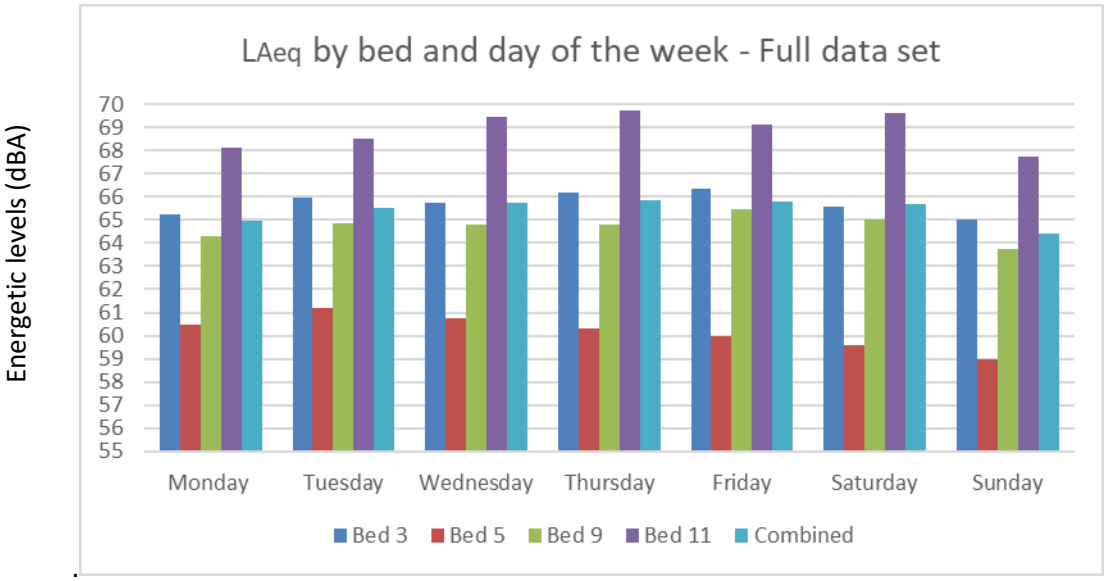


Figure 6.9 L_{Aeq} by day of the week over the 11-weeks of data collection

Figure 6.9 illustrates the same data now averaged by day of the week. There was little difference between weekdays 65.6dB (SD 4.54) and the weekend 65.1dB (SD 4.67) (t-test 3.76, df=6327, p,0.05). Thursday was the noisiest day with an average L_{Aeq} 65.9dB (SD 5.09) and Sunday the quietest with an average L_{Aeq} of 64.4dB (SD 3.37) (t=4.68, df=1774, p<0.05). Thursdays also demonstrated the greatest L_{Aeqhr} variation across the four bed spaces, which as for table 6.1 demonstrated statistical significance for all combinations with the exception of beds 3 and 9 (table 6.2).

Thursdays	11 x 3	11 x 5	11 x 9	3 x 5	3 x 9	9 x 5
t- stat	10.22	25.58	14.07	12.99	1.28	14.71
df	454	454	454	454	454	454
p value	$1.61x10^{-22}$	$2.56x10^{-90}$	$7.41x10^{-38}$	$2.55x10^{-33}$	0.1	$1.23x10^{-40}$

Table 6.2 One tailed T -tests for each bed combination demonstrating that with the exception of bed spaces 3 and 9, all other combinations of bed spaces were significantly noisier than the other on Thursdays.

Despite the individual variation in average dB per bed space, each of the bed spaces demonstrated a similar variation of approx. 10dBA between the quietest and the noisiest days for each individual week of the 11-weeks data collection. Figures 6.10 -6.13 indicate the mean, interquartile range and outliers for each hour and bed space over the 11-weeks of measurement. Bed space 11 demonstrates the widest variation in L_{Aeq}, although for the first two days of measurement (12.00hrs 6/7/2015-12.00hrs 8/7/2015) when L_{Aeq} was ≈60dB the bed space was unoccupied.

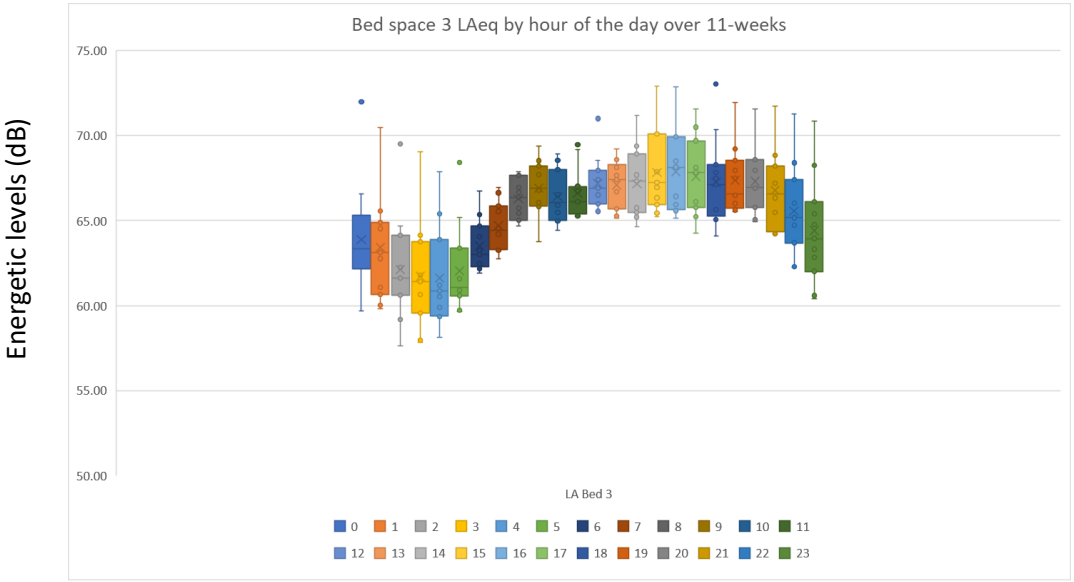


Figure 6.10 L_{Aeq} variation within each hour over the 11-weeks for bed space three

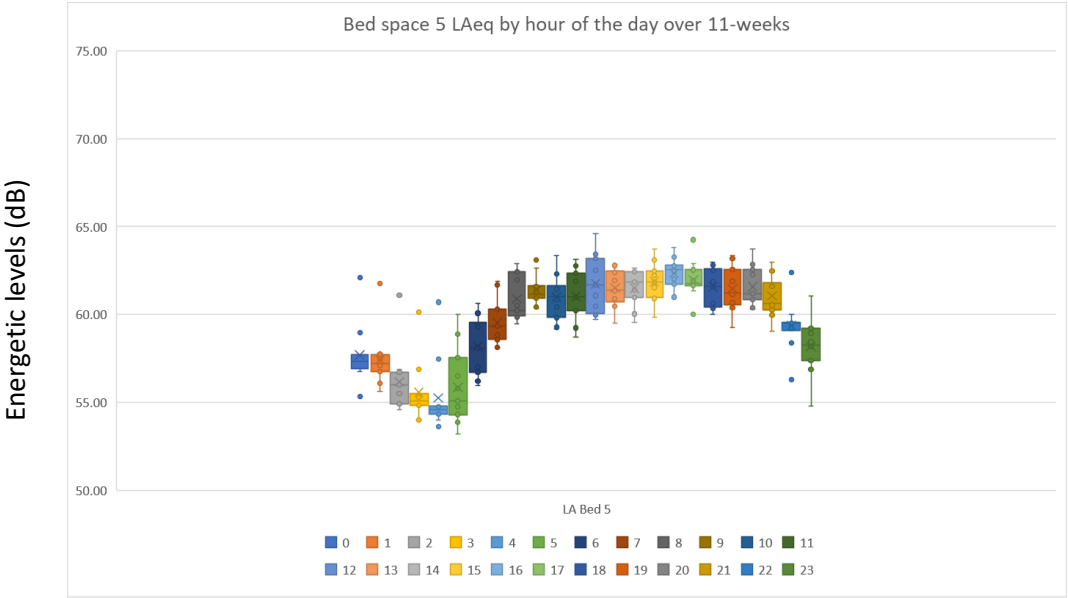


Figure 6.11 L_{Aeq} variation within each hour over the 11-weeks for bed space five

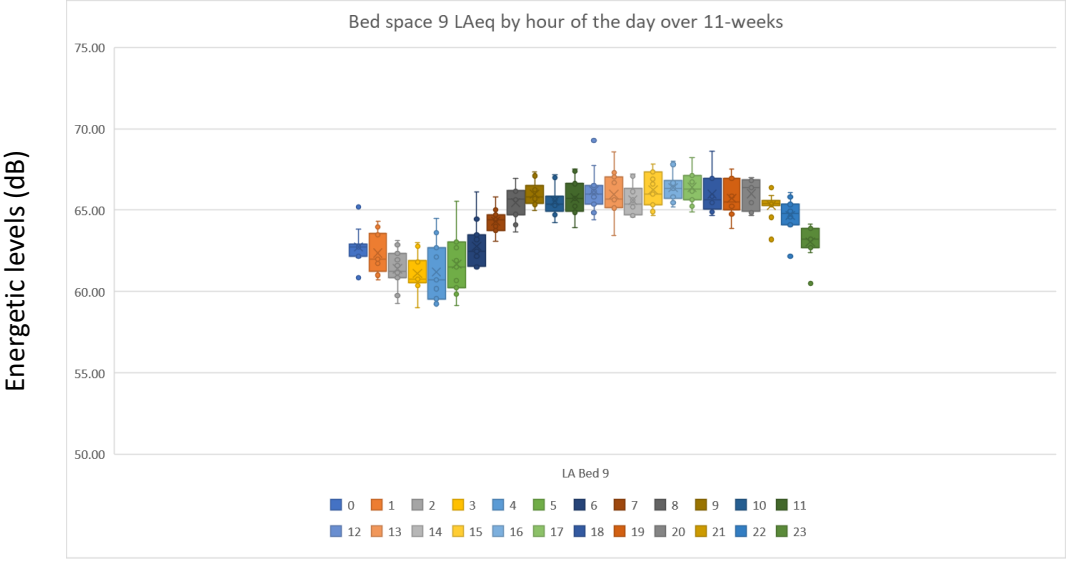


Figure 6.12 L_{Aeq} variation within each hour over the 11-weeks for bed space nine

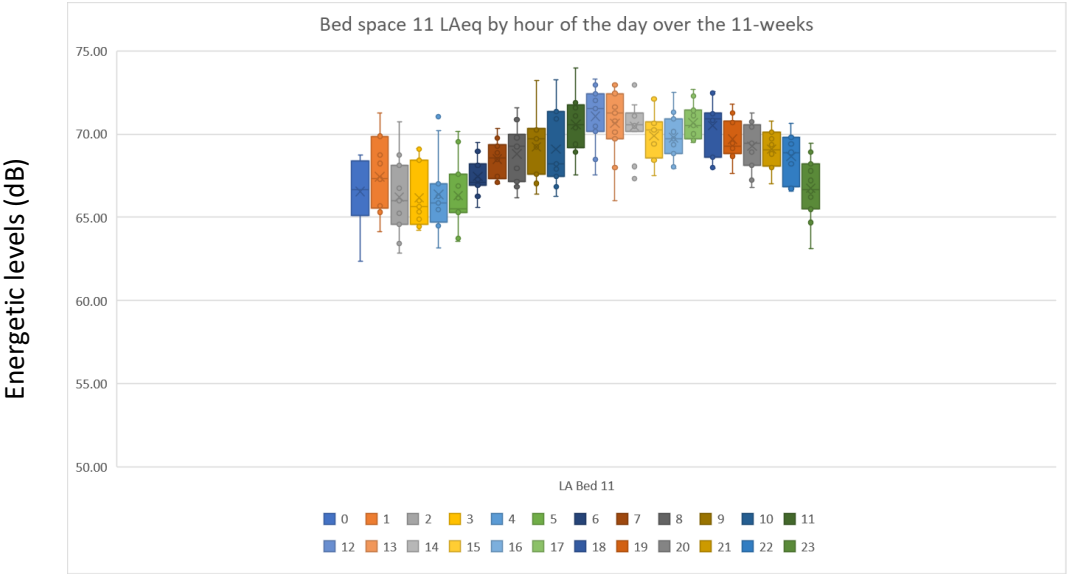


Figure 6.13 L_{Aeq} variation within each hour over the 11-weeks for bed space eleven

The 1-minute energy-based averages identified that the loudest recorded L_{Amax} was 109.5dB measured at bed space 11 at 21:58hrs on 12/7/2015. When the 1-minutes energy-based averages were reviewed for all four bed spaces for the complete study period, L_{Amax} was ≥80dB for 19.5% of the time, ranging from 5.1% (bed space 5) to 38.2% (bed space 11) (figure 6.14). Figure 6.14 also identifies the percentage of time that L_{Aeq} was ≥65.5dB and ≥50dB for the period of the study. These cut off points were chosen as 65.4dB was the average $L_{Aeq271days}$ for all four bed spaces and 50dB is essentially the minimum $L_{Aeq1min}$ recorded during the data collection period, with only 350 datapoints (0.09%) being ≥50dB, 16 datapoints (0.004%) ≥46dB and the lowest recorded value being 45.1dB.

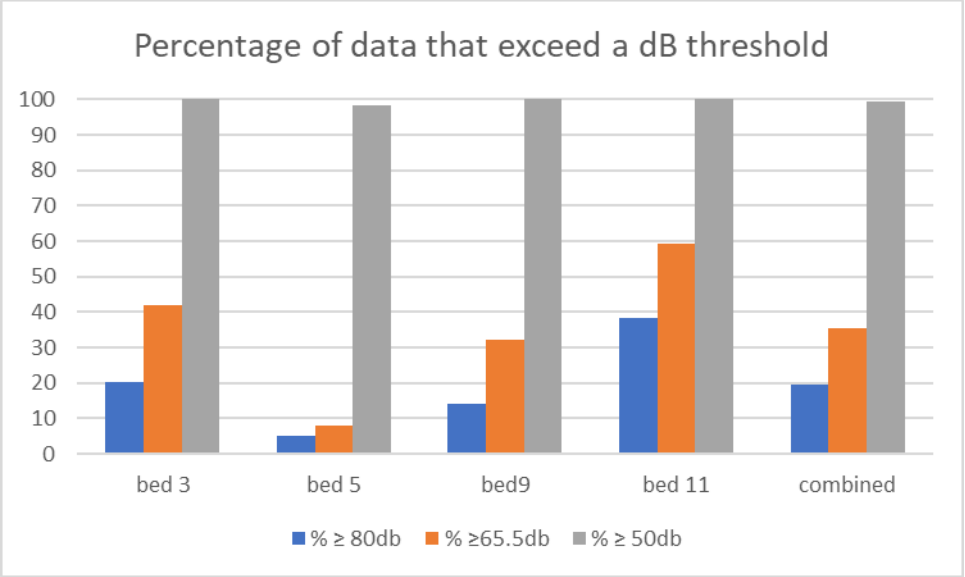


Figure 6.14 Percentage of data (minute averaging) exceeding a given dB threshold for each bed space over the 11 weeks of data collection (80dB = $L_{Amax;}$ 50 and 65.5dB = L_{Aeq}).

In the absence of full frequency analysis, C-weighted data was collected as a means of identifying whether there was low frequency content in the sound field. For bed spaces 3 and 9 this demonstrated a similar pattern of consistent low frequency sound. Bed space 5 also demonstrated a low frequency content, although this was not as great as in beds 3 and 5 (Table 6.3 and figures 6.15 - 6.18). It is likely this is due the influence of systems such as air conditioning units, but also the different boundaries (see figures 4.3 - 4.7 in chapter 4) associated with these bed spaces and may indicate the presence of a standing wave. It is however difficult to explain the situation in bed space 11, where $L_{Ceq68days}$ is lower than $L_{Aeq68days}$. It is most likely that an error occurred during the programming of the DAQ unit, the C-weighted data for this bed space was therefore discounted from any further analysis.

	$L_{Aeq68days*}$	$L_{Ceq68days*}$
Bed space 3	65.74	79.51
Bed space 5	60.2	62.32
Bed space 9	64.73	80.34
Bed space 11	68.93	55.35

Table 6.3 Average L_{Aeq} and L_{Ceq} in dB for data collection between 6/7/15 and 23/9/15. Please note bed space 5 data collection was for 67days and the remaining bed spaces for 68 days each

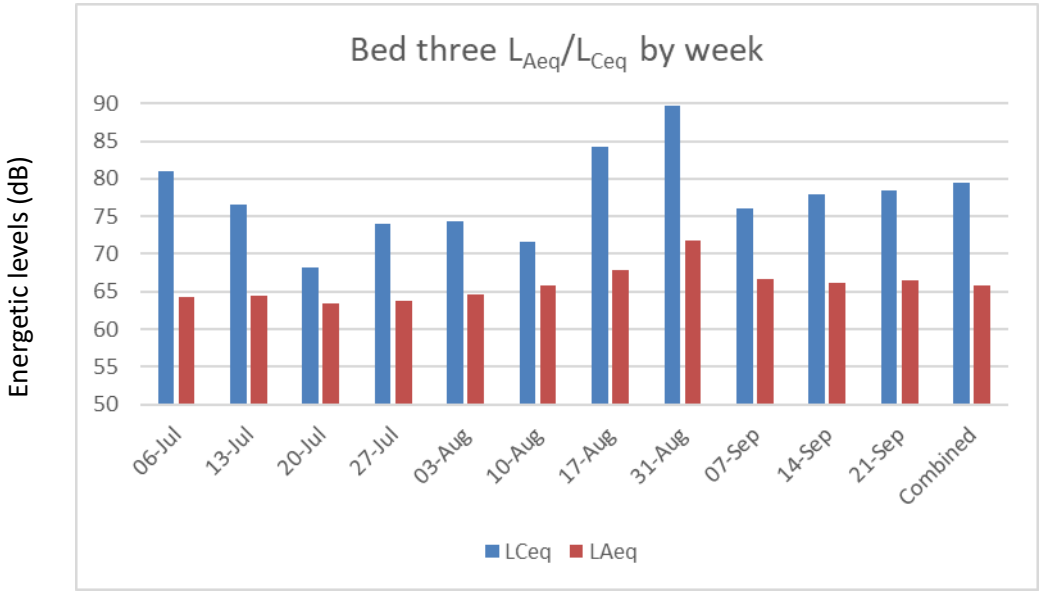


Figure 6.15 L_{Aeq} and L_{Ceq} plotted by week for bed space three across the period of the study

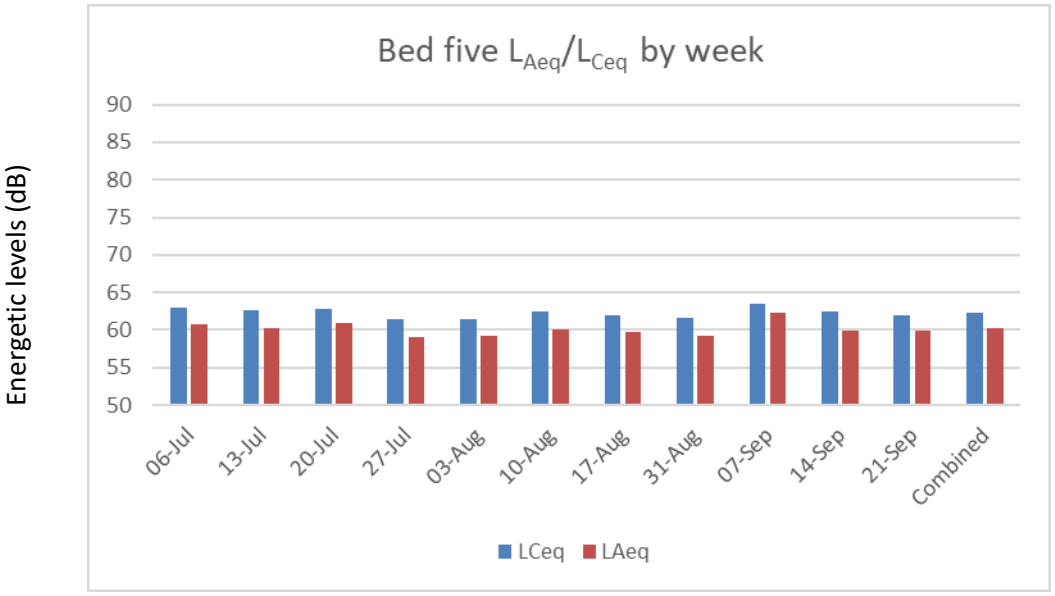


Figure 6.16 L_{Aeq} and L_{Ceq} plotted by week for bed space five across the period of the study

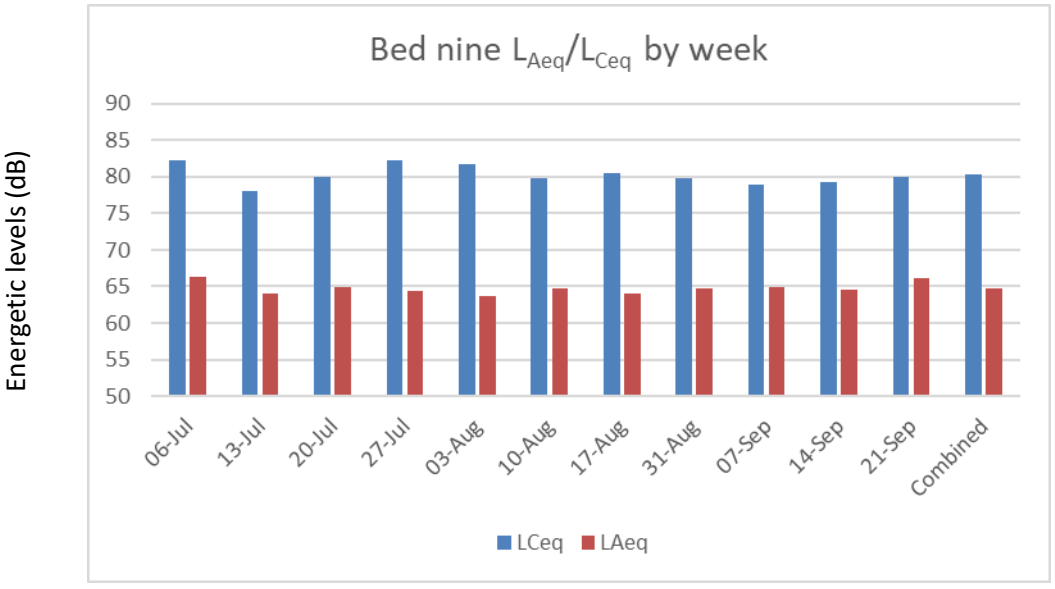


Figure 6.17 L_{Aeq} and L_{Ceq} plotted by week for bed space nine across the period of the study

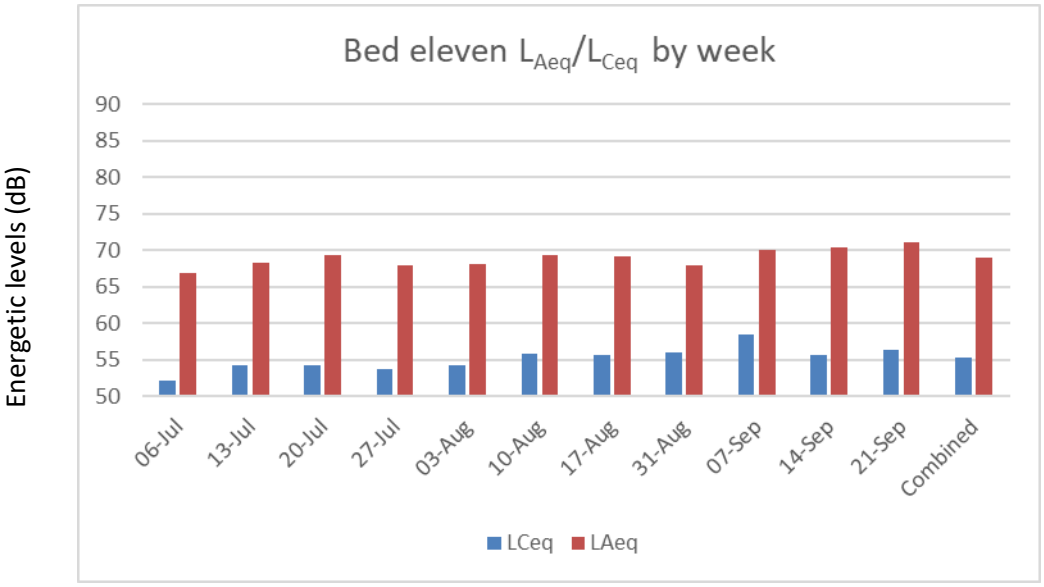


Figure 6.18 L_{Aeq} and L_{Ceq} plotted by week for bed space eleven across the period of the study

Figure 6.19 demonstrates the bed spaces retain their individual differences in sound pressure levels and show similar patterns between L_{Aeq}, L_{Ceq}, L_{90} and L_{Amax} when 1-minute average levels are compared by bed space.

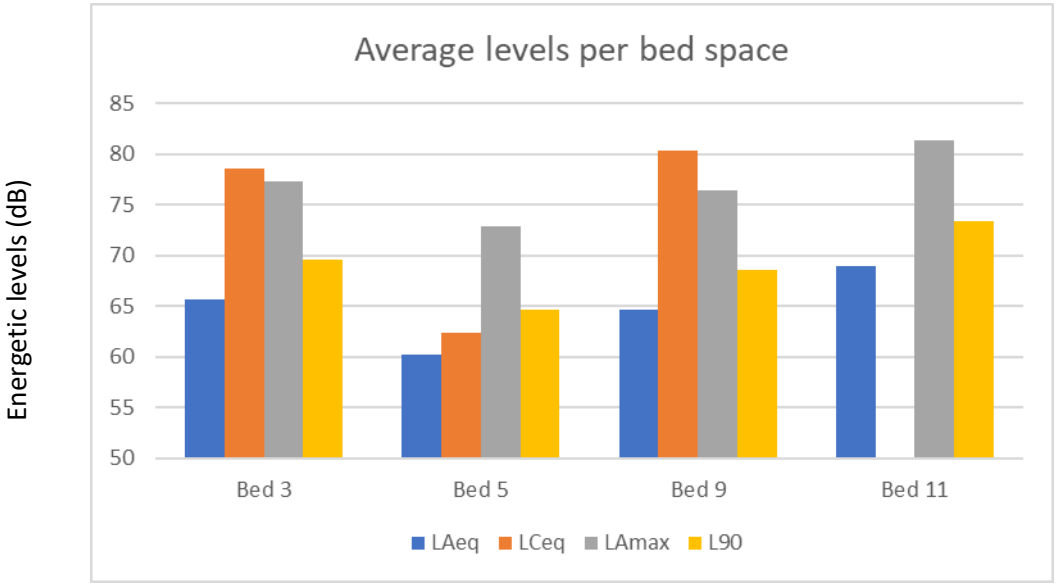


Figure 6.19 Average 1-minute levels by bed space over the 11-weeks of data collection. Data for L_{Ceq} not available for bed space eleven

6.4.2 Potential restorative time

The total data set of 370,054 minutes demonstrated 234,195 minutes (63.3%) of time where $L_{R2B} = L_{Amax} - L_{90min}$ is ≤17.7dB. Unfortunately, it was not possible due to the size of the dataset to identify how many of the minutes were in five-minute episodes to fully represent restorative periods as defined by Park and colleagues[97] with an adjustment in the calculation using L_{Amax} in place of L_{Cpk}. Therefore, the data presented here is identified as potential restorative time (PRT), rather than restorative periods, and is time within which there is the possibility for restorative periods. This potential restorative time (PRT) varied during the day, night and by bed space see figure 6.20. Bed space nine demonstrated the greatest period of PRT 74.6%, bed space three 65.8%, bed space eleven (side room) 60.3% and lastly bed space five 52.2%; potential restorative time was greater at night than during the day.

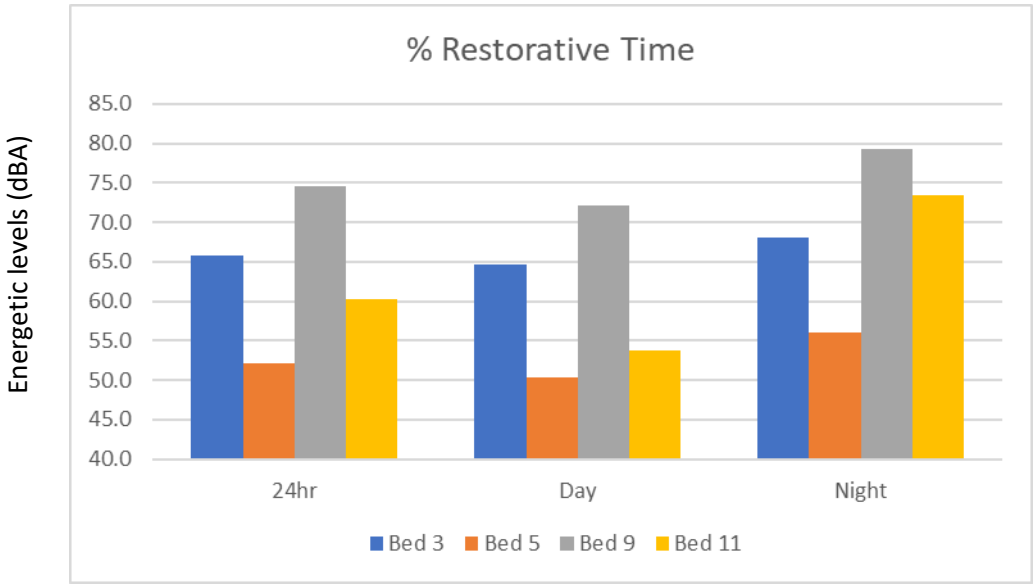


Figure 6.20 Potential restorative time per bed, by day and by night

6.5 Discussion

Despite a number of technical and human factor problems initiating this study, a continuous, distributed, longitudinal study measuring the sound pressure levels at four beds spaces was possible. A pragmatic decision was made to use the representative bed spaces containing the four working NPL-Minim devices and install a laptop using the LAN connection to record and store the data. This resulted in a smaller, alternative study than was originally proposed. The NPL-Minim and MEMS technology enabled reliable, discreet and continuous SPL measurement over eleven weeks, with one ten-day period of loss of data, due to a power failure. This provided a total of 271 days out of a potential 292 days of data, at 1-minute intervals across the four bed spaces, which provided a large dataset to understand sound pressure levels in an ICU. Two previous studies have measured sound for similar lengths of time in multiple bed spaces in an intensive care unit. The first, Park and colleagues (2015)[92] measured using conventional devices, suspended across the head end of the bed in eight side rooms for a total of 474 days, of which 337 were occupied days. More recently, Darbyshire and colleagues[98] measured for a total of 248 days using an array of 16 microphones over each of four beds in one open bay. For this latter study, the actual device and occupancy data are not reported. Devices similar to the NPL-Minim are likely to be of greater utility in the ICU; they are smaller, thus more discreet and considerable cheaper to install than conventional devices. Therefore, should sound level recording become common, it is likely that devices similar to the NPL-Minim will be utilised. This study suggests that these devices are suitable for long term, continuous, distributed use.

The results are higher[24,56,62-65,67,69-71,73,76,77,81,83,85,86,88,91,93,94] or consistent[57-61,66,68,70,75,78,82,84,87,89,90] with other studies measuring sound in the ICU, although direct comparison is difficult due to the varying methods of reporting results across these studies. The noise levels were higher than reported in the largest study[97],

this may be explained by a difference in occupancy and thus activity. Park and colleagues (2014)[97] report an occupancy of approx. 71% for the beds studied, although measured separately for occupied and unoccupied periods; occupancy in our study was 93%. The pattern of sound over a 24hr period compares well with results from preliminary work completed on site in 2011 and 2012[74,80]. The consistency of high noise levels in the GICU is likely due to the built environment. The unit was opened in the early 1980's and therefore precedes all guidance quoted in the literature review. Despite major refurbishment and expansion, acoustic properties were probably not considered sufficiently important to address. Two publications are commonly cited that suggest SPL in ICU's are excessive[16,43] more recently standards have been published which again suggest similar levels are justified[41,42]. These publications identify that noise levels should not exceed 35dB(L_{Aeq}) day/ 30dB(L_{Aeq}) night with sound events not exceeding 40dB (L_{Amax})[16] or 45dB (L_{Aeq}) day/ 35dB(L_{Aeq}) night[41]. The majority of studies measuring noise are unable to report sound pressure levels this low at any time of the day or night, whatever their reported activity. Data from this study identified only 16 recordings from 370,054 recorded for L_{Aeq} at 1-minute intervals ≤46dB L_{Aeq} and none ≤45db; 99.6% of the data was above 50dB L_{Aeq}, this included recording for periods when the bed spaces were empty. It therefore seems appropriate that these standards are revised, based on evidence that may now be available, to find a more realistic goal and recommend alternative methods of protecting patients from noise annoyance.

Three studies report L_{Aeq} measurements taken in an empty room, the first reported an average of 45dB L_{Aeq}[64], the second[91] 43.5dB L_{Aeq} during the day and 42.0dB L_{Aeq} at night. The last[79] reports a number of measurements ranging from a completely empty room with all equipment off at 34.1dB L_{Aeq} increasing to 63.6dB L_{Aeq} when a variety of equipment was running with alarms sounding. This suggests

that background noise excluding equipment noise is greater than or close to the recommended levels, the inclusion of essential equipment then increases noise levels far beyond the recommendations.

Further support for reviewing the standards can be found in studies that have attempted to reduce SPL using behavioural interventions[60,81,93,94,184,185,189,190]. A study by Tainter and colleagues[81], reported a statistically significant reduction in night-time noise following the introduction of a quiet time policy from 23.00-07.00hrs each night. The reduction of 6.4dB however was in maximum noise levels, with no reduction in minimum sound level, in addition there was an observer present collecting data throughout the measurement period, which could have influenced the change in behaviour. The authors clearly identify that this change is not sufficient to make a meaningful impact[81]. Similar studies[60,184,185] despite achieving statistically significant results, have failed to make meaningful changes to sound pressure levels following a period of behavioural modification. Two recent studies[93,94] identify that using a visual noise warning device alone reduces sound levels and suggest that other units should utilise this device[93,] indeed as before, both studies demonstrate statistical significance; it is unlikely however, that reduction of 3.9dB[93] and1.35dB[94] would be acoustically or clinically significant. The results of these studies suggest that ambient noise levels cannot be impacted sufficiently by behavioural intervention alone and that there is a need to address the sources that comprise background noise levels in an ICU. Additionally, it appears that there is a misunderstanding by many individuals undertaking and reporting this research of the necessary modifications pressure, frequency and duration, required in the sound environment to make a real impact on patients, visitors and staff. Two studies[189,190] which introduced a package of sleep protective measures, have demonstrated an improvement in patient reported sleep, and slightly improved reduction, compared with the above, in night-time A-weighted

equivalent SPL of 7.6dB[189] and 7dB[190]. Neither reduced SPL to recommended guidance levels, but both achieved a very high level of compliance with their respective sleep bundle. Again, comparison between studies is difficult due to an inconsistency in study measures of SPL and a wide diversity in initial measures of sound. Addressing equipment noise and unit design is likely to be of greater benefit and a more sustainable way of achieving noise levels closer to the current guidance[16,41-43]. To have any impact, this will require international guidance to persuade large medical equipment providers and regulators to change their design and practice.

In this study across the 24hr period, two relative peaks of sound were identified, one at midday until 13.00hrs, consistent with the end of the ward round held outside the clinical area when the medical staff would arrive back on the unit; lunchtime, when patients able to eat, would be served a meal and the end of the morning visiting period at 12.30hrs. The second peak was at 17.00-18.00hrs, a time when a bed to bed ward round occurs and booked surgical patients arrive post-operatively. Other studies report an increase in noise when there is an increase in personnel especially during ward rounds[57,64,68,85]. In common with other studies[56,65,68,79,90,91], this study demonstrated a diurnal variation, with a reduction in overall night-time noise and another subtle reduction between 02.00-06.00hrs. The 3.5dB reduction in night-time (23.00-07.00hrs) noise levels demonstrated statistical significance and may be discernible to the human ear. This reduction however, is unlikely to provide an appropriate environment for sleep and restoration as the average SPL far exceeds the recommendations from WHO for night time SPL[41,42].

The unit admits both planned (elective surgery) and emergency admissions from medical and surgical specialties. Emergencies may arrive at any time during a 24hr

period. Elective admissions are more predictable and most arrive between 16.00hrs-midnight after their surgery. A study comparing medical with surgical ICU's demonstrated surgical units were far noisier during the day than at night, whereas medical units have less of a diurnal variation[85]. This may go some way to explaining why a combined unit has higher than average sound pressure levels and also why the unit is generally quieter on Sunday, when there is no elective surgery. The unit was built in the 1980's, Shield and colleagues suggest in their ward-based study that noise level in wards built after 2000 were quieter[54]. Given the potential for harm and the evidence that sound levels are increasing over time[50], it would seem appropriate that new guidance, regarding the acoustic properties of the built environment, is applied retrospectively when an older unit is refurbished.

Side rooms are commonly thought to provide a quiet environment, however in this study L_{Aeq}, L_{Amax} and L_{90} were higher than in any other individual bed space, this demonstrated statistical significance. Not all studies report SPL recorded in side rooms versus multibed bays/rooms, indeed many of the studies from the US would likely have all patients cared for in single bed rooms. Several studies that report on side rooms and multibed bays suggest there is no difference between the two[75-77,88,90]. However when comparing the studies presented in table 2.1 in the literature review, this suggests that the single/two person rooms may be quieter. Without understanding the context, it is not possible to identify any relationship, this could be due to many unreported factors, including the age of the built environment. It is likely that in an ICU with a mix of side rooms and multi-bed bays, side rooms are used for sicker patients[88] who require more equipment and intervention. Side rooms are also used for patients with resistant infections and patients at the end of life, where privacy for them and their family is important. Interestingly, a study located on UK wards also identified that single rooms had some of the highest

levels of noise[54]. For the period of this study the side room had the lowest patient occupancy at 91.4%, but the highest average acuity (mean APACHE II[202] - 20.9), whereas bed space 5 had an occupancy of 96.2%, similar to bed spaces 3 and 9, but the lowest acuity (mean APACHE II - 15.9). An increased APACHE II score has previously been shown to correlate with an increase in sound pressure levels[92].

The average SPL across the four bed spaces varied by 8.7dB, representing a doubling in loudness from bed space 5 to bed space 11, the side room. This is not only statistically but clinically significant and requires some explanation, especially as this was not predicted. The difference in acuity may go some way to explaining the difference and the lack of recognition, prior to the study of this variance. The difference in L_{Aeq} and L_{Ceq} also implies detection of different sound frequencies. Bed spaces 3 and 9 were not significantly different, however bed space 5 showed significant difference to both bed spaces 3 and 9. The difference of 5.5dBA (bed space 3 and 4.5dBA (bed space 9), are also potentially clinically or practically significant, but is likely masked by the variability in the SPL. This suggests that each bed space has its own acoustic environment, impacted by the built environment as well the transient features associated with ICU's already discussed, this has potential implications for the patients cared for in these differing environments. Some factors may be obvious, for example, access to bed space 11 is next to a door out of the unit used to take patients in beds to the CT Scanner, at the time of the study this door did not have a soft closure mechanism, or the simple fact that most medical equipment in an ICU is located at the head end of the bed. This might be characterised by analysing the statistical levels, where L_5 and L_{10} may be highly represented and potentially have a greater impact on L_{Aeq} than L_{90}, suggesting many short periods of loud noise. This idea is examined further in the next chapter. Future unit design should consider the impact of

reverberation and ideally include the removal of noise sources from the head end of the bed[98].

Three definitions of restorative periods are found in the literature. The earliest definition by Ryherd and colleagues in 2008[67] could not be applied in full to this dataset, as data was not collected for $L_{Cpk.,}$ however data for L_{Aeq} and L_{Amax} was collected. Ryherd and colleagues identified five-minute periods of time that were quieter, defined as between 47-48dB L_{Aeq} and 52-53dB $L_{Amax.}$ In the study reported here for the entire dataset of 370,054 minutes, only 212 (0.06%) minutes of data were ≤49dB L_{Aeq} and 87 (0.02%) minutes ≤53dB L_{Amax} and therefore directly comparable to Ryherd and colleagues. Tegnestedt and colleagues[77] also utilised five-minute periods and L_{Cpk} but increased L_{Amax} to <55dBA, in this dataset only 306 minutes (0.08%), were <55dB L_{A7ax}.

Therefore, the most recent definition[92] was used replacing L_{Cpk} with $L_{Amax,}$ despite the knowledge that a maximum L_{Aeq} is not directly equivalent to a peak. This definition however provided sufficient data for comparison; however, it was not possible to identify and measure only the periods that occurred for ≥five minutes, it was therefore identified as potential restorative time, rather than defining these restorative periods. This data demonstrated greater potential restorative time at night and a different distribution of sound across the bed spaces than for decibels. Bed space 9 demonstrated the greatest cumulative potential restorative time, followed by bed spaces 3, then 11 and lastly 5, whereas in decibels measured by L_{Aeq} bed space 5 was the quietest followed by 9, then 3, and lastly 11. This data provided sufficient information to suggest it worth considering restorative time again in the next study, where it is possible to measure restorative periods.

Sleep studies have demonstrated that patients in ICU have highly fragmented sleep architecture with reduced periods or absence of stage three NREM and REM

sleep[62,154,158,159,164,165] and environmental noise may not be the main contributor to arousals and awakenings in critically ill patients[62,63,164,168,169]. Restorative periods may provide some level of explanation as to how and why patients sleep in such a noisy environment and move our thinking forward from just reducing average sound pressure levels to providing a more positive soundscape[36,205] and therefore acceptable environment for healthcare.

6.6 Conclusion

Measuring sound using a distributed and continuous approach is possible and provided a large dataset. Sampling of sound levels across the ICU demonstrated consistently high levels of sound, in keeping with a unit caring for both medical and surgical patients and its built environment, with many of the variables, night/day, bed spaces, being statistically, although in most cases not practically/clinically significant. The average SPL difference between the individual bed spaces, however demonstrated both statistical and practical significance. This has potential implications for the patients cared for in these differing environments and requires further exploration. Multiple studies measuring noise in the ICU identify that the current standards are unachievable, however a review of these standards will require robust evidence on which to base any new recommendations. Current evidence suggests that behaviour modification without consideration of the sources of ambient noise may not sufficiently address the problem. Data from this study identified the potential for considerable restorative time, this phenomenon will be analysed further in the next chapter. Future study on the sources of sound is required to understand how the complex cacophony of sound emanating from equipment, alarms, clinical and housekeeping tasks, and conversation can be better understood with regards the impact on patient, visitors and staff.

Chapter Seven

Study Three: Sound in Time

7.1 Aim

To identify the key sources and prevalence of sound disturbance in four bed spaces in the general intensive care unit.

7.2 Introduction

The previous chapter described the process of distributed sound measurement in one general intensive care unit. The results demonstrate the tremendous noise levels encountered in such an environment. The study described in this chapter 'Sound in Time', was designed to understand better the sources of the noise and to provide greater specificity about noise in an individual bed space. A bespoke data collection tool was developed to enable collection of detailed observational data of the sources of sound. Data was collected for 1-hour periods over one month. From this data, the number of episodes of sound for the total period of observation (50hrs), the percentage each source represented with the total sources of sound and the percentage of time for each source was calculated. Annoyance can be defined as '*a person's individual adverse reaction to noise*'[206]. It was not possible in this study to measure annoyance; however, several authors have identified loudness as an important aspect of annoyance[207,208,209]. We therefore describe a perceived loudness scale, where each source was ascribed a value on this scale. This was then compared with the sound pressures levels measured during this study to identify any relationship between number of episodes, perceived loudness and actual sound pressure levels. Each 1-hour period of observation was graphically represented for the sound pressure levels and annotated with sound sources. A detailed description of four of these 1-hour

periods of observation is included at the end of the chapter. These include examples of scenarios demonstrating the impact of a patient admission at another bed space, patient deterioration, visitors at a bed space, helicopter noise and the last demonstrating a relatively flat sound picture providing a period of restorative time. Individual sound peaks are analysed utilising the statistical parameters. Restorative time for each period of observation was calculated.

7.3 Methods

7.3.1 Study Setting

The study was set in an 18-bedded adult, general intensive care unit (GICU) as described in chapter 4. During this study data was collected at four bed spaces (beds 3, 5, 9, 11) located in the ICU, bed space 11 being a side room.

7.3.2 Ethical Approval

Ethical approval was granted by the Office for Research Ethics Committees Northern Ireland REC reference:15/NI/0106 IRAS project ID:128446 on the 2nd June 2015 (Appendix 1- Letters dated 2nd June 2015 and 8th June 2015). For this phase of the study no identifiable patient data was required. Observational data was collected using a specifically designed tool during the period of sound recording described in the previous chapter. The data was collected manually using a paper spreadsheet that did not contain any patient identifiable data. The datasheets were stored securely in a locked office and the data transcribed onto an electronic copy of a similar spreadsheet in Excel, to enable analysis. All electronic data was stored on a password protected PC at St George's University Hospitals NHS Foundation Trust.

7.3.3 Participants

Bed spaces were only studied if they were occupied, but no patient data were collected. Therefore, there were no participants directly involved in this phase of the study. Fifty, one-hour periods of observation took place, divided between the four bed spaces. Data were collected at the patient's bedside; 13 hours of data were collected at both bed spaces 5 and 9, and 12 hours each at bed spaces 3 and 11.

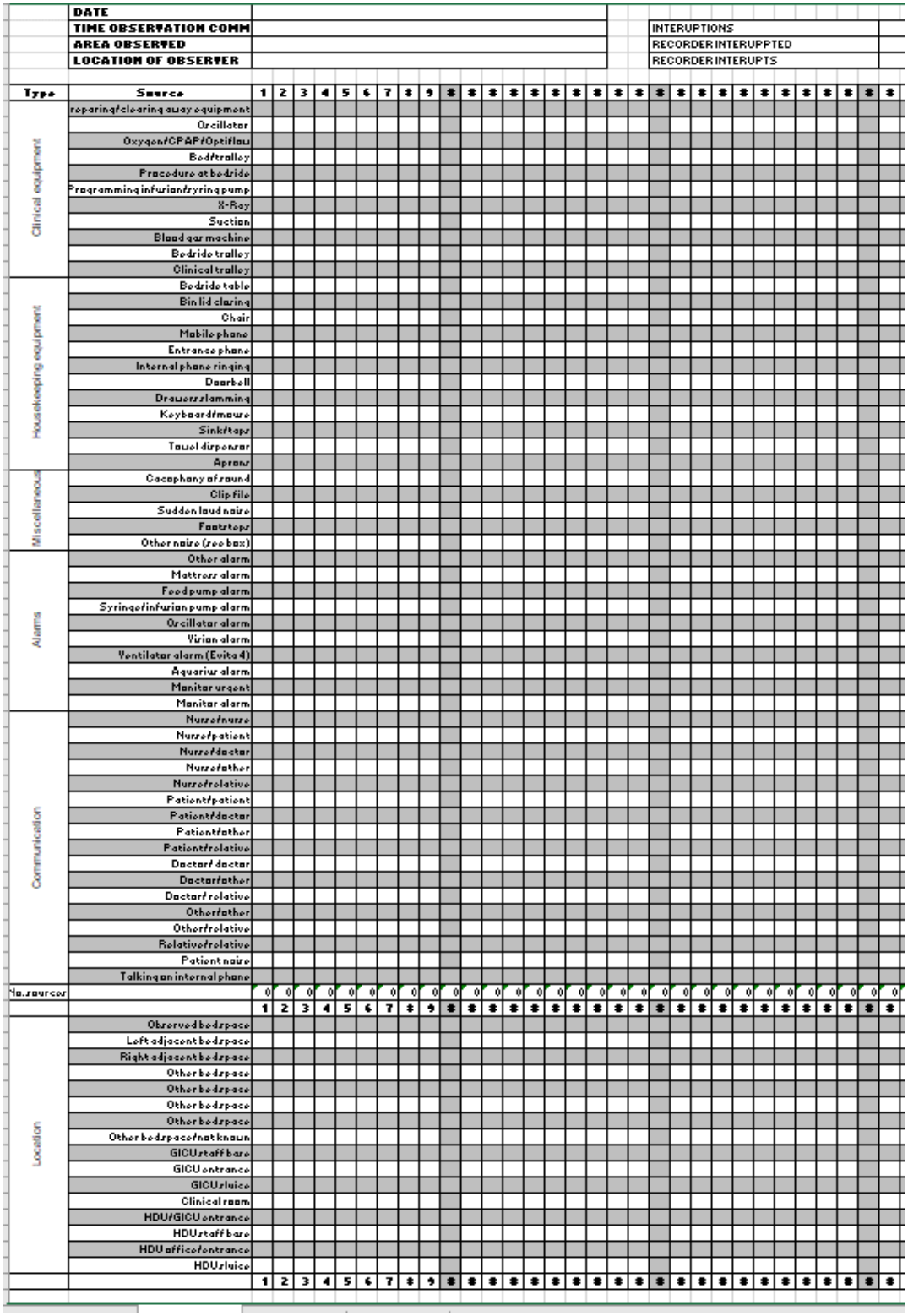
7.3.4 Datasheet development

A data collection tool was developed specifically for this study during March 2013, this was referred to as the 'Sound in Time' datasheet. The concept was developed from an activity follow sheet used by the NHS Institute for Innovation and Improvement (www.institute.nhs.uk/theatres_resources disbanded on 31st March 2013). This was an A3 landscape sheet with various activities located on the left and right-hand sides of the data sheet and each minute of the hour recorded across the top of the data sheet (Appendix 2).

To identify the potential sources of sound, a one-hour period of observation took place on the GICU. Initially, each sound source was noted and coded into seven categories; communication, clinical equipment, housekeeping equipment; hand washing, furniture, IT/communications equipment and miscellaneous. This was shared with the clinical staff of the GICU to provide assurance that the sound sources and categories generated from them were inclusive, recognisable and credible. Subsequently four further one-hour periods of observation took place in different locations on the GICU at different times of the day, on different days of the week including a Saturday, to ensure the majority of sound sources were identified along with their prevalence and finalise the categories. To improve the tools authenticity, on each occasion the tool was shared with the staff working that

day, to ensure it remained inclusive, recognisable and credible. The final tool contained 55 sources, sub-divided into five categories: communication (n=17), clinical (n=11), housekeeping (n=12), alarms (n=10) and miscellaneous (n=5), listed with the most common potential sources appearing near the centre of the list to ease data collection. A further section was added to identify the locations of the sound source, the observed bed space, adjacent bed spaces, other bed spaces, the staff base; sluice, clinical room and entrances. Fig 7.1 illustrates a section of the observation sheet.

Two further hours of piloting occurred in May 2015, to ensure the tool remained fit for purpose and to practice using the tool over a one-hour period using a stop watch to identify the minutes, but also to enable synchronisation with the NPL Minim once installed. No changes were made at this time, although it was apparent that data recording would now occur in the ICU area only, which made the majority of the HDU sections redundant. The data collection sheet was developed in Excel (Microsoft, 2010) and was printed in A3 size. To ensure the researcher had adequate hearing to enable detection of the sound sources, a hearing test using pure tone audiometry, was completed on both ears in July 2013 in the department of Audiological Medicine at St George's Hospital. This demonstrated hearing within normal limits (Appendix 3).



DATE	
TIME OBSERVATION COMM	
AREA OBSERVED	
LOCATION OF OBSERVER	

INTERUPTIONS	
RECORDER INTERUPPTED	
RECORDER INTERUPTS	

Type	Source	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Clinical equipment	repairing/clearing away equipment																														
	Oscillator																														
	Oxygen/CPAP/Optiflow																														
	Bed/trolley																														
	Procedure at bedside																														
	Programming infurian/syringe pump																														
	X-Ray																														
	Suction																														
	Blood gas machine																														
	Bedside trolley																														
	Clinical trolley																														
Housekeeping equipment	Bedside table																														
	Bin lid closing																														
	Chair																														
	Mobile phone																														
	Entrance phone																														
	Internal phone ringing																														
	Doorbell																														
	Drawers slamming																														
	Keyboard/mouse																														
	Sink/taps																														
	Towel dispenser																														
	Apron																														
Miscellaneous	Cacophany of sound																														
	Clip file																														
	Sudden loud noise																														
	Footsteps																														
	Other noise (see box)																														
Alarms	Other alarm																														
	Mattress alarm																														
	Feed pump alarm																														
	Syringe/infurian pump alarm																														
	Oscillator alarm																														
	Virian alarm																														
	Ventilator alarm (Evita 4)																														
	Aquarius alarm																														
	Monitor urgent																														
	Monitor alarm																														
Communication	Nurse/nurse																														
	Nurse/patient																														
	Nurse/doctor																														
	Nurse/other																														
	Nurse/relative																														
	Patient/patient																														
	Patient/doctor																														
	Patient/other																														
	Patient/relative																														
	Doctor/doctor																														
	Doctor/other																														
	Doctor/relative																														
	Other/other																														
	Other/relative																														
	Relative/relative																														
	Patient noise																														
	Talking on internal phone																														
No. sources		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Location	Observed bedspace																														
	Left adjacent bedspace																														
	Right adjacent bedspace																														
	Other bedspace																														
	Other bedspace																														
	Other bedspace																														
	Other bedspace																														
	Other bedspace/not known																														
	GICU staff base																														
	GICU entrance																														
	GICU sluice																														
	Clinical room																														
	HDU/GICU entrance																														
	HDU staff base																														
	HDU office entrance																														
	HDU sluice																														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30

Figure 7.1 A section of the ‘Sound in Time’ observation sheet

7.3.5 Data collection

All data was collected by a single observer, the author. To validate the data, another nurse had been trained to complete the data sheet. The intention was that a 10% random selection of observations would be completed concurrently and the datasheets compared for similarity. However, due to the delay in commencing the sound pressure level data collection, this person was not available during the period of observation, the majority of which was completed by the author in annual leave time. Data was collected for 50 hours, divided into one-hour periods from 12/07/2015 -12/08/2015. As shown in figure 7.2, the data equally represented each day of the week, hour of the day and bed space.

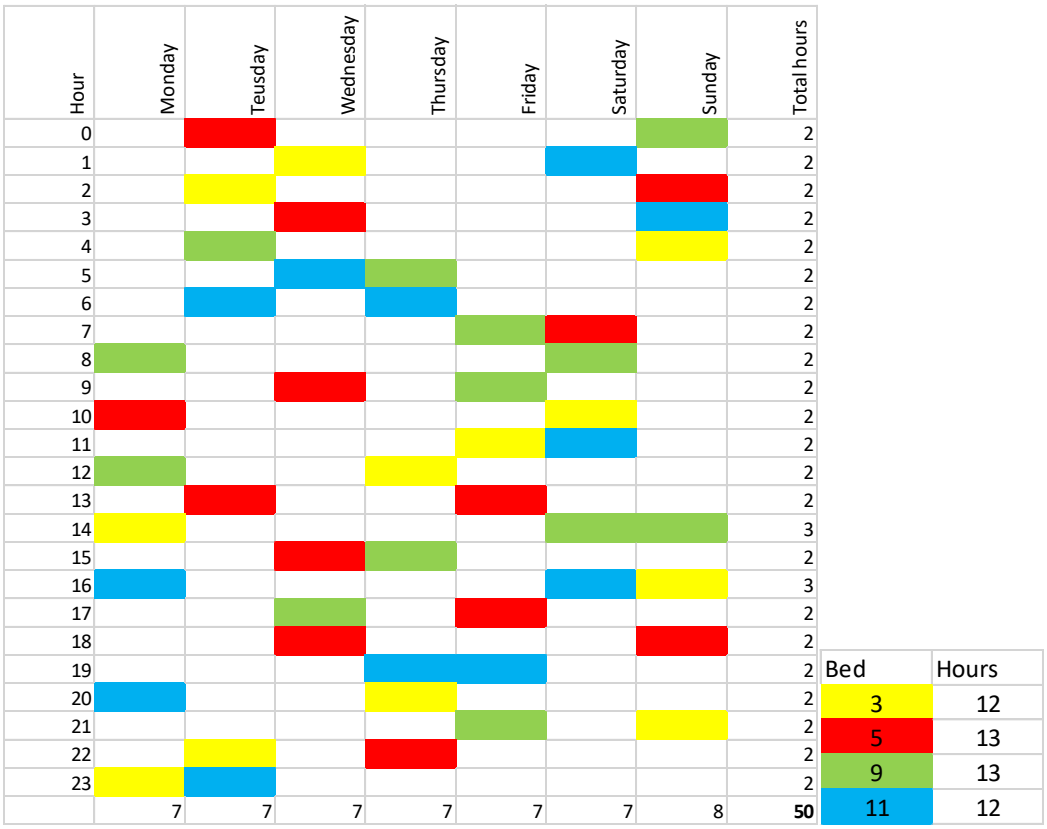


Figure 7.2: Representation of the period of data collection for each bed, hour of the day and day of the week

The data was collected as close as possible to the head end of the bed, in order to experience the sound as the patient might hear, but without disrupting clinical activity. This varied for each period of data collection and was dependant on the activity at the bed space observed and the adjacent spaces. The observer usually sat at the side of the bed, but when this was not possible, they sat at the foot of the bed. At the start of each observation the time was synchronised with the lap top collecting the SPL data. A stopwatch was set to count up to one hour, for each minute the sources of sound were noted, however each source was only noted once for each minute. Therefore, the data represents number of different sources per minute, rather than an actual representation of the time frame for each source.

7.3.6 Data Analysis

The manually collected data was transcribed to an Excel spreadsheet, this enabled calculation of the episodes of noise from each of the sources per observation, the number of different sources for each minute and the location of the source (Appendix 4). Therefore, a total of 60 episodes for each source was possible for each hour of observation or a total of 3000 for the 50 hours of observation. The general intensive care unit has two shifts; the day shift (08:00 – 20.00hrs) and night shift (20:00 – 08.00hrs). For the purpose of measuring perceived loudness in time frames similar to those used in urban acoustic studies, daytime and night time were defined as daytime 07.00hrs -23.00hrs and night time 23.00-07.00hrs[16]. Of the 50hrs observed, 34hrs were within the daytime and 16hrs during the night time. The 55 sources of sound provided a potential of 3300 episodes per hour of observation and thus a total of 165000 episodes over the 50 hours of observation. The data was analysed for the total number of sources over the 50 hours of observation, for the 34 hours of day time and 16 hours of night time sources of sound observed. The location of sound was also captured during

the observation periods; however, it was not always possible to identify the location for each source e.g. observed, bed space, staff base, adjacent bed space.

For each of the periods of observation the L_{Aeq} for each of the four bed spaces was compared against the bed space under study to understand the SPL over the hour of observation with those of the other bed spaces (Appendix 5). Each of the 55 sources of sound were retrospectively assigned a level on a perceived loudness scale, 5 being the most dominant to 0, not significant, this was identified from the location. Therefore, noises that emanated from the head end of the bed were assigned a higher rating, than similar sounds that originated from elsewhere in the unit. This was also compared with the sound pressures levels to identify any relationship between number of episodes, perceived loudness and the actual sound pressure level at the time of the observation. A graphical illustration of $L_{Aeq1min}$, $L_{Ceq1min}$, $L_{Amax1min}$, L_{5min}, L_{90min} was made for each of the 50 periods of observation (Appendix 6). Additionally, for each of these periods the L_{Aeq1hr}, L_{Ceq1hr}, $L_{Amax1hr}$, L_{5hr}, L_{90hr} were calculated, as were the mean and total episodes of noise per observation. To illustrate various events during the observations, four of these one-hour periods, one from each bed space, were analysed in detail. As a part of this analysis, the one-hour period of observation was graphically illustrated as noise level compared against the statistical parameters, to demonstrate the percentage of time sound pressure levels exceeded an individual decibel level for the time period under observation. Where particular events occur, such as the helicopter landing, a visitor at a bed space, an admission at an adjacent bed space and the impact of a patient deteriorating, these individual events are illustrated graphically utilising all the energetic levels to help describe the sound environment. Using the definition adapted from Park and colleagues[97] restorative time (RT) was also calculated for each period of observation (see chapter 2, section 2.10). In this study it was also possible to calculate restorative time for periods of ≥five minutes.

7.4 Results

7.4.1 Sources

A total of 16784 episodes of disturbance from a noise source were identified during the 50 hours of observation. The average number of episodes of individual sources per observation was 336 (range 145-524) increasing to 351 episodes if the observation occurred during day time hours (07:00-23.00hrs) and reducing to 304 episodes during the night (23.00-07.00hrs).

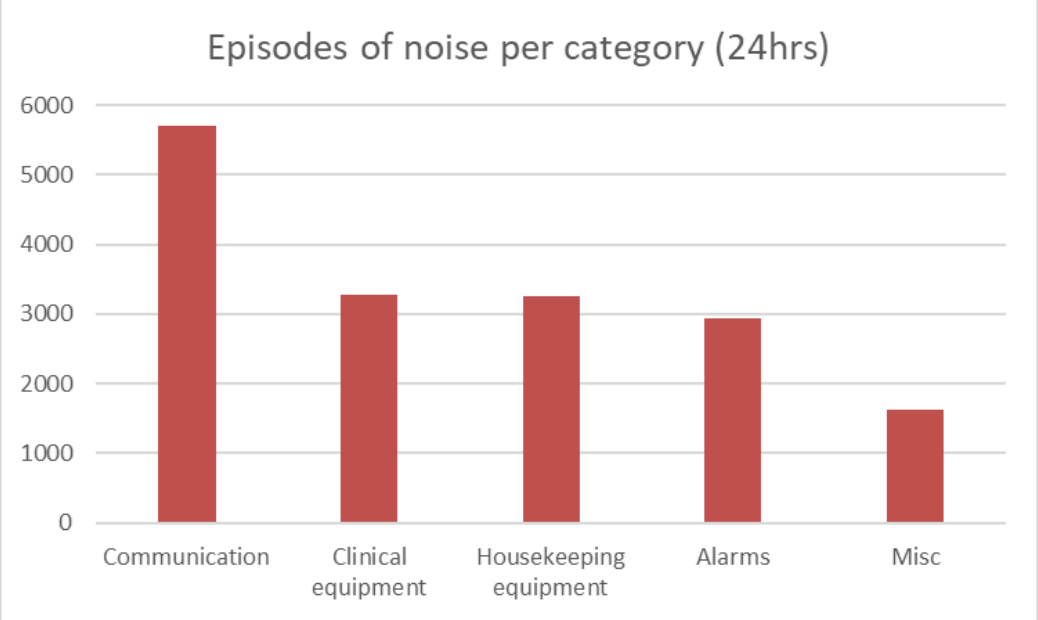


Figure 7.3 Episodes of noise by category over the 24hr period

Category	24hrs		Day		Night	
	% TSS	n	% TSS	n	% TSS	n
Communication	33.95	5699	39.2	4673	23.03	1120
Clinical equipment	19.55	3282	18.06	2153	23.03	1120
Housekeeping equipment	19.36	3247	19.1	2277	18.81	915
Alarms	17.51	2939	14.24	1698	25.51	1241
Misc	9.63	1617	9.39	1119	9.62	468
		16784		**11920**		**4864**

Table 7.1 Episodes/percentage of total sound sources (TSS) of noise by category during the 24hr period, day and night

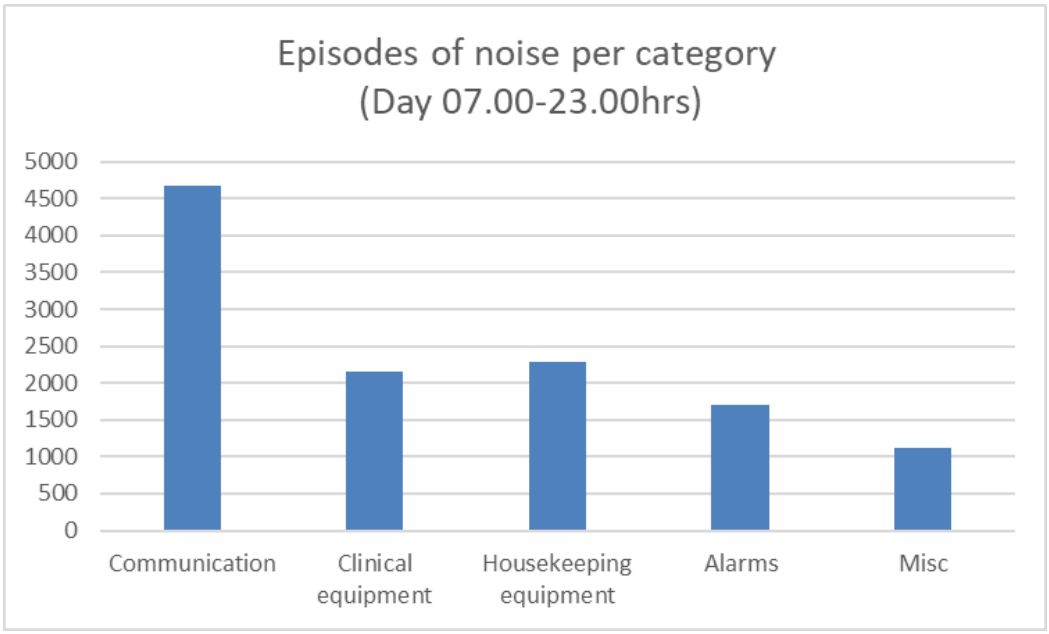


Figure 7.4 Episodes of noise by category during the day

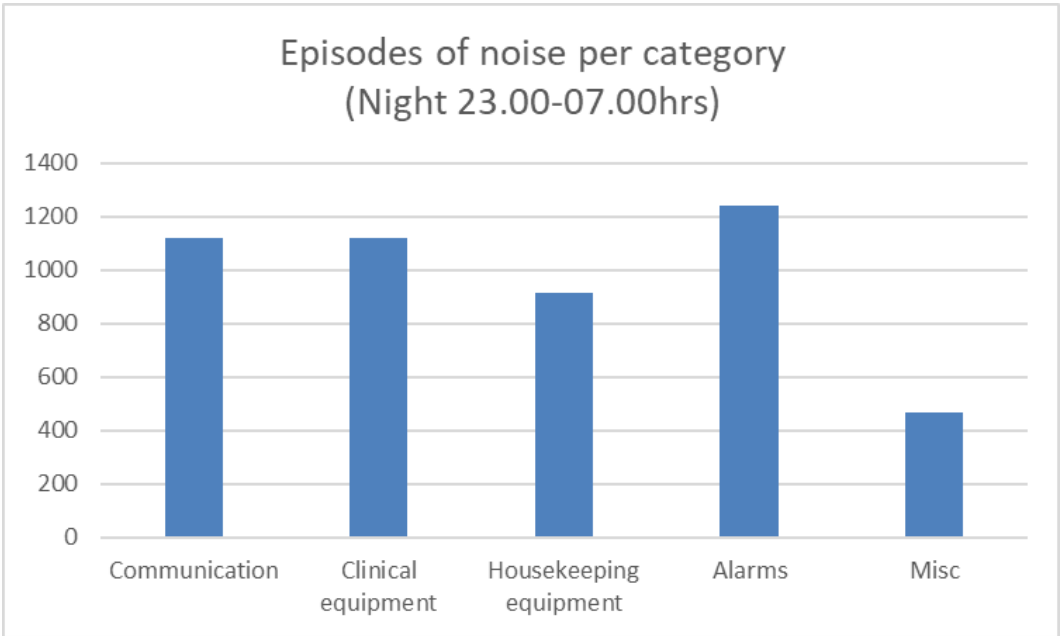


Figure 7.5 Episodes of noise by category during the night

Of the five categories of sound sources, the communication category was most prevalent over the period of data collection (33.95%), with the clinical and housekeeping categories being similar in number of episodes (figure 7.3 and table 7.1). This distribution was similar for the day time hours (figure 7.4), but at night, the alarm category (25.51%) became the most prevalent (figure 7.5).

The communication category created the greatest number of episodes, this had a total of 17 sources within it and was the largest category (see table 7.2). Nurse/nurse communication was the greatest single source of noise resulting in 1595 episodes over the 50 hours of observation. This represented 9.5% of the total percentage of sound sources and occurred at least once during 53.2% of the observed minutes. The next most frequently occurring noise was from the miscellaneous category, 'other' noise', resulting in 1060 episodes or 6.32% of the sources of sound and occurred in 33.47% of the observed minutes. This consisted of a variety of sources, such as keys being dropped, curtains being pulled, the shredder, intermittent pneumatic compression devices, clicking pens, doppler and the air conditioning units. The third highest number of episodes (n= 1004) resulted from bin lids closing causing 5.63% of the sources of sound and occurring for 33.47% of the observed minutes. The next highest-ranking episodes were for nebulisers/oxygen, monitor alarm, doctor/doctor, nurse/patient and nurse/doctor communication, a procedure at the bedside and aprons being unrolled from their holder. The top 25 noise sources included those that occurred on ≥200 episodes and accounted for 85.6% of the sources of noise. Two sources included in the 'Sound in Time' datasheet after piloting were not observed, these were patient/patient communication and the oscillator.

	TOTAL	% of total sound sources	% of observed minutes
Nurse/nurse	1595	9.50	53.17
Other noise (see box)	1060	6.32	35.33
Bin lid closing	1004	5.98	33.47
nebs/Oxygen/CPAP/Optiflow	945	5.63	31.50
Monitor alarm	829	4.94	27.63
Doctor/ doctor	813	4.84	27.10
Nurse/patient	743	4.43	24.77
Procedure at bedside	686	4.09	22.87
Nurse/doctor	678	4.04	22.60
Aprons	624	3.72	20.80
Ventilator alarm (Evita 4)	575	3.43	19.17
Mattress alarm/pump noise	558	3.32	18.60
Preparing/clearing away equipment	542	3.23	18.07
Syringe/infusion pump alarm	438	2.61	14.60
Patient noise	415	2.47	13.77
Footsteps	413	2.46	13.83
Clinical trolley	347	2.07	11.57
Talking on internal phone	332	1.98	11.07
Towel dispensor	322	1.92	10.73
Chair	321	1.91	10.70
Programming infusion/syring pump	256	1.53	8.53
Internal phone ringing	241	1.44	8.03
Nurse/other	225	1.34	7.50
Sink/taps	205	1.22	6.83
Other alarm	200	1.19	6.67
Drawers slamming	195	1.16	6.50
Aquarius alarm	178	1.06	5.93
Patient/relative	174	1.04	5.80
Nurse/relative	155	0.92	5.17
Blood gas machine	154	0.92	5.13
Keyboard/mouse	154	0.92	5.13
Other/other	142	0.85	4.73
Patient/doctor	133	0.79	4.43
Bed/trolley	130	0.77	4.33
Relative/relative	120	0.71	4.00
Entrance phone	117	0.70	3.90
Bedside trolley	89	0.53	2.97
Sudden loud noise	84	0.50	2.80
Feed pump alarm	72	0.43	2.40
Monitor urgent	68	0.41	2.27
X-Ray	65	0.39	2.17
Doctor/other	65	0.39	2.16
Clip file	60	0.36	2.00
Suction	59	0.35	1.97
Patient/other	53	0.32	1.77
Doctor/ relative	39	0.23	1.30
Doorbell	31	0.18	1.03
Mobile phone	22	0.13	0.73
Vision alarm	18	0.11	0.60
Other/relative	17	0.10	0.57
Bedside table	11	0.07	0.37
Cacophony of sound	9	0.05	0.30
Oscillator alarm	3	0.02	0.10
Oscillator	0	0.00	0.00
Patient/patient	0	0.00	0.00
TOTAL	**16784**		

Table7.2 Demonstrates the number of noise sources during the whole period of observation, the percentage of time for each sound source and the percentage of time that each sound source was heard during the observed hours (50hrs). The colours represent the various categories blue =communication; pink=clinical equipment; purple =housekeeping equipment; green=alarms; orange =miscellaneous.

7.4.2 Day and night

Of the 55 sources, 31 provided the top 25 for both day and night, but the ranking changed as seen in tables 7.3, 7.4 and 7.5. The communication source is less dominant at night, due mainly to fewer staff and visitors. Alarms and other noises such as the oxygen supply, drawers slamming and keyboard sound appear to be more prevalent at night. This was particularly noticeable with the mattress alarm/pump noise source, which was ranked 22 during the day and 2 at night. It made up only 1.45% of the sound sources and occurred in 8.48% minutes observed in the day time, but at night it resulted in 7.92% of the total sources and occurred in 40.1% of the observed night time minutes.

Source	Day	Night
Nurse/nurse	1	→1
Other noise (see box)	2	↓5
Bin lid closing	3	↓6
Doctor/ doctor	4	↓16
Nebs/Oxygen/CPAP/Optiflow	5	↑3
Nurse/patient	6	↓8
Nurse/doctor	7	↓12
Procedure at bedside	8	↓11
Monitor alarm	9	↑4
Aprons	10	→10
Ventilator alarm (Evita 4)	11	↑7
Preparing/clearing away equipment	12	↑9
Footsteps	13	↓18
Syringe/infusion pump alarm	14	→14
Talking on internal phone	15	↓26
Patient noise	16	↑13
Clinical trolley	17	↓19
Towel dispensor	18	↓20
Nurse/other	19	↓40
Chair	20	↓17
Internal phone ringing	21	↓29
Mattress alarm/pump noise	22	↑2
Patient/relative	23	↓48
Sink/taps	24	↓27
Nurse/relative	25	↓38
Programming infusion/syring pump	26	↑15
Blood gas machine	36	↑21
Other alarm	30	↑22
Aquarius alarm	31	↑23
Keyboard/mouse	34	↑24
Drawers slamming	28	↑25

Table 7.3 Ranking for the top 25 sources observed during day and night time

DAY TIME 07.00-23.00hrs	Total	% of total sound sources	% of observed minutes
Nurse/nurse	1168	9.80	57.25
Other noise (see box)	744	6.24	36.47
Bin lid closing	711	5.96	34.85
Doctor/ doctor	704	5.91	34.51
Nebs/Oxygen/CPAP/Optiflow	607	5.09	29.75
Nurse/patient	548	4.60	26.86
Nurse/doctor	522	4.38	25.59
Procedure at bedside	521	4.37	25.54
Monitor alarm	495	4.15	24.26
Aprons	444	3.72	21.76
Ventilator alarm (Evita 4)	378	3.17	18.53
Preparing/clearing away equipment	353	2.96	17.30
Footsteps	307	2.58	15.05
Syringe/infusion pump alarm	300	2.52	14.71
Talking on internal phone	276	2.32	13.53
Patient noise	274	2.30	13.43
Clinical trolley	244	2.05	11.96
Towel dispensor	224	1.88	10.98
Nurse/other	219	1.84	10.74
Chair	215	1.80	10.54
Internal phone ringing	203	1.70	9.95
Mattress alarm/pump noise	173	1.45	8.48
Patient/relative	173	1.45	8.48
Sink/taps	152	1.28	7.45
Nurse/relative	145	1.22	7.11
Programming infusion/syring pump	142	1.19	6.96
Other/other	140	1.17	6.86
Drawers slamming	137	1.15	6.72
Patient/doctor	127	1.07	6.23
Other alarm	119	1.00	5.83
Relative/relative	110	0.92	5.39
Aquarius alarm	105	0.88	5.15
Entrance phone	97	0.81	4.75
Keyboard/mouse	94	0.79	4.61
Bed/trolley	85	0.71	4.17
Blood gas machine	69	0.58	3.38
Bedside trolley	65	0.55	3.19
Doctor/other	64	0.54	3.14
Sudden loud noise	59	0.49	2.89
Feed pump alarm	59	0.49	2.89
Patient/other	53	0.44	2.60
Monitor urgent	52	0.44	2.55
Clip file	39	0.33	1.91
Doctor/ relative	39	0.33	1.91
Suction	35	0.29	1.72
X-Ray	32	0.27	1.57
Doorbell	27	0.23	1.32
Mobile phone	18	0.15	0.88
Other/relative	17	0.14	0.83
Vision alarm	16	0.13	0.78
Bedside table	10	0.08	0.49
Cacophony of sound	9	0.08	0.44
Oscillator alarm	1	0.01	0.05
Oscillator	0	0.00	0.00
Patient/patient	0	0.00	0.00
Total	**11920**		

Table 7.4 Demonstrates the number of noise sources during daytime hours (07.00-23.00hrs), the percentage of time for each sound source and the percentage of time that each sound source was heard during the observed hours (34hrs)

NIGHT TIME 23.00-07.00hrs	Total	% of total sound sources	% of observed minutes
Nurse/nurse	427	8.78	44.48
Mattress alarm/pump noise	385	7.92	40.10
Nebs/Oxygen/CPAP/Optiflow	338	6.95	35.21
Monitor alarm	334	6.87	34.79
Other noise (see box)	316	6.50	32.92
Bin lid closing	293	6.02	30.52
Ventilator alarm (Evita 4)	197	4.05	20.52
Nurse/patient	195	4.01	20.31
Preparing/clearing away equipment	189	3.89	19.69
Aprons	180	3.70	18.75
Procedure at bedside	165	3.39	17.19
Nurse/doctor	156	3.21	16.25
Patient noise	141	2.90	14.69
Syringe/infusion pump alarm	138	2.84	14.38
Programming infusion/syring pump	114	2.24	11.88
Doctor/ doctor	109	2.24	11.35
Chair	106	2.18	11.04
Footsteps	106	2.18	11.04
Clinical trolley	103	2.12	10.73
Towel dispensor	98	2.01	10.21
Blood gas machine	85	1.75	8.85
Other alarm	81	1.67	8.44
Aquarius alarm	73	1.50	7.60
Keyboard/mouse	60	1.23	6.25
Drawers slamming	58	1.19	6.04
Talking on internal phone	56	1.15	5.83
Sink/taps	53	1.09	5.52
Bed/trolley	45	0.93	4.69
Internal phone ringing	38	0.78	3.96
X-Ray	33	0.68	3.44
Sudden loud noise	25	0.51	2.60
Suction	24	0.49	2.50
Bedside trolley	24	0.49	2.50
Clip file	21	0.43	2.19
Entrance phone	20	0.41	2.08
Monitor urgent	16	0.33	1.67
Feed pump alarm	13	0.27	1.35
Nurse/relative	10	0.21	1.04
Relative/relative	10	0.21	1.04
Nurse/other	6	0.12	0.63
Patient/doctor	6	0.12	0.63
Mobile phone	4	0.08	0.42
Doorbell	4	0.08	0.42
Oscillator alarm	2	0.04	0.21
Vision alarm	2	0.04	0.21
Other/other	2	0.04	0.21
Bedside table	1	0.02	0.10
Patient/relative	1	0.02	0.10
Doctor/other	1	0.02	0.10
Oscillator	0	0.00	0.00
Cacophony of sound	0	0.00	0.00
Patient/patient	0	0.00	0.00
Patient/other	0	0.00	0.00
Doctor/ relative	0	0.00	0.00
Other/relative	0	0.00	0.00
Total	**4864**		

Table 7.5 Demonstrates the number of noise sources during night time hours (23.00-07.00hrs), the percentage of time for each sound source and the percentage of time that each sound source was heard during the observed hours (16hrs)

7.4.3 Location

Multiple sources of sound from different locations were possible at the same time. Sounds emanating from the observed bed space occurred in 2236 episodes or 74.5% of the observed minutes. 1520 episodes (50.67% of the time) sound was sourced from the staff base in the GICU. The adjacent and other bed spaces also produced many of the sources of sound noted. Table 7.6 lists the main sound locations observed, many occurring simultaneously.

Location	Episodes	% of observed minutes
Observed bed space	2236	74.53
Left adjacent bed space	1180	30.33
Right adjacent bed space	853	28.43
Other bed space	842	28.06
Other bed space	325	10.83
Other bed space	53	1.76
Other bed space	5	0.17
Other bed space/not knov	1165	38.83
GICU staff base	1520	50.67
GICU entrance	102	3.4
GICU sluice	26	0.87
Clinical room	170	5.67
HDU/GICU entrance	140	4.67
Total	**8617**	

Table 7.6 Episodes and percentage of observed minutes per location of source

The median and interquartile range was calculated for the total number of episodes per bed space (table 7.7). This demonstrates that in bed space 11 there were the least total episodes, but a similar number of dominant episodes (see section 7.11). This suggests that bed space 11 being a side room may have less ingress of sound sources.

	Bed 3		Bed 5		Bed 9		Bed 11	
	Total episodes	Dominant episodes	Total episodes	Dominant episodes	Total episodes	Dominant episodes	Total episodes	Dominant episodes
Median	356	142	336	138	348	160	248.5	145.5
IQR	84	35	58	54	62	46	55	45

Table 7.7 Median and IQR for total episodes and dominant episodes (rated at 4 or 5 in the perceived loudness scale)

7.4.4 SPL during 'Sound in Time' observations

The average SPL ($L_{Aeq50hrs}$) across all units during the 'Sound in Time' observation was 65.1dB (SD 3.98) with little variation between the 34hrs of daytime measurement (07.00-23.00hrs) 66.3dB (SD 3.37) and 16hrs of night time (23.00-07.00hrs) 62.7dB (SD 3.81) although there was a small reduction in sound levels to 61.7dB (SD 3.95) between 02.00- 06.00hrs. This was consistent with the data from the 271days of distributed sound data (figure 7.6), as was the data for each bed space (figure 7.7).

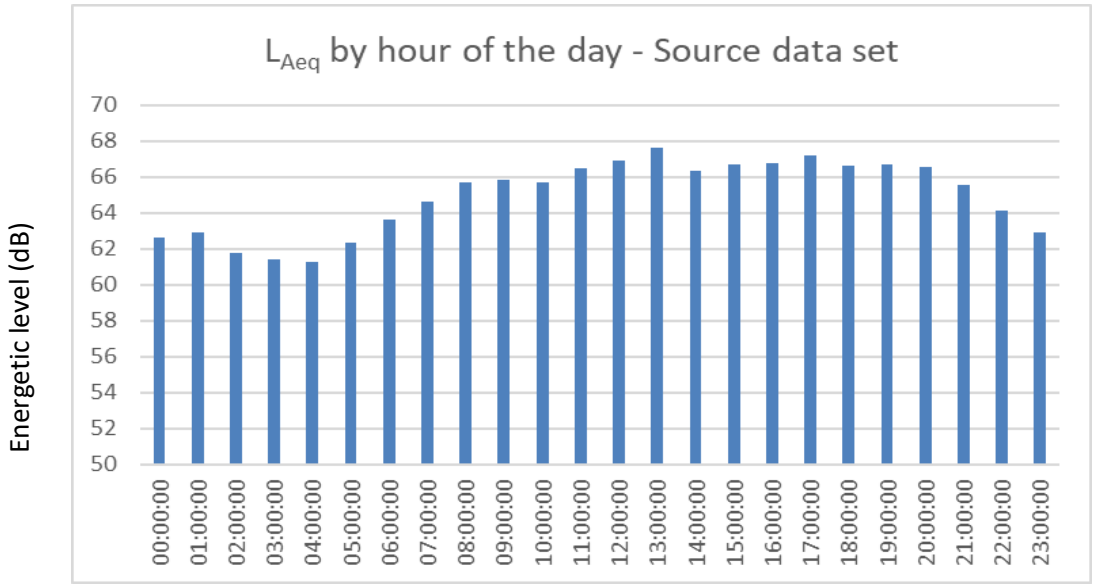


Figure 7.6 Combined average L_{Aeq} for each hour for the Source data (Sound in Time)

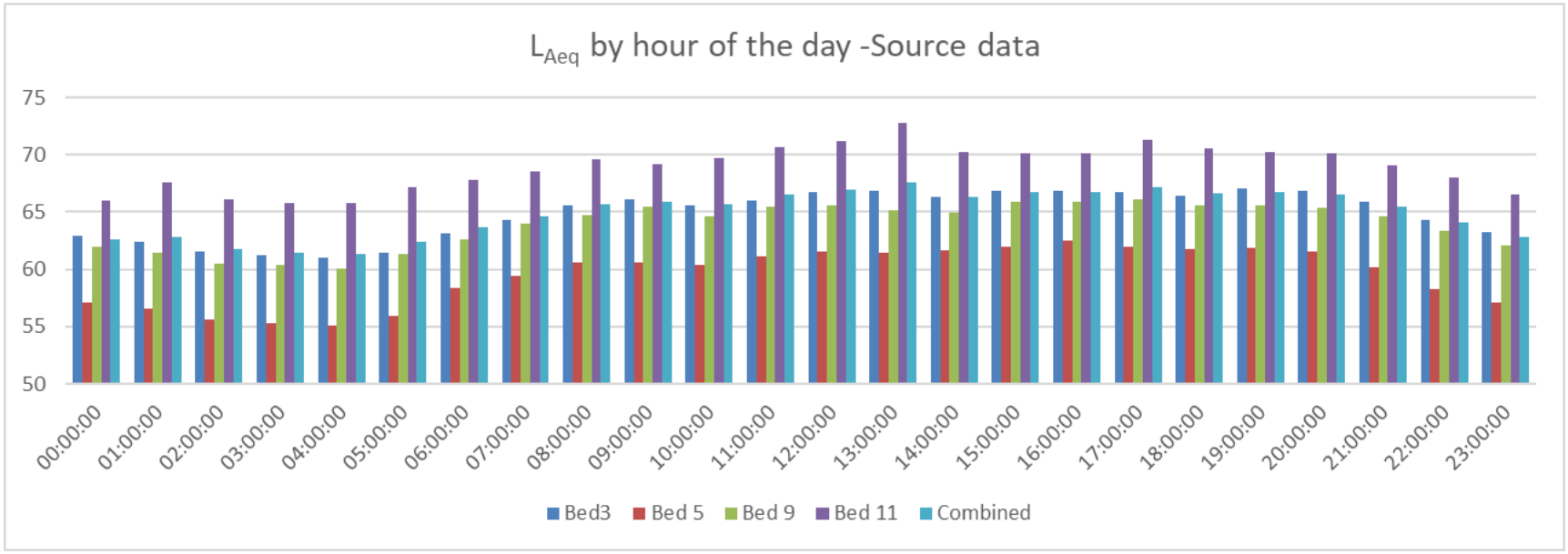


Figure 7.7 Average L_{Aeq} for each bed space and hour for the Source data (Sound in Time)

During the one-hour periods of observation the highest average SPL of 73.9dB was recorded at bed space 11 during observation 23, this took place between 11.10-12.09hrs. During this observation the average maximum SPL was 87.5dB, with individual minute recording as high as 94.9dB.

7.4.5 Perceived loudness

The data for the number of sound sources per observation and the average A-weighted sound for the one-hour periods of observation were compared. Figure 7.8 identifies the relationship between L_{Aeqhr} vs. number of episodes for each of the 50 periods of observation. The correlation coefficient identifies (R^2 =0.032) no relationship between the number of episodes of sound and average A-weighted sound. This is not surprising, as each of the sources of sound vary in decibel level, frequency and duration. Therefore, an alternative method of describing the relationship between the sound sources and sound pressure levels was to be identified.

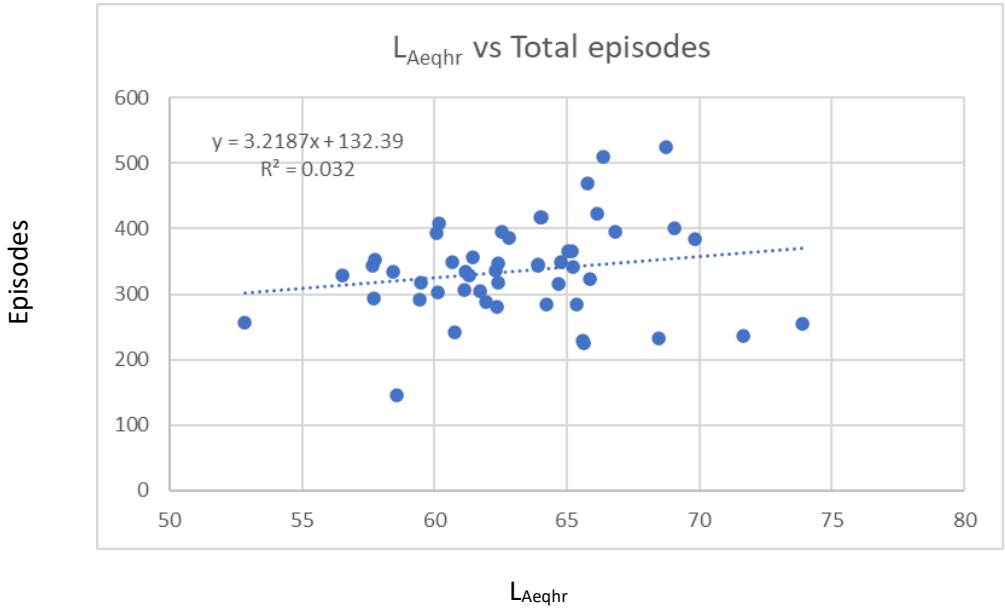


Figure 7.8 Scatterplot demonstrating the number of sources of noise vs.L_{Aeqhr} for the 50 periods of observation

The 55 sources of sound were assigned a level of perceived loudness using a scale from 5 - dominant sound to 0 - not significant. The scale was designed to identify perceived loudness from the location of the source to the patient's head. Table 7.8 identifies the rating for each of the sources. Alarms and machinery sound featured in the most dominant ratings groups 5 and 4.

Source	Perceived loudness
Bin lid closing	5
Chair	5
Drawers slamming	5
Sudden loud noise	5
Cacophony of sound	5
Syringe/infusion pump alarm	5
Oscillator alarm	5
Ventilator alarm (Evita 4)	5
Aquarius alarm	5
Monitor urgent	5
Mattress alarm/pump noise	4
Feed pump alarm	4
Monitor alarm	4
Vision alarm	4
Other alarm	4
Programming infusion/syringe pump	4
Preparing/clearing away equipment	4
Procedure at bedside	4
Oscillator	4
Patient noise	4
Aprons	4
Internal phone ringing	4
Towel dispensor	3
Sink/taps	3
Entrance phone	3
Doorbell	3
X-Ray	3
Nurse/Nurse	3
Nurse/Doctor	3
Nurse/Patient	3
Nurse/Relative	3
Nurse/Other	3
Patient/Patient	3
Patient/Doctor	3
Patient/Relative	3
Patient/Other	3
Doctor/ Doctor	3
Doctor/Other	3
Doctor/ Relative	3
Other/Other	3
Other/Relative	3
Relative/Relative	3
Footsteps	2
Other noise (see box)	2
Clip file	2
Talking on internal phone	2
Suction	2
Blood gas machine	2
Bed/trolley	2
Clinical trolley	2
Bedside trolley	2
Nebs/Oxygen/CPAP/Optiflow	2
Bedside table	2
Mobile phone	2
Keyboard/mouse	1

Table 7.8 Perceived loudness scale

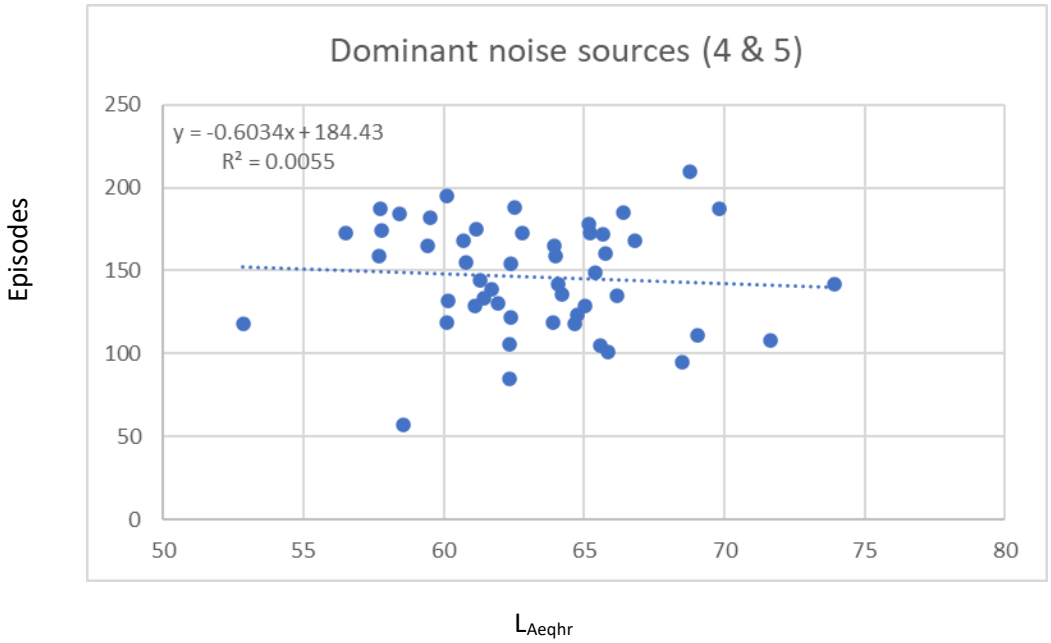


Figure 7.9 Scatterplot demonstrating the number of sources of noise ranked as 4/5 vs.L_{Aeqhr} for the 50 periods of observation

Figure 7.9 also demonstrates no relationship (R^2=0.0055) between the L_{Aeqhr} and the number of sources ranked at 4/5 for the hour period of observation.

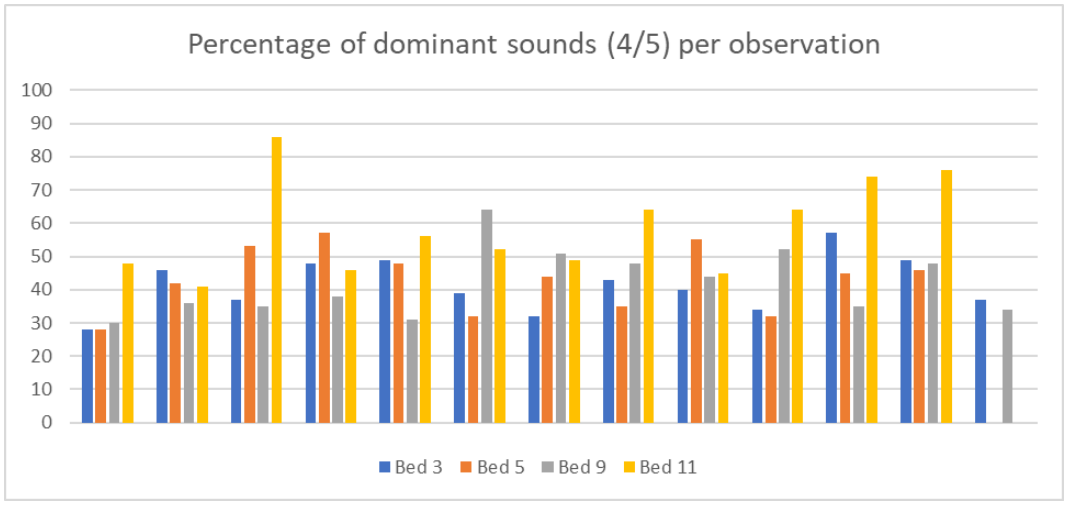


Figure 7.10 Percentage of dominant (rated 4 or 5) sounds per one-hour observation

No relationship could be found between sound pressure levels either L_{Aeqhr} or L_{5hr} and any variation of total episodes, episodes ranked as 4/5 or ranked as 5, the

most dominant, for the all 50 periods of observation or any other combination, even in those periods of observation with ≥50% dominant sounds (Figure 7.10).

7.4.6 Examples of individual one-hour observation periods

The following sections (7.4.6.1 - 7.4.6.4) analyse in detail four one periods of observation, one at each bed space, to illustrate various common scenarios within the GICU. The helicopter landing, a visitor at a bed space, an admission at an adjacent bed space, the response to a patient deteriorating and mid-week afternoon with nothing in particular occurring during the period of observation.

7.4.6.1 Observation 3 Bed space 5 18:10hrs 120715

This bed space is in an open area (one of four beds), by a window opposite the entrance to the high dependency unit, it has no beds adjacent but three bed spaces diagonally opposite to the left, as shown in figure 4.1 in chapter 4. The observer was sat towards the end of the bed by the window. Sound pressure levels were L_{Aeq1hr} 60.1dB ($L_{Aeq1min}$56.9- 66.7dB); $L_{Amax1hr}$ 72.9db, $L_{Amax1min}$ 86.5dB, L_{Ceq1hr} 63.7dB and statistical parameters L_{5hr} 64.6db, L_{10hr} 63.9dB, L_{25hr} 60.3dB, L_{50hr} 57.5 L_{75hr} 55.2dB and L_{90hr} 53.4db. Figure 7.11 demonstrates for each of the statistical parameters, the percentage of time sound pressure levels exceeded an individual decibel level during the period under observation. The average A-weighted sound level for the period of observation is marked by a dotted black line. It can be seen that only L_{90} did not cross this line at any point, L_{25} exceeded this average level for 50% of time, with L_5 and L_{10} consistently exceeding this level. This demonstrates that apart from two peaks of sound, the sound environment was relatively consistent across the hour. The helicopter landed during this observation, initially coming into land at about 18.33hrs and causing sound levels to rise to $L_{Aeq1min}$

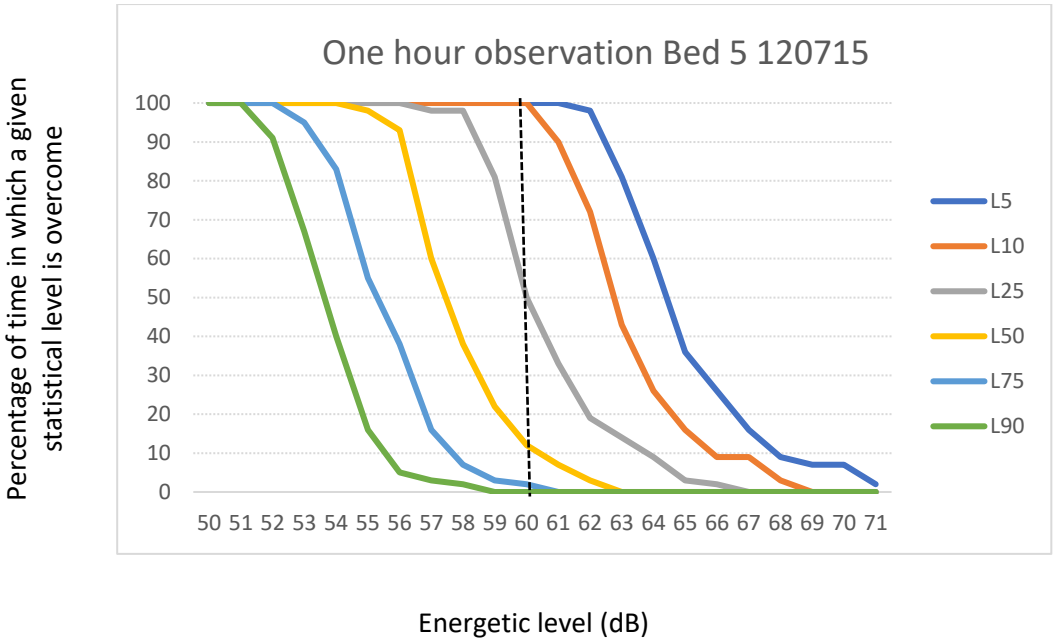


Figure 7.11 Representation of the six statistical parameters over the1-hour period. The black dotted line identifies the L_{Aeq1hr} 60.1dB

66.7dB, $L_{Ceq1min}$ 68.6dB and L_{Amax} 83.94db. A visitor was attendant at the bed space and spoke for 45 of the 60 minutes observed, at 19:01hrs the visitor shouted to another visitor who was looking for the patient's location, this caused a L_{Amax} for this minute of 85.6dB and $L_{Aeq1min}$ 65.2dB (see figure 7.12).

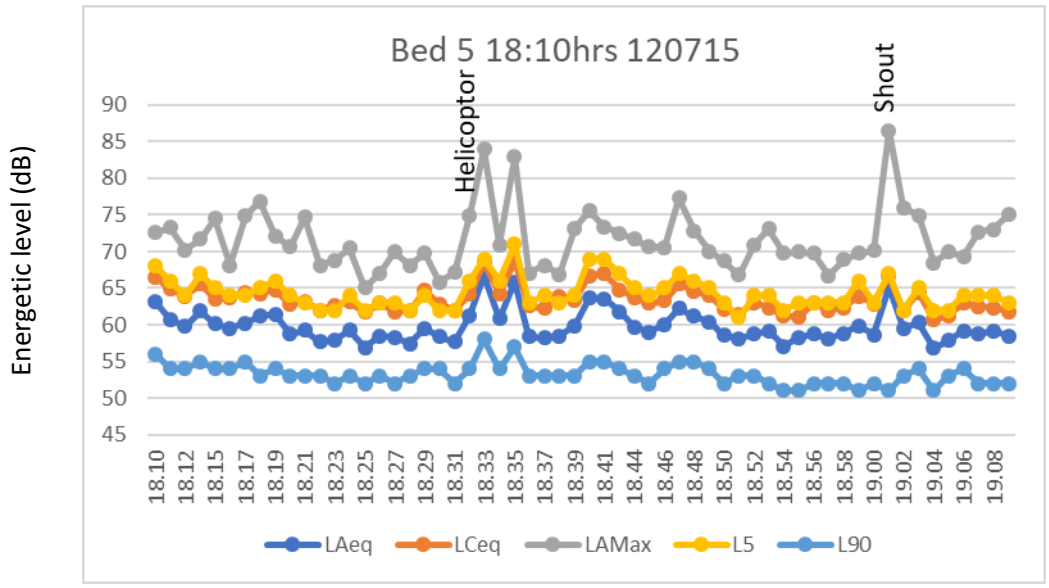


Figure 7.12 One-hour observation at bed space five

To understand the sound peaks better, figures 7.13 and 7.14 demonstrate these periods in more detail. Data in this study was measured at 1-minute intervals and therefore there is not the detail available as for study 1a in chapter 5. However, figure 7.16 shows that all statistical parameters were impacted during the two peaks at 18.33 and 18.35hrs, suggesting the impact was for longer than the short, sharp increase in sound levels at 19.01hrs which did not impact L_5, L_{10}, L_{25} or L_{50} demonstrated in figure 7.17.

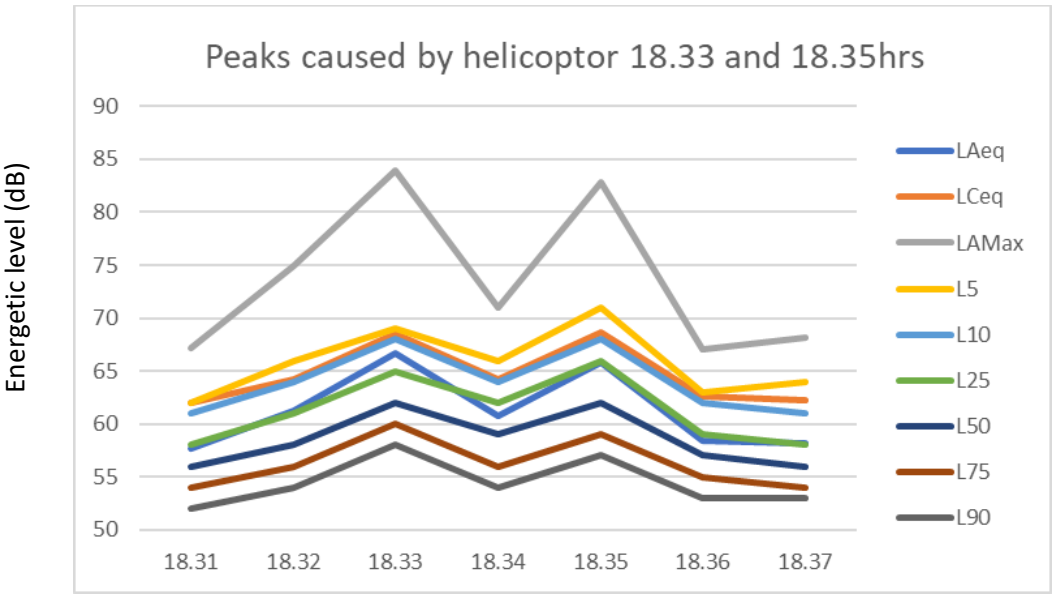


Figure 7.13 Energetic levels for a period demonstrating a peak in sound caused by the helicopter landing

During the one-hour period of observation 394 episodes of noise sources were observed, with a mean of 6.6 sources per minute (range 3-12), this was greater than the average for daytime observations of 351 episodes, however less of the sound originated from sources rated as 4 and 5 on the perceived loudness scale (31.6%; n=111). The helicopter was not one of the sound sources on the datasheet and therefore not included in this calculation. Noise sources were noted from the observed bed space, the surrounding bed spaces and the staff base during this observation.

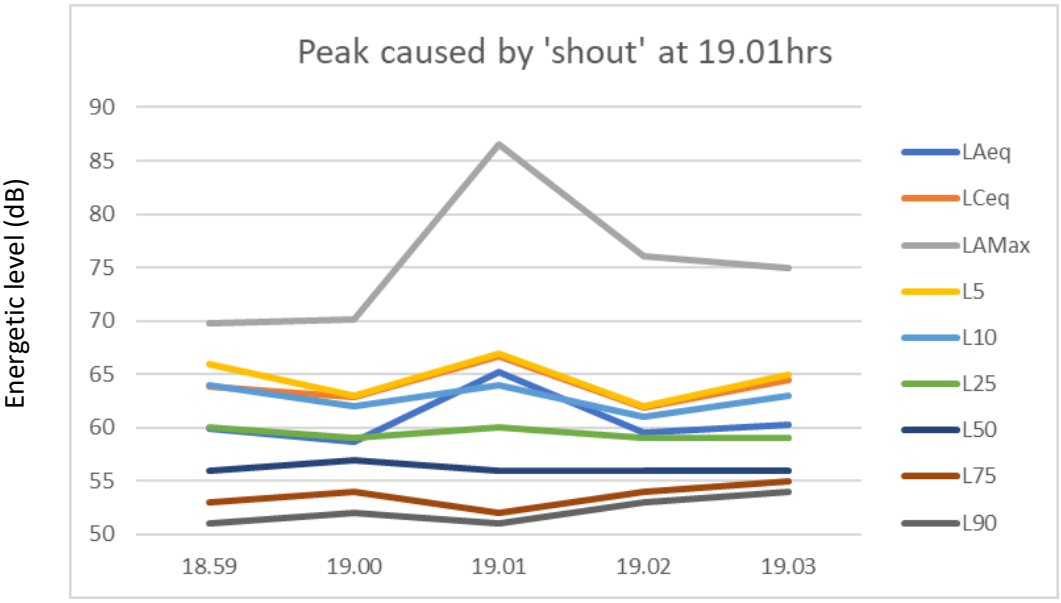


Figure 7.14 Energetic levels for the period demonstrating a peak in sound caused by a visitor shouting out to another visitor

These included preparing/clearing away equipment (n=1), nebuliser (n=14), bed/trolley (n=1), procedure at bedside (n=17), internal phone ringing (n=13), programming infusion/syringe pump (n=6), bedside trolley (n=5), chair (n=6), a mobile phone being used as a calculator (n=2), drawers slamming (n=2) , clip file (n=2), footsteps (n=8) and the pump for the alternating pressure boots (n=55). Alarms included the mattress (n=1), syringe/infusion pump (n=10), ventilator (n=15), Aquarius (n=3), other (n=2) and the monitor (n=3). The basin and bin areas caused bin lid closing (n=24), sink/taps (n=5), towel dispenser (n=8) and aprons (n=15). Communication: nurse/nurse (n=22), nurse/patient (n=15), nurse /doctor (n=21); nurse/other (n=1), nurse/relative (n=13) and patient/doctor (n=1). At the staff base: entrance phone (n=2), doorbell (n=3), keyboard/mouse (n=1) and talking on internal phone (n=4). During this observation there were no periods with L_{Aeq}<50dB or L_{Amax} <55dB for ≥five minutes, based on the relative to background SPL, there was one period of five minutes of restorative time, which occurred for 9.5% of the observed time.

7.4.6.2 Observation 18: Bed space 3 01:00hrs 220715

This bed space is in an open bay, one of four beds, with a bed space either side of it and one diagonally opposite but furthest away. The observer was sat at the head end of the bed space, between bed spaces 2 & 3. Sound pressure levels were L_{Aeq1hr} 57.8dB ($L_{Aeq1min}$55.0-71.2dB); $L_{Amax1hr}$70.3db and $L_{Amax1min}$84.4dB, L_{Ceq1hr} 61.4dB and statistical parameters L_{5hr} 62.1dB, L_{10hr} 59.3dB, L_{25hr} 56.6dB, L_{50hr} 55.2dB, L_{75hr} 54.4dB and L_{90hr}53.9dB.

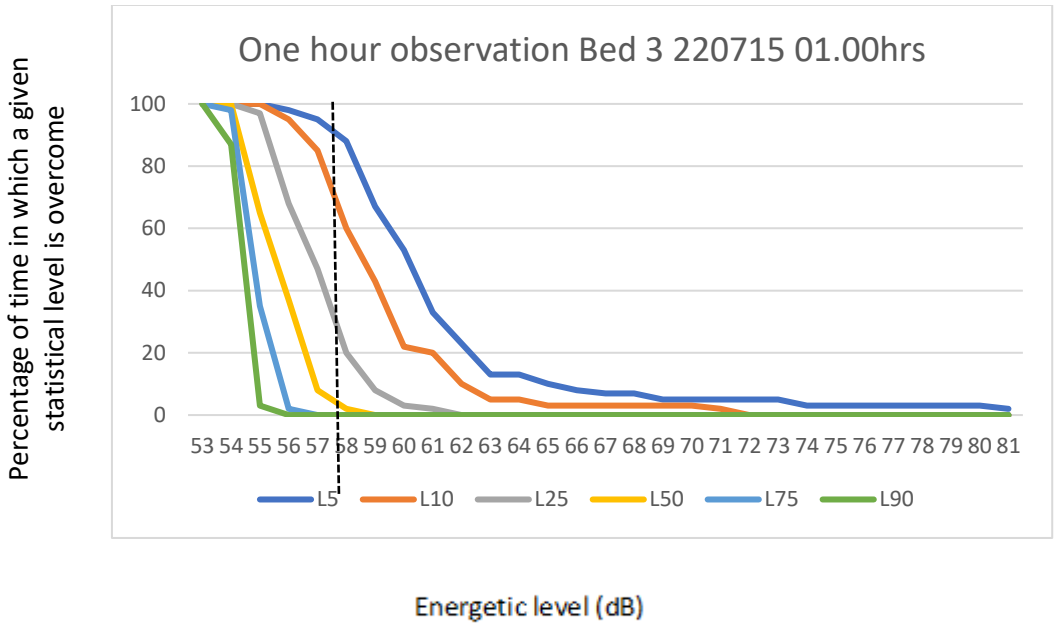


Figure 7.15 Representation of the six statistical parameters over the 1-hour period. The black dotted line identifies the L_{Aeq1hr} 57.8dB

Figure 7.15 demonstrates for each of the statistical parameters, the percentage of time sound exceeded a particular decibel level, again the average A-weighted SPL for the period of the observation is marked on the graph. It can be seen that this provides a very different pattern of sound than in observation 3 figure 7.11, with the majority of sound being within a very tight range, however the slopes for L_{10} and L_5 suggest frequent, very short periods of high noise levels, where L_{10} exceeded the average A-weighted level just over 60% of the time and L_5 for about 90% time, which is consistent with figure 7.16 and the description of sound below.

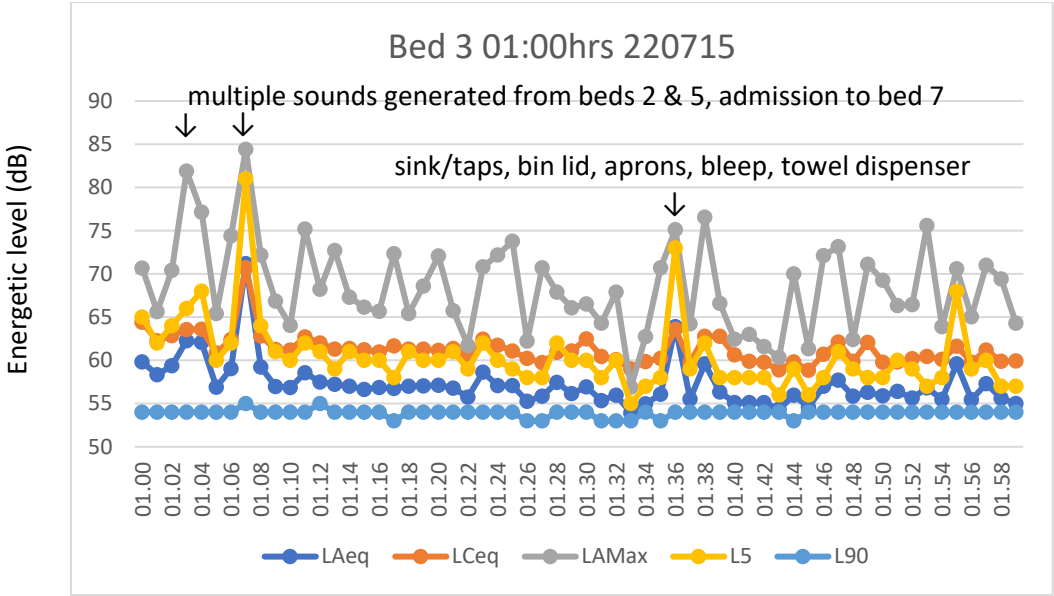


Figure 7.16 One-hour observation at bed space three

During this observation a total of 353 episodes of noise sources were recorded, higher than the night time average of 304 episodes, with a mean of 5.9 sources (range 4-9) recorded each minute. Of these 174 episodes (49.3%) of sounds were rated 4 or 5 on the perceived loudness scale. Soon after the observation commenced, a patient was admitted to bed seven. This bed space is on the other side of the unit, behind bed space 5 (see figure 4.1, Chapter 4). This caused an instant increase in personnel and therefore communication and a plethora of alarms. To understand this period of sound better, figures 7.20 and 7.21 demonstrate this in more detail. Figure 7.17 highlights two peaks of sound, one at 01.03hrs and another at 01.07hrs. The first impacts mainly L_5, L_{10}, L_{Amax} and L_{Aeq} and is most likely related to preparation at bed space seven for the admission, noise including oxygen at bed space two and alarms at beds adjacent to bed space three and is consistent with the increased amount of noise emanating from sources rated 4 or 5 on the perceived loudness scale. The second peak represents the arrival of the admission to bed space 7, although this bed is distant from the observed bed space, the sound generated by equipment and communication

appears to have impacted all energetic measures at this bed space. Figure 7.18 supports this suggesting multiple short, high peaks of noise, prolonged during these seven minutes.

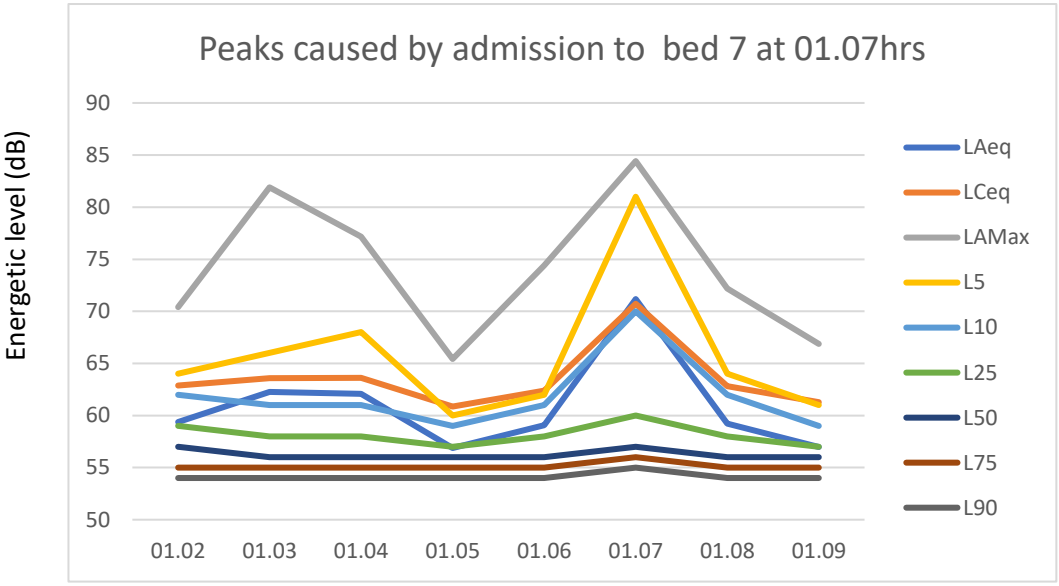


Figure 7.17 Energetic levels recorded at bed space three, demonstrating the impact of sound from adjacent bed spaces and in particular an admission to bed space seven

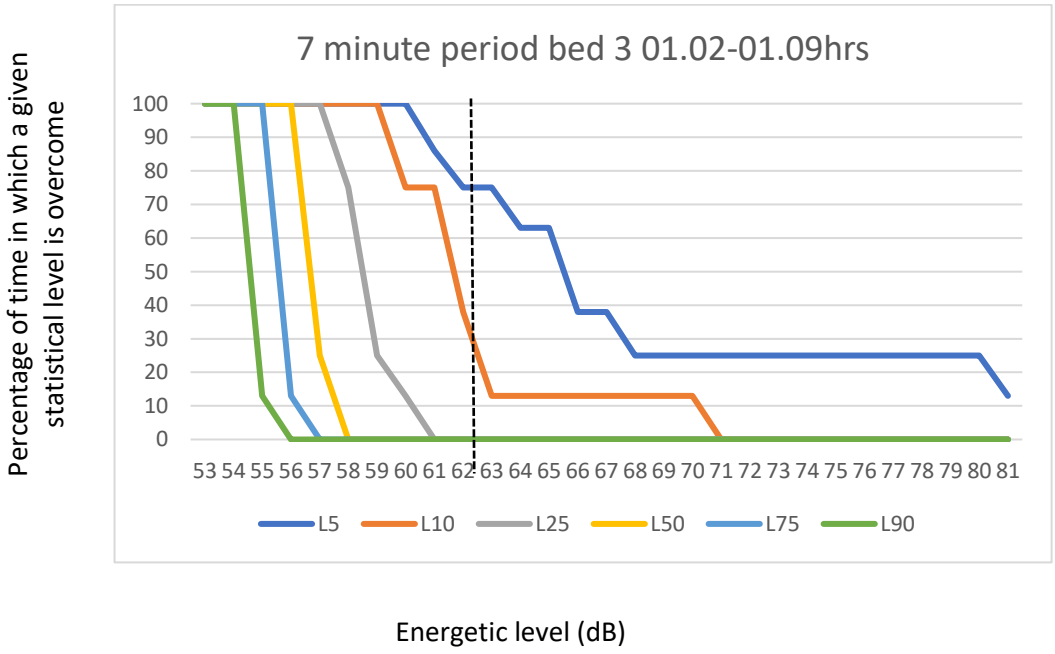


Figure 7.18 Representation of the six statistical parameters over a 7-minute period recorded at bed space three during an admission to bed space seven. The black dotted line identifies the $L_{Aeq7minutes}$62.2dB

Throughout the one-hour observation period, oxygen could be heard from an adjacent bed space being delivered via a tracheostomy mask, as well as the noise of the mattress pump from the observed bed space. For this observation the majority of noise emanated from areas other than the observed bed space. During the observation the following clinical and housekeeping noises could be heard from the observed or adjacent bed spaces: preparing /clearing away equipment (n=2), a procedure (n=6) programming a syringe or infusion pump (n=3), suction (n=2), bed/trolley (n=3), footsteps (n=7), chair (n=12), slide sheet (n=1), doorbell (n=1), drawers slamming (n=7); the following alarms: syringe/infusion pump (n=2), feed pump (n=1), ventilator (n=16), monitor (n=22) other (n=7); communication: nurse/nurse (n=17), nurse/patient (n=19), nurse/doctor (n=11) and patient noise (n=12). From the staff base there was doctor/doctor communication (n=27), talking on internal phone (n=7), the blood gas machine (n=2), label printer (n=2), bleep (n=1), keyboard/mouse (n=1) and the entrance phone (n=4). At the foot of bed space 3 there is a sink and bin, (see figure 4.1, chapter 4) this resulted in the bin lid closing (n=14), sink/taps (n=4), towel dispenser (n=7) and aprons (n=8) and example of the increase in noise caused by the use of this handwashing/PPE facility is identified in figure 7.19 below. This shows a peak at 01.36hrs impacting L_{Aeq}, L_{Amax}, L_5 and L_{10} whilst a member of at staff ran taps, took soap from the soap dispenser, dried their hands, taking towels from the towel dispenser and discarded the dirty towels into the bin, at the same time there was some conversation between a nurse and a doctor, a bleep sounded and oxygen was running at bed space 2.

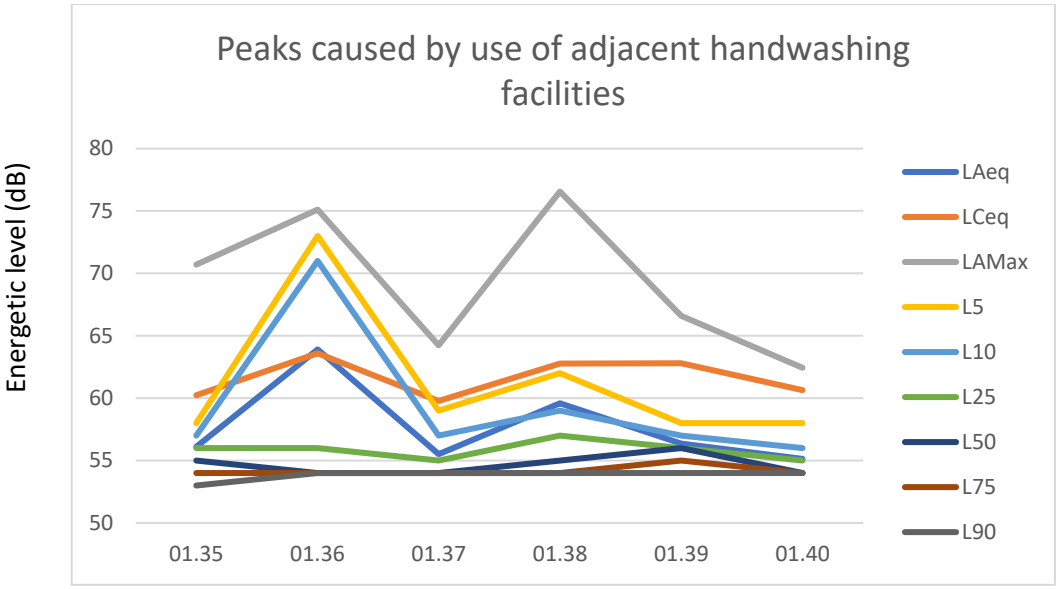


Figure 7.19 Energetic levels recorded at bed space three, demonstrating the impact of sound from adjacent hand washing facilities

Later at 01.38hrs another member of staff discards some rubbish into the bin, concurrently there was the background sound of oxygen at bed space 2, a monitor alarm and footsteps, causing a momentary increase in L_{Amax}, but less of an impact of the other energetic levels.

During the one-hour observation there were no periods with L_{Aeq}<50dB or L_{Amax} <55db for ≥five minutes, however if restorative periods (RP) are calculated based on the relative to background SPL then there were 25 minutes of RP over four episodes ranging from 5-7minutes accounting for 45.8% of the observed time.

7.4.6.3 Observation 30 Bed space 11 18:50hrs 300715

This observation was in the side room during a period of patient deterioration, the observer was stood at the foot end of the bed to avoid impacting on the clinical care required. The patient was initially managed with non-invasive ventilation, while a number of diagnostic tests took place including an echo and ultrasound,

towards the end of the observation the patient requires intubation. Sound pressure levels were L_{Aeq1hr} 69.8dB ($L_{Aeq1min}$58.9-80.1dB); $L_{Amax1hr}$81.4dB and $L_{Amax1min}$94.9dB and energetic values and L_{5hr}75.6dB, L_{10hr} 73.7dB, L_{25hr} 69.3dB, L_{50hr} 64.9dB, L_{75hr} 62.6dB, L_{90hr} 61.4dB. Data for L_{Ceq} was not available for this bed space.

Figure 7.20 demonstrates for each of the statistical parameters, the percentage of time sound pressure levels were exceeded, as well as a comparison with the average A-weighted level for the period of observation 30. This demonstrates yet another pattern of sound during this period of observation. This observation recorded the greatest range of sound pressures levels from 58-95dB. All statistical parameters crossed the averaged A-weighted sound pressure level, identifying a large number of peak sounds, occurring for a variety of time periods, distributed throughout the period of observation. L_{90} exceeded the average A -weighted level on just under 2% occasions, L_{75} 5%, L_{50} 15%, L_{25} 15% and L_{10} and L_5 70%.

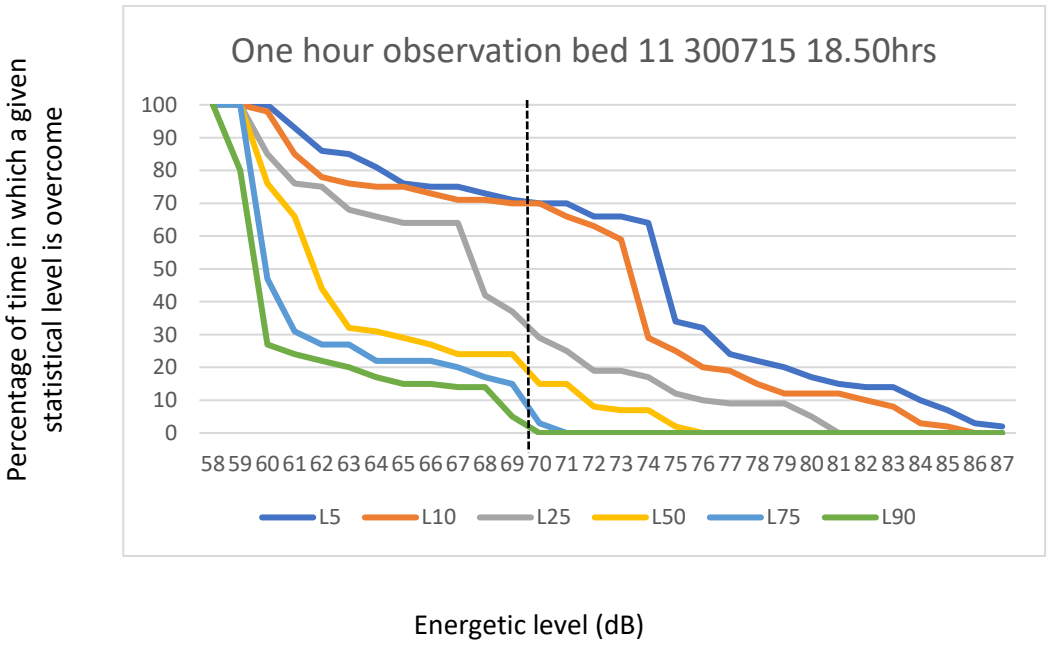


Figure 7.20 Representation of the six statistical parameters over the 1-hour period. The black dotted line identifies the L_{Aeq1hr} 69.8dB

This is consistent with figure 7.21 and the increased number of noise sources, demonstrating the high level of activity and consequent high noise levels within this room.

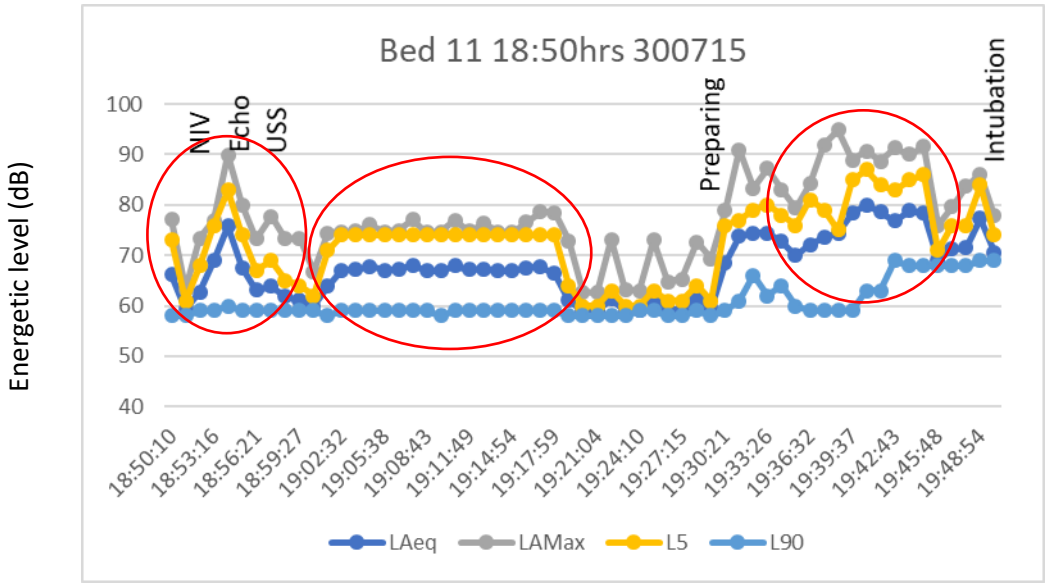


Figure 7.21 One-hour observation at bed space eleven

The high level of activity is further illustrated by the three figures 7.22, 7.23 and 7.24 below, highlighted by the circles on figure 7.21 above. The first figure, 7.22, highlights the peak at 18.54hrs where new equipment to help the patient breath and two investigations take place. These increase activity, alarms and communication with L_{Amax}, L_{Aeq}, L_5, L_{10}, L_{25} and L_{50} all raised during this peak. The second figure of this series, 7.23, demonstrates that soon after this peak, sound levels for L_{Amax}, L_{Aeq}, L_5, L_{10}, L_{25} and L_{50} were consistently raised for a period of 18 minutes. The last figure 7.24, highlights a period of greater intensity of sound, where all energetic levels are consistently raised, identifying that the sounds levels were constantly raised during this period.

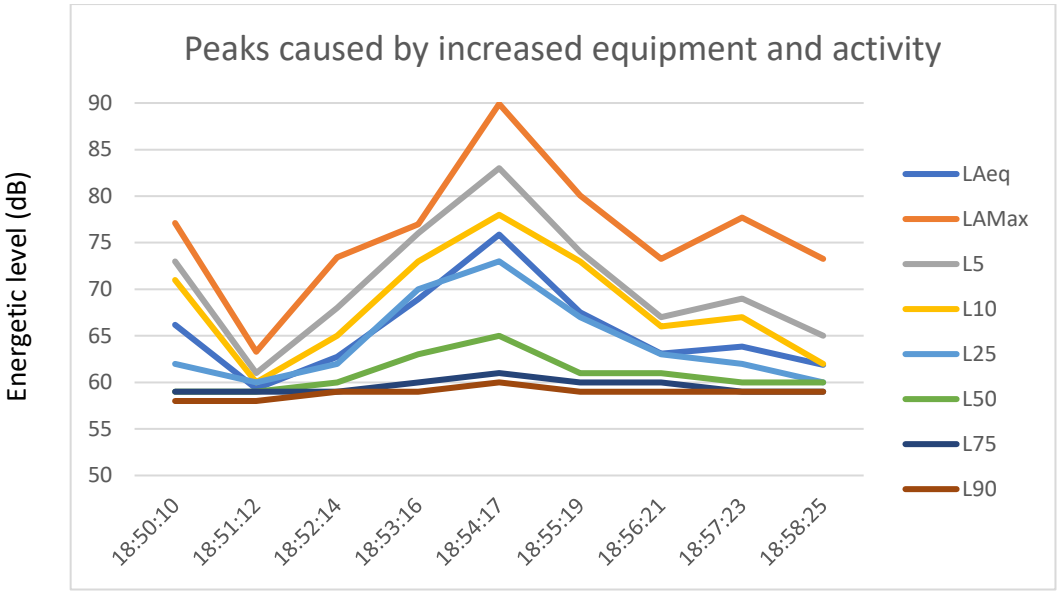


Figure 7.22 Energetic levels recorded at bed space eleven, demonstrating a peak in activity

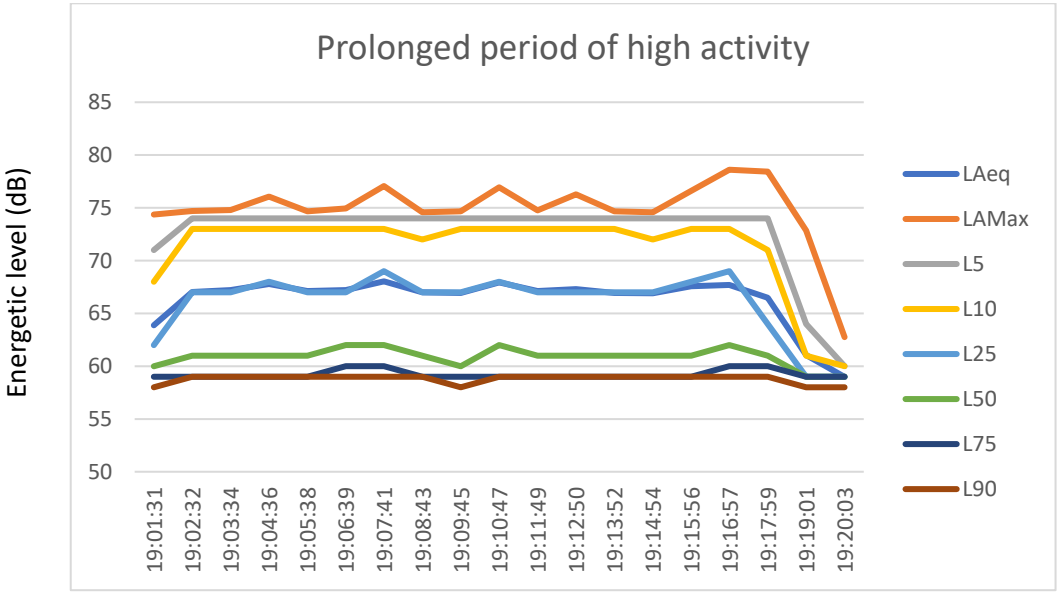


Figure 7.23 Energetic levels recorded at bed space eleven, demonstrating a prolonged period of increased activity

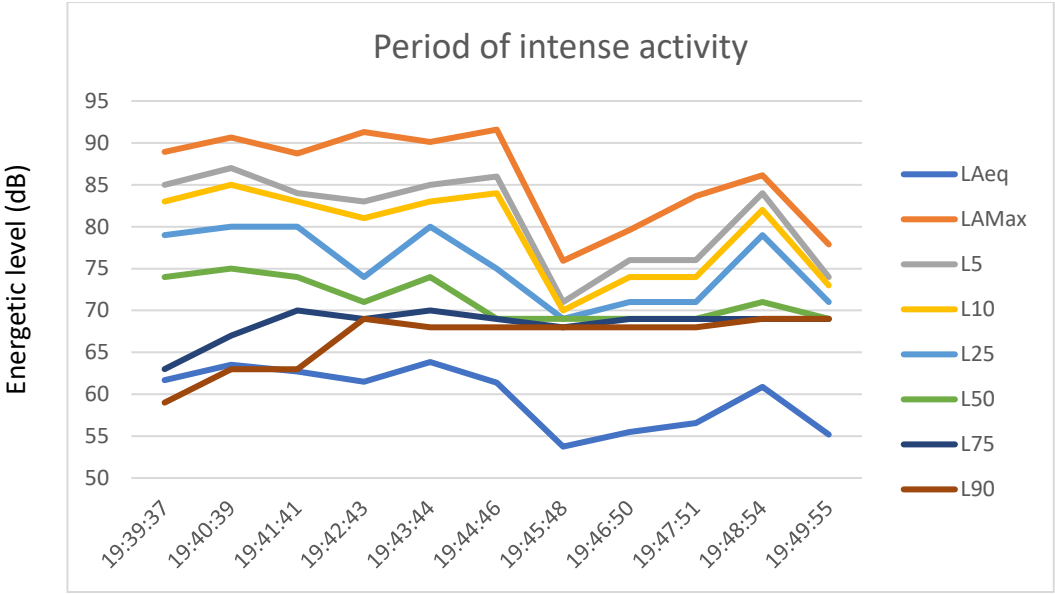


Figure 7.24 Energetic levels recorded at bed space eleven, demonstrating a period of intense activity

During this observation 384 episodes of noise were noted, considerably higher than the average for daytime, with a mean of 6.4 sources (range 3-10), all of which occurred in the observed room. Of these, 187 (48.7%) were rated as 4 or 5, consistent with alarms, and machinery sound, but also illustrating that half of the sound was from other sources, in this case often communication and the sound of oxygen through the NIV which was present throughout the observation. These included preparing/clearing away equipment (n=41), procedure at bedside (n=36), programming infusion/syringe pump (n=3), clinical trolley (n=8) and other noises (n=24) including equipment being wheeled into the room (n=5), the door opening and closing (n=13), the blinds being lowered (n=2), bin lid closing (n=25), drawers slamming (n=1), sink/taps (n=6), towel dispenser (n=6), aprons (n=10) and sudden loud noise (n=2). Alarms included mattress (n=19), syringe/infusion pump (n=1), NIV (n=15), ventilator (n=2), monitor urgent (n=19) and monitor (n=11). Communication: nurse/nurse (n=20), nurse/patient (n=12), nurse/doctor (n=34), patient/doctor (n=22), doctor/ doctor (n=5) and patient noise (n=10).

During this observation, there were no periods with L_{Aeq}<50dB or L_{Amax}<55db for ≥five minutes, however if restorative periods (RP) are calculated based on the relative to background SPL then there were 25 minutes of RP over three episodes ranging from 5-11 minutes each, accounting for 42.4% of the observed time.

7.4.6.4 Observation 40 Bed space 9 15:00hrs 060815

The observation was in an open bay (one of six beds on this side of the unit), all beds were occupied apart from one of the adjacent beds. The observer took advantage of the empty bed space to sit at the head of the observed bed. Sound pressure levels were L_{Aeq1hr}64.8dB ($L_{Aeq1min}$58.9- 80.1dB); $L_{Amax1hr}$77.8dB and $L_{Amax1min}$94.9dB, L_{Ceq1hr} 78.8dB and energetic values L_{90hr}60.1db and L_{5hr}68.5db. The pattern of sound (figure 7.25), was similar to observation three, the first period discussed, where sound was distributed across the statistical levels, with occasional peaks of sound caused by equipment alarms and the phone ringing as can be seen in figure 7.26. L_{Ceq} is reported for this bed space, however it shows little variation during this or many of the other observations at bed space 9. This may be due to the air conditioning unit which is located immediately behind the light fitting and thus the microphone, however this position is not unusual for the other bed spaces.

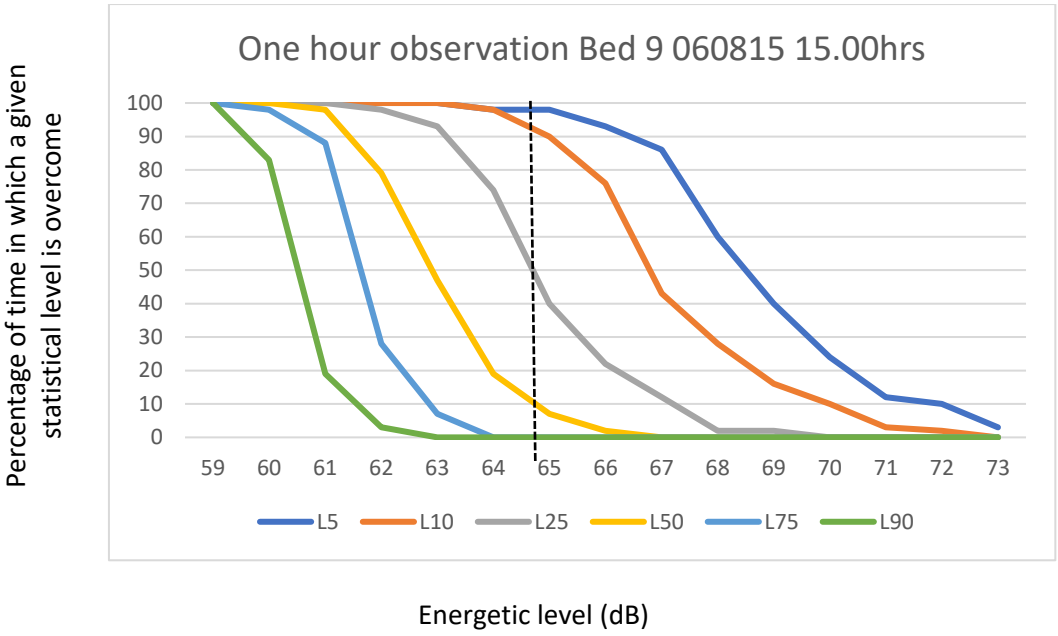


Figure 7.25 Representation of the six statistical parameters over the 1-hour period. The black dotted line identifies the L_{Aeq1hr} 64.8dB

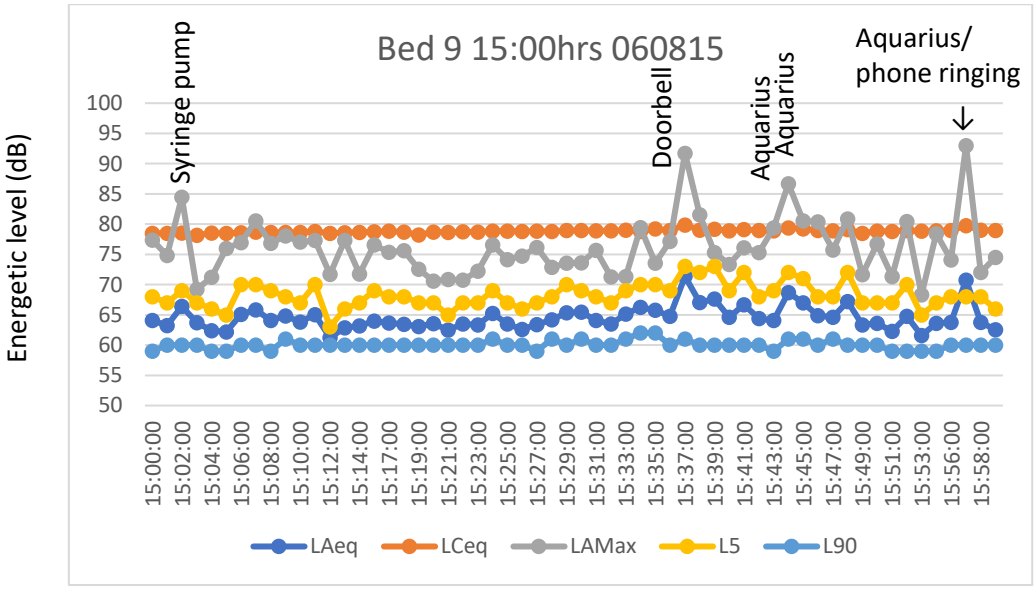


Figure 7.26 One-hour observation at bed space nine

During this observation 350 episodes of noise were noted, which is average for day time episodes in this study, with a mean of 5.8 sources per minute (range 3-9). These included 123 episodes (35.1%) of sources rated at 4 or 5 and 53.1%

(n=186) episodes were from items rated as 3, many were communication. All episodes included preparing/clearing away equipment (n=13), bed/trolley (n=8), programming infusion/syringe pump (n=3), blood gas machine (n=1), clinical trolley (n=5), bedside table (n=1), chair (n=7), entrance phone (n=6), internal phone ringing (n=7), doorbell (n=1), drawers slamming (n= 5), keyboard/mouse (n=2) , other noises (n=4) including printing labels, shredder, door slamming, clip file (n=1) and footsteps (n=6). At the end of the bed was a sink and bin, this resulted in: bin lid closing (n=23), sink/taps (n=6), towel dispenser (n=12) and aprons (n=15). Alarms: mattress (n=2), syringe/infusion pump (n=9), ventilator (n=4), Aquarius (n=11), monitor (n=11) other (n=6). Communication: mobile phone (n=2), talking on internal phone (n=11), nurse/nurse(n=24), nurse/patient (n=19), nurse/doctor (n=8), nurse/other (n=16), nurse/relative (n=18), patient/other (n=1), patient/relative (n=46), doctor/ doctor (n-21), doctor/other (n=4), doctor/ relative (n=2), relative/relative (n=2) and patient noise (n=7).

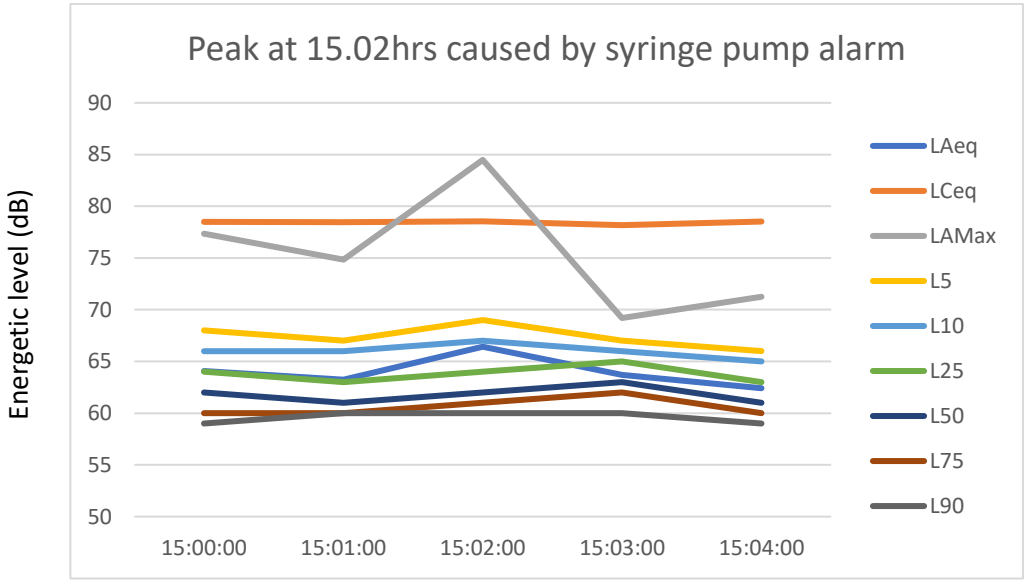


Figure 7.27 Energetic levels recorded at bed space nine, demonstrating a peak from a syringe pump from an adjacent bed space

A number of peaks of noise can be seen in figure 7.26. One caused by a syringe pump alarming at bed space 10 (figure 7.27), increased L_{Amax}, L_{Aeq}, but only marginally impacted L5 and L10, suggesting a very short period of increased noise.

Another peak (figure 7.28) caused by the Aquarius alarming (a piece of equipment for renal replacement therapy) at the adjacent bed space, simultaneously with the sound of a bin lid closing and the telephone ringing, caused a longer effect impacting L_{Amax}, L_{Aeq}, L_5, L_{10} and L_{25} persisting intermittently over the next few minutes.

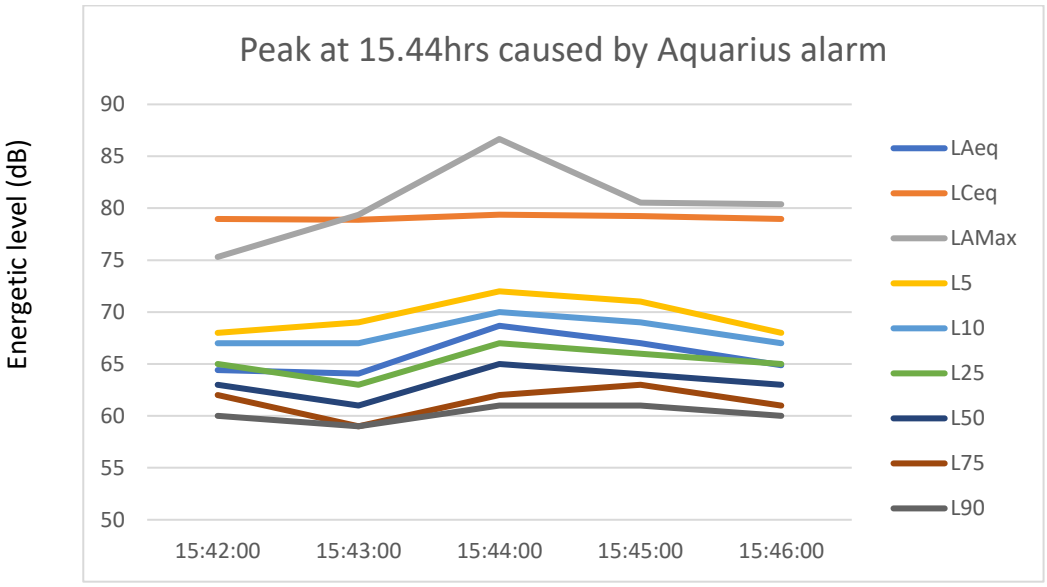


Figure 7.28 Energetic levels recorded at bed space nine, demonstrating the impact of prolonged equipment alarms alongside the telephone ringing and a bin lid closing

There were no periods with L_{Aeq}<50dB or L_{Amax}<55dB for ≥five minutes, however if restorative periods (RP) are calculated based on the relative to background SPL then there were 27 minutes of RP in one episode, accounting for 46.5% of the observed time.

7.4.7 Restorative periods

Applying either of Ryherd and colleagues[67] or Tegnestedt and colleagues[77] calculations of restorative time, there were no periods of restorative time during the 50 hours of observation. However, if the adapted Park and colleagues[97] description is utilised, there were 1215 (41.5%) minutes in periods of ≥five-minutes of restorative time in 115 episodes, with a mean number of episodes per observation of 2.3. Day time RT was 34.4% (mean episodes 2.1) and night time 56.4% (mean episodes 2.7). The mean number of minutes of restorative time per observation was 24.3 minutes (SD 17.2) and a mean number of episodes of restorative time per observation of 2.3 (SD 1.51).

7.5 Discussion

This study of noise sources in one intensive care unit benefited from concurrent continuous SPL measurement alongside the identification of sources of noise using a bespoke 'Sound in Time' methodology. The study was equally representative of the four bed spaces, each of hour of the day and each day of the week; data was collected over an extended period of time; one month, which enabled a broad representation of the sound environment. Sound pressure levels were similar to those recorded in study two, suggesting they were representative of the sound environment in the GICU. Data collection was prospective, this enabled accurate identification of the sources of noise; the datasheet was developed from an established method of collecting information over a period of time. Furthermore, noise behaviour in urban studies can be described using five descriptors, interval (between sound sources), frequency (number of occurrences in a given time), duration (length of time), perceived loudness and location[210]. The design and application of the 'Sound in Time' data collection tool, enabled some but not all of this data collection, interval was collected, but not if multiple occurrences appeared within a minute, the duration was not measured. A

perceived loudness scale was applied retrospectively to indicate which sources may have most influenced the sound pressure levels. Although the location of sound was reported on the 'Sound in Time' datasheet, it is difficult to know the proportion of episodes that were generated at the observed bed space rather than at another bed space or another area within the unit. For one data collector, in such a noise rich environment to collect all this data contemporaneously, would not be possible. A formal process to ensure rigour or trustworthiness[211] was not formally followed during the development of the 'Sound in Time' datasheet, bias was introduced as tool development, data collection and analysis were completed by one individual with little external input.

Many previous sound studies report sources of sound[60-62,64,68,70,71,73,77,79,82,85,86,88,89], in most cases this was as part of the discussion rather than as part of the study methodology. Three studies[95-97]have investigated noise sources as the primary purpose of the study. Stephens and collegues[95] employed a quality improvement methodology; a survey was completed by staff, relatives and patients to identify factors in the unit that participants felt were particularly noisy. Unfortunately, neither the methodology or the results are described clearly in the report, and although the report provides some useful information, it is clear that this is not a suitable methodology to objectively understand sources of sound in an ICU. The remaining two studies consider noise sources using a structured methodology[96,97] employing different techniques to identify the sources of noise (described in greater detail in section 2.5, chapter 2). The first by Xie and colleagues[96] prospectively identified pre-defined major sources of noise during night time hours (23.30-07.00hrs), using a data collection tool based on the five descriptors commonly utilised in urban acoustic studies as described above. This framework enabled not only the collection of noise sources but also the duration and interval between noises. Xie and colleagues did not measure actual loudness or the

prevalence of sources during the day. The study was limited to major sources identified by the literature which included talk, ventilator alarm, monitor alarm, pump alarm and humidifier. The authors suggested that it is rare for multiple sound sources to occur concurrently, data from the 'Sound in Time' study would suggest this is not the case and is supported by other authors, who described the hospital soundscape as a cacophony of sound[205]. The results leading to this conclusion in Xie and colleagues were likely influenced by the limited number of sources observed or possibly due to the detailed nature of the data collection itself, limiting multiple reporting. While this methodology provided a selected and detailed understanding of these major sources, comparable with urban acoustic studies, it did not enable an understanding of the true soundscape, as the keynote sounds, signals and sound marks[20] may have been excluded. The understanding of a soundscape captures the multi-dimensional relationship between the sound source, the physical environment and the perceptual interaction with the physical sound[21,22].

An alternative method of reporting noise sources which might identify the true soundscape of an intensive care unit was employed by Park and colleagues[97] (described in greater detail in chapter 2). These researchers created a sound recording in a single room of ≈67 hours duration over three days, the room was empty for 11 hours between two patients. To enable actual recording of sound, everyone who entered the room was required to provide informed consent, making this methodology extremely difficult to replicate in a multiple bed bay, for multiple bed spaces or for a prolonged period of time. A weekday 24-hour period of this recording was then analysed retrospectively by a team of six non-clinical research assistants. Six categories were defined these were patient, staff verbal, staff activity, alarms, medical devices and unidentified, these categories contained 28 sources of noise. This methodology enabled a detailed analysis of the frequency,

duration and a range of sound pressure levels for the annotated sources, but was not able to provide detailed information on all the actual sources of noise nor their location, relying on descriptions such as ‘metallic object scrapping’ or ‘paper noise’. Using only one 24-hour recording from a single room limited the accurate depiction of the sound environment as it risked capturing atypical events, especially as the consent process may change individual and team behaviours.

In their study, Park and colleagues[97] identified 27412 separate sources in 24 hours (mean 1142 per hour), compared with the ‘Sound in Time’ study with 16784 over 50 hours of data collection (mean 336 per hour), suggesting that the ‘Sound in Time’ study may have under represented the number of sources. This is possible due to the limitations of prospective data collection by a single observer and the design of the methodology, which only recorded an individual source once per minute, even when it occurred more than once per minute. Reviewing the datasheets, the first 25 observations resulted in 8163 sources of sound, whereas the second set of 25 resulted in 8621 sources, this may suggest that over time annotation of multiple sources improved. It is also possible that retrospective analysis, as completed by Park and colleagues[97], may over represent sources by attributing sounds inaccurately.

To improve validity of source recognition, location and duration, future study might employ several methods including a structured data collection tool combining a broad representation of noise sources as represented in the ‘Sound in Time’ tool, with descriptors such as those utilised by Xie and collegues[96]. This would require more than one observer at one time, each observing for a specific selection of sources. To ensure greater accuracy and definition of sound sources, combining prospective and retrospective analysis of the observation period may prove an effective study design. It would appear appropriate to measure actual SPL rather

than relying on perceived loudness. This study demonstrates the impact of ingress of sound sources from locations other than the observed bed space. Any sound is of course important to the overall sound environment for the patient and therefore is important to measure. This therefore requires either an actual measure of SPL for each sound generated and reported and/or a rating for perceived loudness that includes some calculation for distance from the source to the receiver of the sound. This in turn may also then require accurate representation of the initial location of the sound source. An alternative future direction might employ machine learning. The devices utilised for SPL measurement in this study were limited in their sampling capacity. Therefore, combining more advanced sampling devices with algorithms to analyse this data with built from human observations, may enable more accurate assessment of sources and their impact on the sound environment.

The results from the 'Sound in Time' study, identified that from the five categories described a priori, 'communication' was the most prevalent category during the day; the night demonstrated a more even distribution of categories with 'alarms' being the most prevalent. The analysis of perceived loudness, suggests that ingress of sound sources from other bed spaces and areas of the unit, may impact the sound environment, with more dominant sounds impacting the soundscape. Several studies highlight communication as a source of noise in the ICU, most commonly described as staff conversation[60,61,64,68,71,73,75,77,82,85,88,89,95-97] but also described as loud voices[61,71,79], clinical rounds, shift change or visiting[85]. Alarms are also widely mentioned[61,62,97], usually described by the piece of equipment they relate to i.e. ventilator[60,70,71,73,77,79,82,85,86,89,96], monitor[60,61,68,70,71,77,72,85,86,88,89,96], intravenous pumps[60,61,68,70,71,73,77,79,85,88,95,96], patient bed[77,], mattress[71] and humidifier[95,96]. The results from the 'Sound in Time' study is consistent with previous findings but provides greater detail of the source and therefore clarity into which sources are most amenable to modification. The most prevalent individual

source of noise was nurse/nurse communication, this held true for both day and night time. Although nursing staff are usually the largest professional group in an ICU, as above, many studies identify staff conversation or staff talking as a common source of noise[60,61,64,68,71,73,75,77,82,85,88,89,95,-97], however none refer to a specific staff group such a nurses being a particular source of noise. Two studies do however highlight greater noise during nurse shift change[86] and at the nursing station[68]. The next most common source for the 24-hour period and day was 'other noise', a collection of unconnected sources including keys being dropped, curtains being pulled, the shredder, intermittent pneumatic compression devices, clicking pens, the doppler and the air conditioning units. Two studies identify items falling on the floor[61,97] as a source of noise, but the majority do not identify sources at such a detailed level. During the night, the second most common source was the mattress alarm/pump, similarly there is only one non-quantifiable comparison contained in the current literature[71]. Of the 55 potential sources of noise, 31 provide the top 25 for both day and night, accounting for 85.6% of the total noise sources over the 24-hour period. This demonstrates consistency in the actual sources of the noise, but some variability in their prevalence at different times of the day. It also provides a manageable and ranked list of sources which might be modifiable.

In comparing day with night time sources there appears to be a pattern. Day time sources are more commonly communication related, including staff groups such as doctors and therapists or relatives who may not be present or so prevalent at night, whereas nurses are a common presence for patients over the 24-hour period. At night, sounds like the mattress alarm/pump, oxygen flow, drawers slamming and keyboard sounds and alarms increase in importance, presumably because they are more perceptible at night. This was particularly noticeable with the mattress alarm/pump noise source, which is ranked 22 during the day and 2

at night. It made up only 1.45% of the sound sources and occurred in 8.48% minutes observed in the day time, but at night it resulted in 7.92% of the total sources and occurred in 40.1% of the observed night time minutes. It is also possible to suggest from the data that staff attempt to work more quietly at night, as sounds such as sink/taps, bin lids and footsteps reduced at night, as did nurse/nurse communication despite retaining the number one ranking.

In the unit studied, the nursing staff numbers do not change at night and there is no evidence to believe alarm parameters may be set more tightly during this time period. Given that these sounds become more apparent at night, it is likely that the alarm level is not reduced. The literature would suggest that alarm management is generally poor and requires a behavioural change response[119]. Many studies have identified that technology is sufficiently advanced to modify alarm triggers or algorithms without reducing patient safety [115,124,134-141], however this may conflict with commercial incentives, with companies marketing alarm management programmes[212] alongside developing advanced alarm systems[213, 214]. It is possible that in the near future alarm systems may be non-acoustic and worn by the nurse responsible for the patient[214,215], however in the meantime the excessive noise levels caused by alarms need to be managed by technical and clinical staff working collaboratively to ensure alarm severity, alarm limits and alarms levels are appropriately set for each patient, on each shift.

Bin lids closing, unrolling of aprons and the sounds associated with handwashing feature prominently during the 24-hour period; these are all easily modifiable[64,95,97]. It is also possible that by planning and changing routine, some communication could take place away from the patient[64]. To enable these changes to occur, the first step is to highlight the level of noise, the noise sources and impact of noise on patients and staff, this alone may reduce noise levels[61,72], however behavioural

campaigns have yet to be proven sustainable and may only reduce maximum noise levels[81,184,185]. To reduce noise levels further it is incumbent on regulators and estates departments to build units that are acoustically competent[72,107,114], that allow staff to provide care to this vulnerable group of patients and patients to receive care without the potential harms noise annoyance may bring[216]. Strategies that may improve the sound environment for the patient such as music[196--198], simple measure such as ear plugs[177-183] and sound masking[72,217,218] should be employed wherever possible.

The four periods of observation provide an illustration of sound pressure levels and noise sources at different bed spaces at different times of the day. Observation 3 at bed space 5 in the evening, demonstrated an average L_{Aeq1hr} of 60.1dB for this bed space. There were however greater sound sources than average, 394 compared with an average of 351 for day time measurement. During this time a visitor spoke to the patient for 45 of the 60 minutes observed, at one-point shouting to another visitor (L_{Amax} 85.6dB) so the patient could be located. The noise level of the shout was comparable to the noise level of the helicopter landing (L_{Amax} 83.9dB), although the duration shorter. Analysis of the sound environment using the statistical parameters provided greater detail about the sound content for each peak, this enables a better understanding of the potential impact on the patient or other receiver of the sound. Sound peaks for the one-hour periods of observation that appear similar, when compared using the statistical parameters demonstrate quite different patterns of sound and therefore possibly impact on the patient or other receiver of the sound. This work may also identify and provide evidence of the most disturbing sounds, such as the alarms, all of which are modifiable, however currently considered a means of providing safe care. To argue that in doing this they may also be causing harm, it is important to

understand their level of disturbance in order to develop studies to find alternatives or to provide direct evidence of harm.

Analysis of perceived loudness demonstrated no correlation between the number of episodes nor the numeric ratings described as dominant and sound pressure levels. This suggests that numbers of episodes as measured in the 'Sound in Time' study or applying the perceived loudness scale, provided an adequate measure of perceived loudness at the patients' head and that the explanation of the acoustic environment is more complex than these simple temporal and spatial descriptors can provide.

Observation 18 at bed space 3 demonstrates the impact of noise ingress in an open bay at night. The L_{Aeq1hr} over the period of the observation is lower than the average for the bed space, however two periods of increased noise are observed, consistent with increased episodes of noise (n=353), when the average at night is 304. The first when a patient is admitted to a bed space (7) on the far side of the unit, noise increases for approximately four minutes ranging from L_{Amax} 81.8 - 84.4dB as the number of attending staff at the bed space increase due to increased communication and alarms as equipment is set up and attached to the patient. It is likely sleep is disturbed for all patients in the open unit and is perhaps an argument for critically ill patients to be cared for in single or two beds rooms where SPL tends to be lower[63,67,72,86,91,92] than in multiple bed bays, restorative time is increased[92] and there are less episodes of noise[96]. The second increase occurs when staff use the wash hand basin facilities located at the foot of the observed bed space L_{Amax}75.1-76.6dB for the four minutes while staff are using this basin. Either side of this second increase, the patient experiences two seven-minute restorative periods, suggesting these periods of noise may impact this patients' sleep. Various sleep studies suggest that environmental noise is not the key

reason for patients' poor sleep in an ICU[62,63,164], restorative periods[67,77,97] may partly explain the phenomenon that patients appear to sleep, albeit poor quality sleep[63,158,159,163,164], while noise levels exceed the commonly recognised 40dB guidance[16,41-43]. Observation 40 was at bed space 9 during the daytime, L_{Aeq1hr}64.8dB consistent with this bed spaces average, the number of episodes of noise (n=350) was also consistent with average daytime. Again, the majority of episodes of noise originated from elsewhere in the ICU. The observation took place during the mid-afternoon visiting period. Despite the SPL being greater than recommended, there was one 27-minute restorative period. The converse of these two observations is shown in observation 30, in the side room, bed space 11. During the hour observation, the patient's condition deteriorates, requiring initially a new treatment, non -invasive ventilation, alongside some diagnostic tests. Later in the hour, as this patient has not responded to the new treatment, increasing numbers of staff are required to stabilise the patient deterioration. During this observation, the noise levels are above the average for this room at L_{Aeq1hr}69.8dB, with a high number of episodes of sound (n=384) recorded, with $L_{Amax1hr}$81.4dB and peaking at $L_{Amax1min}$94.9dB. Unlike the previous observation, this noise was consistent with the patient clinical needs, being in a side room this is less likely to have been intrusive to other patients. Much of the noise level may be to do with the room acoustics, which are thought to be poor, due to this bed space recording the highest average SPL for the period of the study. The mean number of episodes per observations was lowest for this side room, however the mean number of dominant sources was similar to the other bed spaces, providing a higher than average percentage of dominant sound sources. This is likely due to less sound ingress from other bed spaces, it is also likely that in a more modern room[54], with well-designed room acoustics[216] the overall noise levels would be reduced, although this may then result in higher annoyance or disturbance for the patient, as background sound is reduced.

This data was not able to demonstrate restorative periods using either Ryherd and colleagues[67] or Tegnestedt and colleagues[77] definitions, however using the adapted Park and colleague's definition, day time restorative periods totalled 34.4% and night time, 56.4%. Park and colleagues[97] however define night time as 21.00- 07.00hrs, therefore to compare results our data need to be re-calculated. This would suggest our data has a different distribution of restorative periods, with day time accounting for 35.4% of periods and night time 50.5% compared with 14% daytime and 46.2% night time restorative periods in Park and colleagues[97] assuming the calculations are similar to those in the comparison literature. A recent study[174] has demonstrated that an increased number of restorative periods per hour is positively correlated with sleep quality. This study utilised L_{90} as the background sound levels and loudness peaks were expressed in units of sone, which is an alternative loudness scale to phon. Sleep quality was self-assessed using the Richards Campbell Sleep Questionnaire. It is important that future study of restorative periods utilise a measure of perceived loudness, in addition to traditional measures of SPL which provide a measure of intensity. The frequency of a sound is very likely to impact sleep quality and quantity as much as the intensity of the sound.

7.6 Conclusion

Communication is the greatest source of noise during the day and alarms are more prominent at night; this is likely due to a reduction in numbers of staff and visitors, such that the alarms that have likely been sounding similarly during the day, are more noticeable at night. Current SPL guidance appears unachievable without a change in ambient sound levels. This research describes in detail the sources of sound; this level of detail appears unique, although far from complete. Understanding the sources of sound at this level of detail and with accompanying SPL data, enables us to consider where any improvements might be achieved. It

is certain that noise levels can be reduced by improving the design and acoustic absorption of the built environment, re-designing the bed space to remove noise sources from the head end, re-engineering the way staff work in an ICU to remove unnecessary communication and noise from the bedside and investing in technical solutions to enable intelligent alarm triggering in order to reduce false alarms and therefore alarm fatigue. To understand the soundscape, however it is necessary to understand an individual's perception as well as the actual sources of sound and the sound pressure levels. Future studies need to include patient, visitor and staff perception of noise in order to achieve the most acceptable environment in which to provide care and to be cared for. A pilot study is described in chapter 8 which considers the perceptions of patients, staff and visitors to the noise in the general intensive care unit.

Chapter Eight

Study Four: Perceptions

8.1 Aim

To understand patient, visitor and nursing staff perception of the GICU soundscape.

8.2 Introduction

Previous studies described in earlier chapters have developed and piloted a means of measuring distributed sound using the NPL-Minim in an indoor environment, identified the sound pressure levels over an 11-week period and the sources of sound during 50hrs of observational study at four beds spaces in one intensive care unit. SPL and source data were analysed in detail using statistical parameters to describe more fully the noise environment at each bed space during four illustrative one-hour observation periods. These enabled greater understanding of the sound environment but do not fully describe the soundscape of an intensive care unit. To achieve this, it is necessary to understand an individual's perception of the sounds they hear, this information will provide insight into the most acceptable environment in which to provide care and to be cared for. This pilot study was designed to identify the keynote sounds, signals and sound marks required to develop individual descriptors of the sound environment of the GICU for use in a later sound scaping study.

8.3 Methods

8.3.1 Study Setting

The study was set in an 18-bedded adult, general intensive care unit (GICU) as described in chapter 4. Data was collected from patients, visitors and staff all bed spaces, with the exception of bed space 1, the second side room.

8.3.2 Ethical Approval

Ethical approval was granted by the Office for Research Ethics Committees Northern Ireland REC reference:15/NI/0106 IRAS project ID:128446 on the 2nd June 2015. Due to delay in collecting this data several extensions were granted (Appendix 1 - Letters dated 2nd June 2015, 8th June 2015, 24th February 2017, 23rd May 2017, 4th January 2018, 11th April 2018). Patient Information Sheets were offered and the study discussed with all potential participants, with consent forms completed for those who agreed to participate (Appendix 7). The data was collected manually using a sound diary developed specifically for this study. The completed diaries were stored securely in a locked office. Data was transcribed into Excel and stored on a password protected PC at St George's University Hospitals NHS Foundation Trust.

8.3.3 Participants

10 each of patients, visitors and GICU nursing staff (4x Band 5; 4x Band 6; 2x Band 7 nurses) meeting the following criteria.

Inclusion criteria:

- Patients requiring ICU for ≥48hrs
- Patients able to answer questions
- Aged ≥18

Exclusion criteria:

- Patients being palliated
- Patients with learning difficulties
- Patients lacking capacity
- Patients, visitors and staff with hearing loss

The intention of this pilot study was to collect a set of base line data, it is expected that excluded groups will be included in the larger study, this may require further pilot work.

8.3.4 Data Collection

Data was collected over two main time periods July to October 2015 and then February 2017 to December 2018. Unfortunately, having commenced data collection, the researcher was moved to work in another Trust, on her return there was very little time available for data collection due to the added workload of a second site and therefore the collection of this data was both fragmented and protracted. As the four NPL-Minim had stopped collecting data by the 23rd September 2015, sound pressure level measurements were not available from this time point onwards**.** Case mix data is presented in table 4.2 in chapter 4 which demonstrates a subtle decrease in acuity during 2017 and 2018, which would not have impacted the selection of patients for this study but may have impacted the sound environment during these latter years. As sound pressure levels were not available after 2015 it is not possible to identify if there was an actual change in these levels.

Informants were asked to keep a structured sound diary (Appendix 8); on 2-3 occasions each day for 2-3 days (to achieve six diary entries per informant). Some patients required support to record this data, this was provided by the nurse caring for them at the time of the data collection or their visitors, and consisted of the nurse or visitor transcribing the patient's verbal responses. On no occasion were both a visitor and a patient consented to complete a diary. The following data was collected:

- *Their identity (i.e. staff including grade, patient, visitor)
- *Age
- *Gender
- The date and time
- Location in the unit (identified by bed space)
- What can you hear?
- How does this sound make you feel?
- Describe the most reassuring/annoying /frightening sound you have heard today

*on the first occasion only

To ensure the patient was not delirious at the time of a data entry, prior to recording an entry, the study patient's CAM-ICU assessment[219] was recorded and an entry included only if the patient was CAM-ICU negative. Likewise, prior to an entry being recorded, patients were asked to rate their pain using a visual analogue scale, any analgesia or sedation received by the patient in the previous four hours was also recorded.

8.3.5 Data analysis

Diary data for the subjective questions, '*What can you hear?'; How does this sound make you feel?'* and *'Describe the most reassuring/annoying /frightening sound you have heard today?'* were analysed using content analysis. The purpose of the analysis was to review the data thematically to identify common words and phrases that may characterise the keynote sounds, signals and sound marks of an intensive care unit from the perspective of three groups of informants. The data will therefore be analysed separately for each participant group. The choice of data collection affects the depth of the analysis, therefore the methodological choice of diaries utilising open ended questioning would not provide the depth that may be possible with interview data, but for the purposes of this study was thought to be most appropriate. Firstly, informants could record their diaries in real time, when a particular sound motivated the participant to record data and secondly when for varying reasons taking time away from the bed space was not desirable due to limited time (nursing staff), limited ability (patients) or a reluctance to leave the bed space (visitors) in order to participate in an interview.

Early definitions of content analysis identified this approach as '*a research technique for the objective, systematic and quantitative description of the manifest content of communication*'[220], however over time this technique has moved away from the quantitative and is use commonly to describe qualitative data, thus a more recent definition is '*a research technique for making replicable and valid inferences from texts (or other meaningful matter) to the contexts of their use'* [221]. Thus, contemporary content analysis describes a family of analytic approaches ranging from systematic to impressionistic[222]. Analysis may be quantitative i.e. facts from the text are expressed as a frequency or qualitative, where data is expressed in words or themes, which requires a degree of interpretation[223]. The process of analysis reduces the volume of text, identifies and groups categories

together to achieve an understanding of the data[223]. Data is systematically read using deductive or inductive reasoning, and codes assigned to indicate meaningful content. An inductive approach to coding is one where patterns emerge and codes are derived directly from the data or data drive[224] and deductive coding is based on known themes, derived from theory, also known as concept driven[225]. Analysis may then be either manifest which describes what the informants actually say, or latent, which seeks to find the underlying meaning and is therefore interpretative[223,2226]. Ideally two researchers should analyse the texts and discuss their results to obtain consensus, this and 'staying true' to the text helps to achieve trustworthiness[223]. The more interpretative the analysis, the more complex trustworthiness becomes.

As this was a pilot study with limited data, the method of analysis chosen was relatively simple. Data were transcribed in an Excel spreadsheet (Appendix 9) under the headings as in the diary i.e. 'What can you hear?'; 'How does this sound make you feel?' and 'Describe the most reassuring/annoying /frightening sound you have heard today'. The raw data for the question 'What can you hear?' was transcribed into word clouds and therefore 'stays true' to the text. Subsequently, in order to provide a quantitative level of analysis, for each informant group and question, common words and phrases were highlighted and counted numerically. As each group provided very different quantities of data, with the richest data coming from visitors and then nursing staff, this is presented in the results as a percentage. Quotes are used to further illustrate the informant's responses and provide a degree of interpretation of that text.

8.4 Results

Thirty-one individuals consented to complete a diary of which 29 were completed by patients (n=8), visitors (n=11) and staff (n=10; 4x band 5, 4x band 6 and 2x band 7 nurses). Two visitors (1& 3) did not return their diaries. Patient diaries in total contained 26 entries, visitor diaries 79 entries and nursing staff 56 entries. Entries varied in size and detail.

8.4.1 Patients

Patients reported hearing a variety of sounds but most commonly identified sound related to conversation such as voices staff, patients, talking, nurses and their nurse (28.9%) of entries or the background noises of the machinery such as the alarms (10.5%), monitors (7.9%) and the air pump on the mattress (10.5%); banging sounds accounted for 7.9% of entries. See figure 8.1-word cloud.

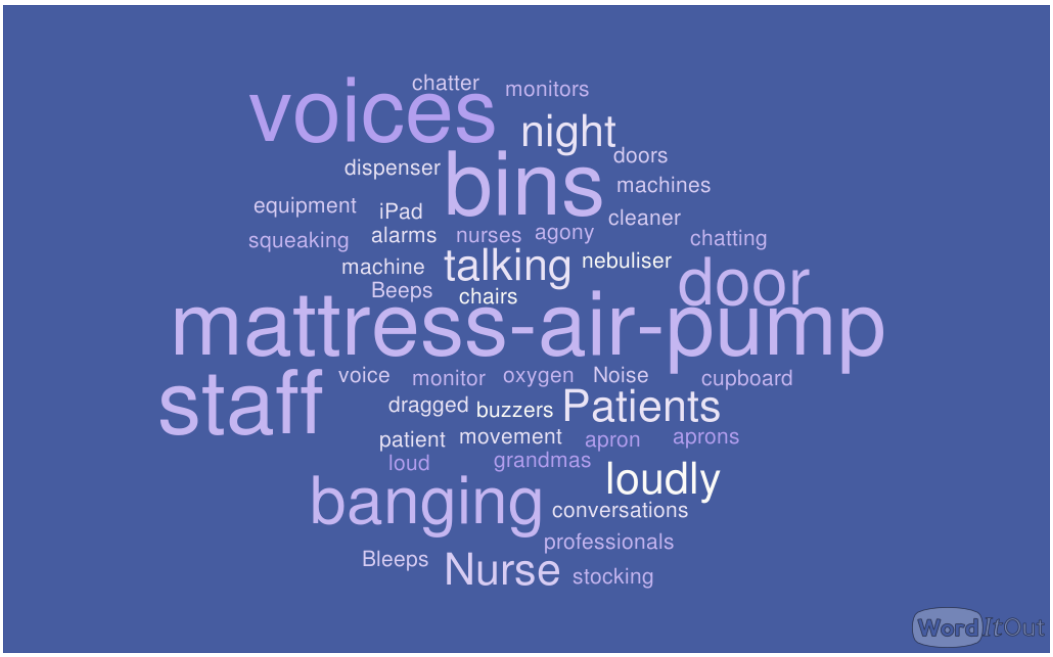


Fig 8.1 Patient word cloud – 'What can you hear?' (Word Clouds were developed using the raw data pre analysis)

In answer to 'How does this sound make you feel?', patients reported in 25% of entries that they were '*OK*' or '*unaffected*' by the sounds they could hear. Words such as '*irritable*', '*frightened*' and '*annoyed*' were used each in 6.25% of entries, as were phrases such as '*woke me up'* and phrases suggesting the patients were unsettled by the noise '*sometimes I wonder if the beeps are coming from my bed space or not'* Patient 1 and '*wondering what they are going to do to me'* Patient 1. The sound was generally acceptable to patients when it was seen to be necessary, quiet and reassuring and described as '*OK'* Patient 4, or '*not affected'* Patient 6, with one patient saying they felt '*reassured, confident, cared for'* Patient 2. However, if the noise was not seen to be necessary or was seen to be excessive then patients described this noise as '*not pleasant, not nice'* Patient 3,' *it makes you jumpy'*, *'unsettled'* Patient 7 or feeling '*irritable*' Patient 4. If the noise was at night, such as when the cleaner moved chairs and emptied bins '*annoyed, trying to sleep'* Patient 4 or when a fire exit door by a patient's bed was used multiple times in the night and banged shut '*It woke me up and frightened me'* Patient 1.

Patients were overwhelmingly reassured by nurses being there or a professional voice of reassurance (59.3%), this was expressed as '*The voice of the nurse asking if I am OK'* Patient 5; '*nurse doing obs'* Patient 7 or words of encouragement '*nurses encouragement using new CPAP*' Patient 6. Patients were also reassured by family presence (14.8%) '*the voice of my mother*' Patient 5 and '*my wife'* Patient 8 and a quiet environment (7.4%) as this suggested nothing was going wrong *'When it's really silent on the ward and I know everything is OK'* Patient 1. Some patients suggested that no sound was annoying (20%); where sound was reported as annoying, these sounds were frequently related to equipment especially bin lids (8%-Patients 1 & 4), the apron dispenser (12% -Patients 1, 7 & 8), the equipment generally *'the noise from the machines I am attached to'* Patient 5; one particular

alarm '*A machine that goes da, da, da, la ,la'* [humidifier] (Patient 3) and loud conversation (12%) including '*too many people talking at once, over each other'* Patient 7. Noises that were perceived as frightening were most frequently associated with a patient in distress (29.2%) '*Patient screaming'* Patient 4; '*at night-time when I can hear a patient crying'* Patient 5 or both loud and sudden (16.7%), *'I have heard one or two bangs, which makes me have flash backs'* Patient 3; '*the sound of the* [fire] *exit door being banged, it wakes me when I am sleeping'* Patient 1.In this category 41.6% patient suggested nothing was frightening.

8.4.2 Visitors

Visitors commonly described three main sounds; alarms (24.8%), staff talking (22.9%) and machinery (11.5%), patient noise, a background 'hum' and music/radio each were 5% of the entries. See figure 8.2-word cloud.

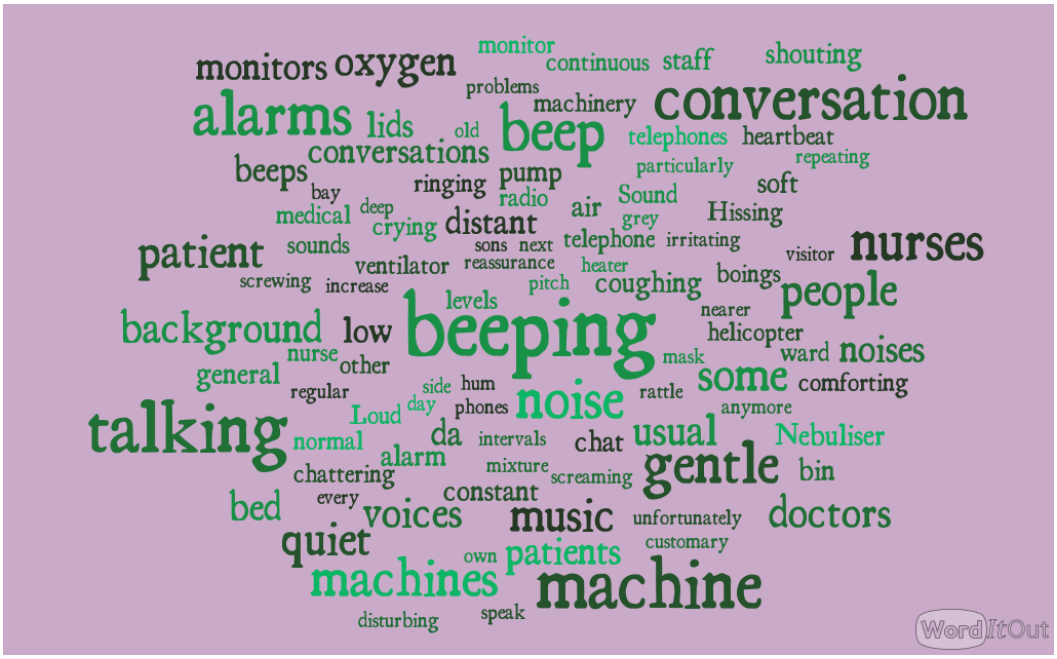


Fig 8.2 Visitor word cloud – 'What can you hear?' (Word Clouds were developed using the raw data pre analysis)

Visitors would frequently describe the sounds they could hear using an adjective such as '*normal*' '*usual*', '*gentle*' '*fine*' or *'comforting*' (Visitors 2, 5, 9, 11 & 13) for machinery sound; '*the normal sounds of the ICU -these are not particularly threatening or disturbing most of the time'* Visitor 11. Nurses' voices or talking as '*reassuring*' *'comforting'* or '*calm*' (Visitors 2, 4, 7, 8 &12) for example '*lovely chat and reassurance from nurses'* Visitor 7. Visitors also remarked that they became familiar with the 'usual' sounds; *'usual mixture -fast becoming familiar unfortunately'* Visitor 11 and *'have a familiarity -which wasn't the case initially'* Visitor 7. Visitors suggested that they were 'OK' (25.6%) and used a wide range of positive verbs such as *'reassured'* (12.2%), '*calm*' (11.2%), '*comfortable'* (5.1%) or '*settled*' (2.1%) when hearing these sounds. Several visitors suggested that the familiar sounds of machinery provided a level of reassurance that their loved one was being cared for well '*whilst this could be worrying also positive as nurses know and respond quickly*' Visitor 9 and '*a good level of background noise, whilst not being disruptive, was very calming, actually makes me feel peaceful*'. Visitors also described the sounds, often the same sounds, in a less positive way, again using many different verbs *'irritable'* (8.2%), *'worried'* (6.1%), '*annoyed*' (4.1%), '*disturbing*' (3.1%), '*scared*' and '*anxious*' (2.1% each), for example '*beeps unsettling to me today'* Visitor 7 and '*invasive in my head'* Visitor 6.

Visitors were commonly reassured as described above by the nurses' or doctors' voices (41%), more specifically they were reassured by the *'nurses answers to questions and comments*' Visitor 7, the '*background chatter from doctor/nurses, I am reassured that there are people around to help if needed'* Visitor 8 and '*being told by* [consultant's name] *that this is a good trajectory'* Visitor 7. Visitors were also reassured by their loved one's voices (17.9%) *'Husband weakly being able to say a word to me'* Visitor 9, '*my sons voice'* Visitor 10, '*recognition in my father's voice of the fact that he knew we were here and had brought the dog'* Visitor 11

and equipment sound (12.8%) '*the relaxing sound of my sons restful breathing with the nebuliser attached'* Visitor 6, '*probably the hissing* [oxygen] *noise, was fairly calming -also on this occasion, the beeping noise too'* Visitor 8, *'Heart monitor, it's very soothing'* Visitor 10, but also by an absence of distressing sounds (16.4%) '*a lack of sounds- no particular alarming sounds over the period of the day*' Visitor 11. One visitor described quiet background music as reassuring '*I like the idea of gentle music. Currently there is Smooth radio which is probably ideal*' Visitor 12. Many visitors stated there were no annoying (42.1%) or frightening (58.8%) sounds. Of those describing annoying sounds, these were most likely the alarms (23.7%) *'the one that makes the da da da di da noise'* [humidifier] Visitor 11*, 'a high pitched alarm going on for ages*' Visitor 10 or sudden, loud noise (7.9%) such as 'doors banging' Visitor 4, '*a loud bang at one point- something fell/dropped elsewhere'* Visitor 7 and or the sound of the oxygen (7.9%) and for one relative the background sound of a radio playing *'there was some quiet music playing somewhere and for some reason I did find that a little annoying'* Visitor 6. There were fewer frightening sounds described, where they were the vast majority related to patients perceived to be in distress either from human sound (14.7%) or alarms (14.7%) being triggered '*the old gentleman's screams and* [patients name] *alarm'* Visitor 6, '*a gargling/choking sound at another bed'* Visitor 7, '*alarms from other patients'* Visitor 8, *'bit of noise as he* [patient] *breathes, I've not heard before'* Visitor 9, *'my sons heart monitor sounded an alarm which was a very frightening moment'* Visitor 13*.* Other frightening sounds came from loud, unexpected noises such as '*the fire alarm'* Visitor 9 and the helicopter landing *'helicopter landing - became very loud very suddenly'*, the landing pad being on the roof of the same block as the GICU. One visitor made a comment about certain sounds being mistaken for noises that may have been associated with the reason for admission '*one of the alarms is very similar to the warning sound when a car door is left open*

or a seat belt not attached -this may be disturbing for patients who have been in an RTA [Road Traffic Accident]' Visitor 11.

8.4.3 Nurses

In recording what they could hear, nurses specifically identified the sources and locations of sound such as conversation from doctors and other nurses (22.9%) '*doctors talking very loudly at nursing station'* Nurse B5-1, *'Doctors speaking at the main desk'* Nurse B6-1 and 'staff voices from bed spaces surrounding bed 2' Nurse B6-2. They also identified conversation as work or non-work related, *'four nurses talking about nurse related issues, two family members talking to their relative* [patient], *monitor alarming, two doctors talking (work related) at main desk*' Nurse B5-2. Similarly, they highlighted alarms (28%) identifying the individual pieces of equipment '*the monitors of bed 4 beeping'* Nurse B6-1 and '*beeping IV pump*' Nurse B5-1. Noise from the gaseous sources (12.1%) were also regularly highlighted '*the Optiflow of bed 2*', Nurse B6-1 '*the hiss of a nebuliser in the next bed space*' Nurse B5-3, as was the telephone '*telephones ringing'* Nurse B7-1 and patient noise (5.1% each) *'patient coughing'* Nurse B6-4. See figure 8.3 - word cloud.

Fig 8.3 Nurse word cloud – 'What can you hear?' (Word Clouds were developed using the raw data pre analysis)

Nurses were also very specific in describing how the noise made them feel '*irritable'* (10.1%), '*annoyed*' (13%), one nurse commenting on doctors speaking loudly at the desk at night reported she was '*annoyed as keeping patients awake'* Nurse B5-1. The act of being asked to complete a diary appeared to make the nurses consider the noise being '*loud*' (13%) and to describe the noise in relation to patient welfare '*I feel that there is a possibility that this may be too noisy for unwell patients. However, the noise is due to work related patient care'* Nurse B5-2, '*didn't notice aprons, trays and packets until I listened for it, however feed pump and pump alarms very loud and annoying'* Nurse B5-4. Another nurse reports frustration when they can hear a monitor alarm in a bed space where staff are present '*why does the nurse behind the curtains not do something about the alarm – frustrated'* Nurse B6-3 or a senior nurse who is '*irritated especially as I see the nurse pressing the mute button and not resolving the problem*' Nurse B7-1. Nurses, like the visitors reported being *'reassured'* or '*OK*' (7.2% each) by the sound.

Nurses are reassured by similar sounds to visitors and patients. They highlight communication between nurses, patients and visitors (25.9%) '*sound of* [a] *nurses voice reassuring a patient when they were frightened'* Nurse B5-2 '*hearing conversation between a nursing colleague, the patient and his relatives at the bed space next to my patient, everyone sounded happy'* Nurse B5-3 and relatives talking with a patient (11.1%) '*relatives talking to a loved one'* Nurse B6-3 .They also describe as do visitors, the background sounds in the unit, such as airflow (18.5%) as reassuring *'airflow through the ventilator is calming*' Nurse B5-1, the *'optiflow noise is very relaxing'* Nurse B6-1 and one nurse the return of a '*regular heart rhythm on* [the] *monitor post cardiac arrest'* Nurse B6-3, as well as a perceived lack of noise (7.4%) '*sound of silence'* Nurse B5-4. Nurses are generally annoyed by the noise related to the equipment alarms (57.7%) '*IV pump'* (Nurses B5-1, B5-3 & B7-1), '*feeding pump'* (Nurses B5-4, B6-2, B7-1) and in particular alarms not being dealt with in a timely manner (Nurses B5-1, B5-2, B6-3, B6-4). They also highlight where noise impacts on their care '*the hissing of the Optiflow was very annoying, it is constant and very close to the patient and myself. I struggled to hear my patients voice over this noise and felt that I had to speak louder to be heard by the patient'* Nurse B5-3 and numerous loud voices (19.2%) '*raised voices -doctors, MDT, not aggressively just the amount of voices all talking at the same time'* Nurse B6-2. Nurses generally relate frightening sounds to patient related events such as when alarm limits are breeched and the nurse needs to identify the problem as well as mange the impact of the noise (40%) '*monitor alarms -red alarms e.g. on desaturation'* Nurse B5-4, '*asystole alarm of the monitor'* Nurse B6-1 and 'ongoing *ventilator alarms'* nurse B6-4. A senior nurse described patient noise as frightening (28%) '*patient coughing violently'* Nurse B6-3, '*sound of vomiting, could not see who it was'* and a '*patient calling help me*' Nurse B7-1. Several senior nurses identified frightening sounds as sudden, loud

events (20%) similar to those identified by patients '*the sound of filter replacement bag being opened*' and '*the sound of an apron being pulled out from a faulty dispenser'* Nurse B7-2, '*a crash from a bed frame'* Nurse B7-1.

8.4.4 Keynote sounds, signals and sounds marks

It is proposed from the data collected in the study that the keynote sounds, those that typified the space in this study were staff conversation, the mattress pump and gaseous sounds such as the high flow oxygen or nebulisers which deliver the background 'hum' of the unit, these latter sounds are perhaps the unconscious sounds of the unit. The signals described as foreground sounds, were the alarms present on all equipment but included the cardiac monitor, the ventilator, the fluid and syringe pumps, as well as patient noise. The sound marks described as culturally important sounds were the beeps of the monitor and the medical bleeps.

8.5 Discussion

The development of structured diary enabled the collection of patient, visitor and nursing staff perceptions of noise in an intensive care unit. In total 29 diaries were completed by patients, visitors and nurses. Data collection was protracted and fragmented, although this did not appear to impact the consistency of the data. Patient diaries contained the least entries per diary and visitors the most. This is unsurprising given the different circumstances of the informants. Patients in the intensive care who were able to complete a diary, remained unwell and often very weak, on some occasions required support from nursing staff or family to complete the diary. Whereas visitors to an intensive care unit, are often visiting for long periods of time without impediment to completing the diary. To enable the patient to understand their stay and illness, patient diaries are now commonly completed by ICU nurses on behalf of the patient, this has been shown to reduce the

symptoms of post-traumatic stress disorder[227] and anxiety and depression[228]. Often visitors, especially close relatives will also make diary entries[229] A study where relatives authored the diaries demonstrated that relatives who completed a diary for their loved one, had significantly lower scores for posttraumatic stress, than relatives who had not completed a diary[230]. This suggests that visitors completing the sound diaries may have found this beneficial, this possibility and the time available, may have encouraged them to enter data. Nurses also provided more entries than patients, although less than visitors. Nurses may not recognise the level of noise in an ICU[153,231] and may even over estimate how noisy it is[87]. Many of the nurses in this study either stated in the diary or verbally how this activity had raised their awareness of noise in the ICU, this may also have encouraged them to complete the diary. Interestingly, the entries by nurses suggested a level of judgement on their colleague's actions, when their perception was of unnecessary noise from conversation or a delay in managing an alarm. Developing interventions that target perception and recognition of the actual noise levels, may reduce unnecessary noise by staff and develop a wider understanding of the problem[87,232]. However, as previously highlighted, studies in ICU that have utilised behavioural interventions to reduce noise however have not demonstrated sustainability[60,64,81,82].

Patients, visitors and nursing staff identified similar but not identical noise sources, all reported staff conversation as a common source of noise; for patients this was the most frequently highlighted, this is totally in accord with the literature, which highlights staff conversation as one of the most common sources of noise alongside equipment and alarms[60,61,64,68,71,73,75,77,82,85,88,89,95-97]. Visitors and staff reported beeps and alarms as the most frequent source of noise, this is consistent with previous reports, whereas patients appear to be more tolerant of alarms than other groups[233]. Visitors and patients reported equipment noise more commonly

than staff. These two differing reports may represent similar sounds, just perceived in a different way, many of which are suitable for modification such as the monitor alarms[61,62,564,68,70,71,73,77,79,82,85,86,88,96,233]. Staff reported gaseous sounds from oxygen and nebulisers more frequently than either visitors or patients, whereas patients frequently reported the noise of the mattress air pump. Visitors diarised comments about the 'hum' of the unit, it is possible that this reflects their description of oxygen devices. This difference may be due to staff having greater recognition of the sources of sound than either the patients or visitors, however for the mattress pump, this awareness was most likely due to the patient's proximity to this device. Visitors and nursing staff highlighted 'other patient noise' more commonly than patient report, for all groups this was highlighted as a frightening sound.

Patients reported sounds as generally acceptable if considered necessary and is consistent with previous study[31], but sounds became frightening or annoying if deemed unnecessary. Sounds in the night and noise emanating from other patients, especially if these were sounds of distress, were identified as frightening, which is consistent with previous patient reports[68,73]. Several patients reported being frightened by hearing a loud, unexpected noise, such as a door banging; for one patient this caused flashbacks. One visitor noted that the sound of one alarm was similar to that of a warning sound when a car door is left open. He was particularly concerned about this, as his father had been involved in a road traffic incident, in which his mother had died (Visitor 11). Flashbacks are vivid experiences recalling aspects of a traumatic even, these may be triggered by various stimuli including sensory, such as a noise and may cause the individual to experiences visual images, sensory stimuli, emotional or physical sensations connected to the event. Flashbacks are one of a number of symptoms of post-traumatic stress disorder[234]. Similar to patients and visitors, staff reported sudden

and unexpected noise as frightening, junior nursing staff reported critical alarms as frightening, this is not surprising given the acuity of the patient group cared for in an ICU, reducing false alarms would be desirable for this staff group.

Bin lids and aprons were particularly annoying to patients; loud voices that carried from other bed spaces and a particular humidifier alarm caused annoyance to all groups. Interestingly this is a device that has an melodic alarm, which as suggested by the IEC 60601-1-8[99] may be more distinguishable, however it may also have the unintended consequence of being a greater annoyance to patients, visitors and staff alike. Staff conversation was highlighted as the most frequent source of sound by patients, patients were however, frequently reassured by hearing the nurses and doctors' voices, as they were by equipment noises including alarms. This may suggest that although conversation is a recurrent feature of the soundscape of an intensive care unit, it may not always be an annoyance. This finding is consistent with studies including patients[73,233] and visitors[233], whereas studies in ICU where staff report is the source tend to conclude that patients find staff noise most disturbing[60]. Interestingly a study in a ward setting rather than ICU, found that staff and patients both found voices most annoying[235]. In this study, one nurse described their difficulty conversing with a patient who was receiving high flow oxygen, identifying she had to shout to enable the patient to hear, all informants identified that too many voices or loud voices was annoying. These differences in the reporting of sound suggest that social context is as important as the spatial and temporal features[31]. Older units, such as the one where this study took place, appear to have poorer acoustics and are reported as nosier[24,54]. Several studies report that noise is a factor in work place stress[67,105,106] and improving room acoustics has been shown to improve speech intelligibility and positively impact the work environment[107,108,109]. One proposed solution for mediating the annoyance or fright caused by hospital workplace

sounds, is to use visual soundscape communication to enable users to understand their current situation[205]. This may well benefit visitors and patients who are electively admitted to an ICU but has limitations for the majority of emergency admissions.

8.6 Conclusion

The purpose of this pilot study was to identify potential keynote sounds, signals and sound marks of an intensive care unit, as well as words and phrases that could be used in future study. The sound diary was successful in identifying a range of sounds and descriptors that would form the basis for further study utilising semantic differential or Q Methodology. Patients, nurses and visitors described similar sounds including conversation, equipment noise and alarms however these descriptions were subtly different. Sound although potentially intense as measured by decibels or frequent as measured in the 'Sound in Time' study may be reported as reassuring by patients, visitors and staff alike. There is however much noise in the unit described as annoying and/or frightening. The context of the sound appears to be the main identifier as to whether a sound is described as reassuring, annoying or frightening. This study identifies a distinctive set of sounds created by the activities of work and care that characterise the keynotes sounds, signals and sound marks of an intensive care unit.

Chapter Nine

Discussion

9.1 Introduction

The aim of this PhD thesis was to describe the soundscape of the General Intensive Care Unit at St George's Hospital, London and to investigate the sources of sound contributing to noise. A novel method for sound measurement using the NPL-Minim and MEMS microphones was tested (Study1) and enabled longitudinal, distributed, continuous sound pressure level monitoring at one-minute intervals, using nine acoustical indicators (L_{Aeq}, L_{Ceq}, L_{Amax}, L_5, L_{10}, L_{25}, L_{50}, L_{75}, L_{90}) across four representative bed spaces in the GICU (Study 2). Sources of sound were identified across the four bed spaces using a 'Sound in Time' methodology constructed and piloted specifically for this thesis. Concurrent study enabled analysis of sound pressure levels during these periods of observation to appreciate the relationship between noise levels, the prevalence and sources of sound in the GICU and perceived loudness (Study 3). Lastly, a method of understanding the perception of sound for patients, visitors and staff was successfully piloted. This identified the keynote sounds, signals and sound marks that will support the development of individual descriptors of the acoustic environment in the GICU for use in a later sound scaping study (Study 4). In completing these studies, the majority of the initial hypotheses were supported, with the exception that in the study 2 the sound pressure levels in the multi bed areas were not higher than in the single side room, despite this being the case in the 15 minutes assessment which was undertaken as a part of the preliminary investigations (Study 1a). Interestingly, the hypothesis that SPL would not be significantly different at night compared with day, is not supported statistically, however from a practical perspective, the SPL difference is clinically irrelevant.

This chapter summarises the studies, highlights the strengths and limitations of the studies and identifies future work.

9.2 Synopsis of study results

9.2.1 Preliminary Studies

Studies 1a-c provided the foundations for the subsequent investigations. Study 1a provided an understanding of the environment to be studied, it identified using 'FAST' averaging that 1-minute data capture was appropriate and the statistical parameters required for subsequent study in this environment. It also provided the researcher with in situ education and training to enable the later investigations. Study 1b identified the suitability and stability of the NPL-Minim and MEMS microphones in the indoor environment and piloted a web-based database for data capture and analysis which sadly was not available for study 2. Lastly study 1c identified the impact of the original mounting structure, a light fitting above each of the ICU bed spaces and defined a correction factor to ensure sound recorded was from the perspective of the users of the bed space, i.e. patient, visitors and staff.

9.2.2 Distributed sound measurement

The four bed spaces produced a total 271 days of data collection out of a potential 292 days, this data complements two previous studies[92,98] that measured sound continuously and in multiple bed space for similar periods of time, utilising alternative devices. This study identifies the stability, suitability and discreetness of the NPL-Minim in providing continuous, distributed sound pressure level measurement. The data demonstrated that the GICU was producing an average daytime L_{Aeq} of 66.4dB and night time of 62.9dB, this is higher[24,56,62-65,67,69,71-73,76,77,81,83,85,81,88,91,93,94] or consistent[57-61,66,68,70,75,78,82,84,87,89,90] to previous study and reflects the built environment[54], case mix[85], occupancy[97] and acuity[92] of the

patients cared for within its walls. Each bed space produced a similar pattern of noise over the 24hr period, but each varied in their average SPL with the side room (bed space 11) producing the highest overall average. Sound pressure levels varied little over the days of the week and were consistently above internationally recognised recommendations[16,41-43], even when the bed space was not in use. Many of the variables, night/day, bed spaces, demonstrated statistically significance, although in most cases not practical/clinical significance. The average SPL difference between the individual bed spaces, in all combinations with the exception of bed space 3 and 9, demonstrated both statistical and practical significance. This has potential implications for the patients cared for in these differing environments and requires further exploration. It may be the reality that current recommendations are not achievable in the ICU environment but before these are rejected, future work should explore methods of mitigating louder and annoying sounds and fully understanding which noises are detrimental and which are not. It may be that sound type and quality are more important than noise. There is an urgency to protect this vulnerable group of patients and the staff caring for them, from the potential harms of noise and noise annoyance.

9.2.3 Sound in Time

A data collection tool was developed and piloted, this contained a total of 55 potential noise sources, grouped into five categories: communication, clinical equipment, housekeeping equipment, alarms and miscellaneous. Data were collected as individual sources encountered each minute, referred to as episodes. The duration of any one source within the minute was not reported neither were multiple episodes of noise from the same source within any one minute. The data was collected in fifty, one-hour periods of observation by one researcher, the author. It was important to collect the observational data concurrently with the continuous, distributed, longitudinal data collection. The data was equally

representative of each hour of the day, day of the week and bed space, and collected as close to the patient as possible to ensure that it represented the sound as the patient may hear it. Similar time frames as used in urban acoustic study[35] were utilised, resulting in 34hrs of day time (07.00-23.00hrs) and 16hrs of night time (23.00-07.00hrs) observations. Each of the 55 sources of sound were retrospectively assigned, from the patients' perspective, a level on a perceived loudness scale. To identify potential annoyance, this was compared with the sound pressures levels and the number of episodes of noise for the period of the observation. Unfortunately, due to the delays in the study, the second person trained in data collection was not available to collect the 10% concurrent readings as planned for validation.

Sound pressure levels during the 'Sound in Time' observation periods were similar to the 271days of distributed sound data and the pattern of sound with bed space 5 recording the lowest SPL's and bed space 11 the highest, was also similar. Thus, demonstrating that the observational periods were representative of the sound environment in the GICU. A total of 16784 episodes of sources were recorded over the 50hrs of observation, an average of 336 episodes per observation. Day time observations resulted in a higher average number of episodes (351) than night-time (304). Communication was the most common source of noise during the day, at night the sound of alarms became more important. Analysis of the sources of sound compared with actual sound pressure levels identified a number of themes which could be explored in future study, including the impact of sound contamination from other bed spaces and areas of the unit on the patient. Review of the four individual observation periods illustrated how various noise sources impacted the environment differently. Each of these observations demonstrated several high $L_{Amax1min}$ with short bursts of high energy sound captured by the L_5 measurement, these were caused by alarms, the helicopter, a shout, equipment

preparation, phone ringing and the doorbell. These 'peaks' of noise were on top of high average ($L_{Aeq1min}$ and L_{Aeq1hr}) and background (L_{90}) sound produced by a wide variety of sources occurring concurrently, emanating from the observed and surrounding bed spaces, as well as the staff base. Examination of each of these four illustrative one-hour periods of observation and the sound peaks contained within them utilising the six measured statistical parameters, provided useful data to understand further the potential annoyance or disturbance caused by various peaks of sound.

9.2.4 Restorative periods

The concept of restorative periods was first described by Ryherd and colleagues[67] and the idea adapted by Tegnestedt and colleagues[77] introducing cumulative restorative time. Latterly the idea has been further developed by Park and colleagues[97] who presented the concept of restorative periods being time when the sound pressure levels were less fluctuant relative to the background noise. These periods may explain how patients in the ICU are able to rest, albeit in short bursts, despite sound pressure levels universally being greater than international recommendations for sleep. By substituting L_{Amax} in place of L_{Cpk}, studies 2 and 3 provided data to explore the concept of restorative periods relative to background noise. The data resulting from the distributed sound data identified a potential for 63.3% of the time to be restorative, with a greater proportion of this time being during night time hours. Unfortunately, the size of the dataset and the need to manually analyse the data, precluded calculating how much of this time occurred in periods of ≥five minutes. The 'Sound in Time' dataset being smaller, was amenable to analysis of ≥five minutes restorative periods relative to background, this identified 115 episodes totalling 1215 minutes (41.5%).

9.2.5 Perceptions

This pilot study utilised diary entries from patients, visitors and nursing staff with the aim of characterising the keynote sounds, signals and sound marks of an intensive care unit. Data collection was fragmented and protracted, due to changes in the researcher's working circumstance. Data were analysed using content analysis to enable quantitative as well as qualitative analysis. Results highlighted that the three informant groups described similar sound sources; however, the individual groups characterised the sources differently. The individual groups also reported the impact of those sounds differentially. The context of the sound appears to be the main identifier as to whether a sound is described as reassuring or a noise annoying or frightening, this was true of all groups of informants. The keynote sounds, which included staff conversation, often reported in the literature as noisy and negative, in this study could be perceived by patients and visitors as reassuring, however signals which included alarms and patient noise, were commonly identified as annoying or frightening. The sound diary was successful in identifying a range of sounds and descriptors that could form the basis for further study.

9.3 Strengths of this thesis

These studies benefitted from robust laboratory and clinical testing of the devices and the impact of the environment on those tools. Preliminary study using conventional devices provided base line SPL data which demonstrated consistency and thus validity for the three studies utilising SPL measurement and with the wider clinical literature. This led to the second major strength which was the size of the dataset, both for SPL and source. Despite the devices being located in a busy clinical area, the impact of the environment on the device was negligible with the devices remaining functional and stable for eleven weeks of study. Likewise, the devices both through installation and use, did not impact on the

ability of the unit to function normally, staff generally disregarded their presence during their working days. There were a number of additional strengths. The four bed spaces utilised for studies 2 and 3 were identified through the case mix and acuity data presented in chapter 4 and their distributed locations, to be highly representative of the bed spaces within the GICU. The source data provided a description of the sound sources not currently available in the literature, adding depth and breadth to the knowledge base. The ability to collect noise source information concurrently with the SPL data, enabled an understanding of clinical situations and how noise or the setting might be modified to improve the environment. This was augmented by the ability to utilise the six statistical parameters to describe individual sound peaks. Study 4 enabled the sound pressure level and source data to be understood from the perception of the various users and demonstrated the clinical relevance of the series of studies.

9.4 Limitations of this thesis

There were a number of limitations associated with the studies described in this thesis. Data collection and subsequent analysis was both protracted and fragmented, caused initially by the delay in installing the NPL-Minim and microphones and latterly by the assignment of the author to another trust. The original plan for study 2 was to Sound Map the whole of the general intensive care unit, to include the 12 beds within the ICU, the 6 beds in the HDU and the two staff bases, one located within each area. This was not possible as we were unable to install a functional system to record across all beds and staff bases. Reluctantly, a decision was made to made to commence the study utilising the four working units. The time delay in turn led to the loss of access to the web-based data base for real-time data analysis and the decision to download the data to a password protected lap top via the LAN connections. Had the web-based data base been available, this would have provided greater information regarding the distribution,

emitting location and density of sound and enabled the production of a sound map for each of the beds with a working unit.

A bespoke data collection tool was developed for the 'Sound in Time' study. This tool still requires validation because there was a need to collect the data while the NPL-Minim remained functioning, at a time when the trained second observer was unavailable. Likewise, the sound diaries were developed specifically for this study, they were based on emotional descriptors of sound (annoying, frightening, reassuring) used in urban sound scaping studies. Again, this methodology was not validated. Studies 2 and 3 reported results for potential restorative time and restorative periods, this work is in its infancy, with limited publications and developing definitions. It is important therefore that the reporting in this thesis is read in context with the current evidence base and might add to the development thereof. Lastly, this thesis received two small grants, which enabled the manufacturing and installation of the data collection tools for study two. In retrospect however, financial resources and the part time status of the researcher, limited the scope of the data analysis, with a large dataset analysed manually rather than with the aid of specialist computer software and expert support.

9.5 Future work

The sound pressure levels across the GICU were higher than international recommendations[35-38], they were however, consistent with the literature[24,50-94, 97] and in particular consistent for a unit caring for both medical and surgical patients and its built environment. Furthermore, data recorded in an empty room exceeded the current guidance, this is also demonstrated in the literature[64,79] where sound pressure levels are close to or exceed the guidance. This suggests that the standards may be correct but are not achievable within current building regulations, bed space layout, equipment design and working practices. Current

evidence[81] suggests that behaviour modification without consideration of the sources of ambient noise may not sufficiently address the problem. It therefore seems desirable that the standards are revised to reflect the reality of an intensive care unit and the large evidence base demonstrating the actual rather than desired sound pressure levels. It is however equally important that equipment manufacturers and building regulations design equipment and environments that reduce as far as possible, noise within the intensive care setting, whilst units must re-design working practices to lower noise at the bed space, especially at the head end of the bed where most of the equipment noise originates[98] and thus most impacts the patient. Future study is required, to understand how the complex cacophony of sound emanating from equipment, alarms, clinical and housekeeping tasks and conversation can be safely modified to reduce the harms to patients and staff, currently associated with this noise. It is likely that this will include sound modification utilising sound masking and noise cancellation devices[193-198], modification of noise from equipment and equipment alarms, but also removing the noise source either to an alternative space[109] or removing it altogether and utilising alternative methods of alert[115,138,140]. Further study is required on noise in side rooms. In this study the side room was the noisiest environment, with the literature identifying similar[54] or more commonly, no difference between side rooms and multi-bed bays[75-77,88,90] yet frequently side rooms are used to care for patients who may be sicker[88] with a greater need for equipment and staff. This study should include reverberation times to understand better the local built environmental differences between alternative designs of bed space which appear to impact the local acoustical environment. It is also important to understand the sound environment of the multi-bed areas, compared with single bedrooms, where ingress of sound emanating from other bed spaces and areas of the unit impacts on patients cared for in these bed spaces.

Although the source data provides greater depth and breadth of information than currently available, it also highlights an inherent problem with collecting complete and accurate datasets in a such a complex and noise rich environment. Three studies have reported on the sources of noise in an intensive care unit[95-97] all utilise very different methodologies, one of these[95] is a survey of patients and staff perceptions, which is unlikely to be robust in identifying sources although highly relevant for sound scaping studies. This provides two studies[96,97] where the methodologies can be compared with the methods utilised for study 3 to identify strengths and limitations of each and thus describe a potential new methodology for future research. Xie and colleagues[96] data collection form was robust and validated including five descriptors from previous urban study[210], interval, frequency, duration, perceived loudness and location. The researcher followed a logical and recognised approach to collecting source data. The detail required to complete this data however, would preclude recording of all observed sources by one individual, especially in a situation such as a large multi-bed bay where the location of sound may be difficult to identify. An alternative is to record sound, annotating the recording retrospectively as in Park and colleagues[97]. This however proved inefficient, utilising six researchers who required ≈350hrs to complete the task and resulting in broad descriptors of sound rather than the actual sound source. It did however identify substantially more separate sources than our study. To improve validity of source recognition, location and duration, future study might employ several methods, including a structured data collection tool combining a broad representation of noise sources as represented in the 'Sound in Time' tool, with descriptors such as those utilised by Xie and colleagues[96]. This would require more than one observer at one time, each observing for a specific selection of sources, it would also appear appropriate to measure actual SPL rather than relying on perceived loudness as in Xie et al. To ensure greater accuracy and definition of sound sources, combining prospective and retrospective analysis of

the observation period may prove an effective study design. Data collection then starts to become very complex, but also potentially financially prohibitive. An alternative for future studies might employ machine learning, utilising sound pressure meters with a greater sampling capacity and developing algorithms to analyse this data, built from human observation.

The concept of restorative periods[67,77,97] requires further investigation. This thesis identifies potential restorative time in study 2 and restorative periods in study 3 using a modified calculation. Each study describing restorative periods has modified the definition, based on the acoustical parameters collected in that report. Currently all definitions rely on measurements of loudness i.e. decibels and do not take account of varying frequencies of sound. Several authors report that sleep, although fragmented, is possible in an ICU, despite the high sound pressure levels[57,58,159], however when similar studies are repeated in healthy subjects, sleep is commonly disrupted by the noise. The concept of restorative periods is therefore appealing, suggesting that it is a phenomenon that is intuitively clinically relevant and possible, but not yet proven. Only one of the sound studies set out to measure restorative periods[77], this study measured sound for just 24hrs continuously in three varying room types; it would therefore be relevant to design a study to measure restorative periods over a longer period and in multiple bed spaces, ideally including measures of frequency as a part of the acoustical parameters. A recent study[174] has demonstrated that an increased number of restorative periods per hour is positively correlated with sleep quality. This study utilised L_{90} as the background sound levels and loudness peaks were expressed in units of sone, which is the measure of loudness or acoustic intensity rather than, phon which measures loudness level and approximately corresponds with sound pressure level. Sleep quality was self-assessed using the Richards Campbell Sleep Questionnaire, which required patients to be well enough to self-report sleep

or provide a retrospective analysis of their perceived sleep quality. Despite the limitations analysing the data produced by traditional measures of sleep in critically ill patients, such a study should also report sleep using polysomnography with or without actigraphy, to understand as well as possible the patients actual sleep in addition to the relevant sound pressure levels, this also enables study in patient unable to self-report. Given the difference in sleep reported in studies in critically ill and healthy subjects, these studies should include all levels of ICU patients (1-3)[203], to understand which patients are most likely to be disturbed by noise levels and those who may benefit from restorative periods.

To understand the perception of sound in an intensive care unit, it is essential that all main user groups are included. Patients are clearly an important group; staff however are also heavily impacted by the noise levels and characteristics of the sound environment. Study 4 provided useful insight into the perception of these user groups, identifying that the physical properties of sound are important; however, the temporal and social context is equally significant[31]. It is therefore important to make the soundscape more positive to all user groups rather than just less noisy[31,1205]. There is minimal research into soundscapes in hospital and in particular intensive care. Further research is needed to understand user perspectives and to validate the findings from this pilot study. Study 4 has provided the foundation for this future study.

9.6 Conclusion

This thesis presents the results of a series of studies which identified the acoustical characterisation of a single intensive care unit. Data were collected at four representative bed spaces. It found that the unit was noisy, $L_{Aeq271days}$ 65.4dB, with a diurnal rhythm that changed little over the week, this was consistent with the published literature for a unit of its age and case mix. Sound pressure levels were

consistent between studies, suggesting reliability in the data. In this study the side room was the noisiest room with an $L_{Aeq68days}$69.1dB and when empty recorded an L_{Aeq} ≈60dB. No data were collected that met the international standard of ≤35dbA.

Fifty hours of observational data identified 16784 episodes of sound, with an average of 336 episodes per hour observed, this was higher in the day time than at night. Communication was the most prevalent category of sound (33.95%) and nurse to nurse conversation the most prevalent source within this category. During the day communication remained the most prevalent source (39.2%), at night however the equipment alarms were more prevalent (25.51%). There is minimal research into the sources of sound in an ICU, it is proposed that combining the best of methods from previous studies and considering the use of artificial intelligence, would provide the most robust data. Analysis of data sets from studies 2 and 3, identified a potential restorative time of 63.3% in study 2 and 115 restorative periods (41.5%) of time measured during study 3. There was greater PRT or RP at night than during the day in both datasets. Further study is required to understand this concept better. The sound diary was successful in identifying a range of sounds and descriptors that would form the basis for further study. Patients, nurses and visitors described similar sounds these descriptions were however, subtly different. The context of the sound appears to be the main identifier as to whether a sound is described as reassuring, annoying or frightening.

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Appendix 1

Ethics correspondence

St George's Healthcare NHS
NHS Trust

GENERAL INTENSIVE CARE UNIT
LEVEL 1, ST.JAMES' WING

St George's Hospital
Blackshaw Road
London
SW17 0QT

Direct Line: 020 8725 3129
Direct Fax: 020 8725 3296
e-mail: [redacted]@stgeorges.nhs.uk

Our Ref:dd/dmt/Heron

1 June 2011

Dr C Heron
Ethics Committee Chair
MRI Department
Ground Floor Lanesborough Wing
St George's Hospital
London SW17 0QT

Dear Dr Heron

Noise feasibility study

I would like to seek your advice regarding a small feasibility study on the General Intensive Care Unit (GICU). We propose to undertake a project, jointly conceived by the GICU and the National Physical Laboratory to assess the acoustical environment in the GICU. This would involve the placement of approximately 10 wireless micro electro mechanical systems (MEMS) microphones to enable the production and validation of a noise map of the clinical area. These microphones record average and maximum noise per minute, no individual voice or conversation is recorded.

Noise is a constant feature in GICU, many patients and their families complain about excessive noise. The aim of this study is to identify whether this system produces a reliable noise map in such an environment and to understand the problem of noise, with the view of developing a joint proposal for further research to improve patient experience. A grant application has been submitted to the NPL Strategic Research Programme to fund this preliminary work.

Due to the nature of this study, we are unsure whether we would be required to submit a full ethics submission or whether review of the protocol would be sufficient, and would be grateful for your advice.

Yours sincerely

[redacted]

Deborah Dawson
[redacted]

cc: Prof. G M Grounds

NHS
National Research Ethics Service

South West London REC 3
Room 4W/12 4 Floor West
Charing Cross Hospital
Fulham Palace Road
London W6 8RF

Telephone: 0203 311 7254

16 June 2011(Amended 23 June 2011)

Deborah Dawson
[redacted]
General Intensive Care Unit
St. George's Healthcare NHS Trust
Blackshaw Road
Tooting, London
SW17 0QT

Dear Ms Dawson

Title of project: **Noise feasibility study (jointly conceived by the GICU and the National Physical Laboratory**
REC reference: **Enquiry outside of application**
Opinion: **Project not considered to be research requiring ethical review**

Thank you for your letter seeking the Committee's advice about the above project.

You provided a description of the project for the consideration of the Committee.

I enclose a copy of our leaflet, "Defining Research", which explains how we differentiate research from other activities. The Sub Committee has advised that the project is not considered to be research according to this guidance. Therefore it does not require ethical review by a NHS Research Ethics Committee.

You should check with St George's Hospital and Medical School what other review arrangements or sources of advice apply to projects of this type. Guidance may be available from the clinical governance office.

This letter should not be interpreted as giving a form of ethical approval or any endorsement of the project, but it may be provided to a journal or other body as evidence that ethical approval is not required under NHS research governance arrangements.

However, if you, your sponsor/funder or any NHS organisation feels that the project should be managed as research and/or that ethical review by a NHS REC is essential, please write setting out your reasons and we will be pleased to consider further.

Where NHS organisations have clarified that a project is not to be managed as research, the Research Governance Framework states that it should not be presented as research within the NHS.

Yours sincerely

[redacted]

Kristy Randall

Committee Co-ordinator

E-mail: [redacted]@imperial.nhs.uk

Enclosure: *NRES leaflet – "Defining Research"*

HSC Business Services Organisation

Office for Research Ethics Committees Northern Ireland (ORECNI)

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HSC REC A

02 June 2015

Miss Deborah Dawson
[redacted]
St George's Healthcare NHS Trust
GICU, St George's Hopsital
Blackshaw Road
LONDON, SW17 0QT

Dear Miss Dawson

Study title:	**A study to identify the acoustical characterisation of an Intensive Care Unit**
REC reference:	**15/NI/0106**
IRAS project ID:	**128446**

Thank you for your letter of 31 May 2015, responding to the Proportionate Review Sub-Committee's request for changes to the documentation for the above study.

The revised documentation has been reviewed and approved by the Chair of the Proporionate Review Sub-Committee, **subject to the conditions specified below**..

We plan to publish your research summary wording for the above study on the HRA website, together with your contact details. Publication will be no earlier than three months from the date of this favourable opinion letter. The expectation is that this information will be published for all studies that receive an ethical opinion but should you wish to provide a substitute contact point, wish to make a request to defer, or require further information, please contact the REC Manager [redacted] RECA@hscni.net. Under very limited circumstances (e.g. for student research which has received an unfavourable opinion), it may be possible to grant an exemption to the publication of the study.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised, **subject to the conditions specified below**.

Conditions of the favourable opinion

The favourable opinion is subject to the following conditions being met prior to the start of the study.

- In the section of the Participant Information Sheet entitled "What is the purpose of the study", the sentence "The individual sounds are being identified....." should be amended to read:
  "The individual sounds (but, again, not the content of speech) are being identified...."

- A sentence should be added after the first sentence of the first paragraph of the "Will my taking part in the study be kept confidential" section of Part 2 of the Participant Information Sheet so that it reads:
  "Your confidentiality will be safeguarded during and after the study; all information collected about you during the course of the research will be kept strictly confidential. In the unlikely event of an incident of unsafe practice being observed, however, a report will be made even if that should result in some breach of confidentiality."

You should notify the REC in writing once all conditions have been met (except for site approvals from host organisations) and provide copies of any revised documentation with updated version numbers. The REC will acknowledge receipt and provide a final list of the approved documentation for the study, which can be made available to host organisations to facilitate their permission for the study. Failure to provide the final versions to the REC may cause delay in obtaining permissions.

- Management permission or approval must be obtained from each host organisation prior to the start of the study at the site concerned.

  Management permission ("R&D approval") should be sought from all NHS organisations involved in the study in accordance with NHS research governance arrangements.

  Guidance on applying for NHS permission for research is available in the Integrated Research Application System or at http://www.rdforum.nhs.uk.

  Where a NHS organisation's role in the study is limited to identifying and referring potential participants to research sites ("participant identification centre"), guidance should be sought from the R&D office on the information it requires to give permission for this activity.

  For non-NHS sites, site management permission should be obtained in accordance with the procedures of the relevant host organisation.

  Sponsors are not required to notify the Committee of approvals from host organisations.

- Registration of Clinical Trials

  All clinical trials (defined as the first four categories on the IRAS filter page) must be registered on a publically accessible database. This should be before the first participant is recruited but no later than 6 weeks after recruitment of the first participant.

  There is no requirement to separately notify the REC but you should do so at the earliest opportunity e.g. when submitting an amendment. We will audit the registration details as part of the annual progress reporting process.

  To ensure transparency in research, we strongly recommend that all research is registered but for non-clinical trials this is not currently mandatory.

  If a sponsor wishes to request a deferral for study registration within the required timeframe, they should contact hra.studyregistration@nhs.net. The expectation is that all clinical trials will be registered, however, in exceptional circumstances non registration may be permissible with prior agreement from NRES. Guidance on where to register is provided on the HRA website.

It is the responsibility of the sponsor to ensure that all the conditions are complied with before the start of the study or its initiation at a particular site (as applicable).

Ethical review of research sites

The favourable opinion applies to all NHS sites taking part in the study, subject to management permission being obtained from the NHS/HSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" above).

Approved documents

The documents reviewed and approved by the Committee are:

Document	*Version*	*Date*
Copies of advertisement materials for research participants [Sound Diary Advert]	1	31 May 2015
Covering letter on headed paper [REC Covering Letter]	1	18 May 2015
Evidence of Sponsor insurance or indemnity (non NHS Sponsors only) [Gallagher Policy]	1	22 August 2014
IRAS Checklist XML [Checklist_19052015]		19 May 2015
IRAS Checklist XML [Checklist_19052015]		19 May 2015
IRAS Checklist XML [Checklist_20052015]		20 May 2015
IRAS Checklist XML [Checklist_31052015]		31 May 2015
Non-validated questionnaire [CRF Patient Diary]	1	01 March 2015
Other [CRF Sound in Time]	2	01 March 2013
Other [Richard Barham Supervisor CV]	1	18 May 2015
Other [Covering letter in response to REC concerns]	1	31 May 2015
Other [Protocol]	1.1	31 May 2015
Other [PIS updated]	1.1	31 May 2015
Participant consent form [Consent Form Diaries]	1	01 March 2015
REC Application Form [REC_Form_20052015]		20 May 2015
Summary CV for Chief Investigator (CI) [Curriculum Vitae]	1	18 May 2015
Summary CV for supervisor (student research) [CV phD Supervisor Barbara Philips]	1	18 May 2015

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

After ethical review

Reporting requirements

The attached document "After ethical review – guidance for researchers" gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Adding new sites and investigators
- Notification of serious breaches of the protocol
- Progress and safety reports
- Notifying the end of the study

The HRA website also provides guidance on these topics, which is updated in the light of changes in reporting requirements or procedures.

Feedback

You are invited to give your view of the service that you have received from the National Research Ethics Service and the application procedure. If you wish to make your views known please use the feedback form available on the HRA website: http://www.hra.nhs.uk/about-the-hra/governance/quality-assurance

We are pleased to welcome researchers and R & D staff at our NRES committee members' training days – see details at http://www.hra.nhs.uk/hra-training/

15/NI/0106	Please quote this number on all correspondence

With the Committee's best wishes for the success of this project.

Yours sincerely

[redacted]

pp Dr Alastair Walker
Vice-Chair – Chair of the Proportionate Review meeting
Email: RECA@hscni.net

Enclosures: *"After ethical review – guidance for researchers"*

Copy to: [redacted] *St George's, University of London*

HSC Business Services Organisation

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HSC REC A

08 June 2015

Miss Deborah Dawson
[redacted]
St George's Healthcare NHS Trust
GICU, St George's Hospital
Blackshaw Road
LONDON, SW17 0QT

Dear Miss Dawson

Study title: **A study to identify the acoustical characterisation of an Intensive Care Unit**
REC reference: **15/NI/0106**
IRAS project ID: **128446**

Thank you for your letter of 05 June 2015. I can confirm the REC has received the documents listed below and that these comply with the approval conditions detailed in our letter dated 02 June 2015.

Documents received

The documents received were as follows:

Document	*Version*	*Date*
Other [Covering letter with final amendments]	1	05 June 2015
Other [PIS version 1.2]	1.2	05 June 2015

Approved documents

The final list of approved documentation for the study is therefore as follows:

Document	*Version*	*Date*
Copies of advertisement materials for research participants [Sound Diary Advert]	1	31 May 2015
Covering letter on headed paper [REC Covering Letter]	1	18 May 2015
Evidence of Sponsor insurance or indemnity (non NHS Sponsors only) [Gallagher Policy]	1	22 August 2014
IRAS Checklist XML [Checklist_19052015]		19 May 2015
IRAS Checklist XML [Checklist_19052015]		19 May 2015
IRAS Checklist XML [Checklist_20052015]		20 May 2015

IRAS Checklist XML [Checklist_31052015]		31 May 2015
IRAS Checklist XML [Checklist_05062015]		05 June 2015
Non-validated questionnaire [CRF Patient Diary]	1	01 March 2015
Other [CRF Sound in Time]	2	01 March 2013
Other [Richard Barham Supervisor CV]	1	18 May 2015
Other [Covering letter in response to REC concerns]	1	31 May 2015
Other [Protocol]	1.1	31 May 2015
Other [Covering letter with final amendments]	1	05 June 2015
Other [PIS version 1.2]	1.2	05 June 2015
Participant consent form [Consent Form Diaries]	1	01 March 2015
REC Application Form [REC_Form_20052015]		20 May 2015
Summary CV for Chief Investigator (CI) [Curriculum Vitae]	1	18 May 2015
Summary CV for supervisor (student research) [CV phD Supervisor Barbara Philips]	1	18 May 2015

You should ensure that the sponsor has a copy of the final documentation for the study. It is the sponsor's responsibility to ensure that the documentation is made available to R&D offices at all participating sites.

15/NI/0106 **Please quote this number on all correspondence**

Yours sincerely

[redacted]

Kathryn Taylor
Committee Manager HSC REC A
E-mail: RECA@hscni.net

Copy to: [redacted] *St George's, University of London*

HSC Business Services Organisation

Office for Research Ethics Committees Northern Ireland (ORECNI)

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HSC REC A

24 February 2017

Miss Deborah Dawson
[redacted]
St George's Healthcare NHS Trust
GICU, St George's Hopsital
Blackshaw Road
LONDON, SW17 0QT

Dear Miss Dawson

Study title:	**A study to identify the acoustical characterisation of an Intensive Care Unit**
REC reference:	**15/NI/0106**
Amendment number:	**Study Extension Request - Feb 2017**
Amendment date:	**24 February 2017**
IRAS project ID:	**128446**

Thank you for your email of 24 February 2017, notifying the Committee of the above amendment to extend the end date of the study until 31 May 2017.

The Committee does not consider this to be a "substantial amendment" as defined in the Standard Operating Procedures for Research Ethics Committees. The amendment does not therefore require an ethical opinion from the Committee and may be implemented immediately, provided that it does not affect the approval for the research given by the R&D office for the relevant NHS care organisation.

Documents received

The documents received were as follows:

Document	*Version*	*Date*
Notice of Non Substantial Amendment [Email from D Dawson]	Study Extension Request - Feb 2017	24 February 2017

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

Providing Support to Health and Social Care

15/NI/0106:	Please quote this number on all correspondence

Yours sincerely

[redacted]

Kathryn Taylor
Committee Manager HSC REC A
Email: RECA@hscni.net

Copy to: [redacted] *St George's, University of London*

HSC Business Services Organisation

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HSC REC A

23 May 2017

Miss Deborah Dawson
[redacted]
St George's Healthcare NHS Trust
GICU, St George's Hopsital
Blackshaw Road
LONDON, SW17 0QT

Dear Miss Dawson

Study title:	**A study to identify the acoustical characterisation of an Intensive Care Unit**
REC reference:	**15/NI/0106**
Amendment number:	**Further Study Extension - May 2017**
Amendment date:	**23 May 2017**
IRAS project ID:	**128446**

Thank you for your email of 23 May 2017, notifying the Committee of the above amendment to extend the end date of the study until 31 December 2017.

The Committee does not consider this to be a "substantial amendment" as defined in the Standard Operating Procedures for Research Ethics Committees. The amendment does not therefore require an ethical opinion from the Committee and may be implemented immediately, provided that it does not affect the approval for the research given by the R&D office for the relevant NHS care organisation.

Documents received

The documents received were as follows:

Document	*Version*	*Date*
Notice of Non Substantial Amendment [Email from D Dawson]	Further Study Extension - May 2017	23 May 2017

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

15/NI/0106:	**Please quote this number on all correspondence**

Providing Support to Health and Social Care

Yours sincerely

[redacted]

Kathryn Taylor
Committee Manager HSC REC A
Email: RECA@hscni.net

Copy to: *Ms* [redacted], *St George's, University of London*

HSC Business Services Organisation

Office for Research Ethics Committees Northern Ireland (ORECNI)

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HSC REC A

04 January 2018

Miss Deborah Dawson
[redacted]
St George's Healthcare NHS Trust
GICU, St George's Hopsital
Blackshaw Road
LONDON
SW17 0QT

Dear Miss Dawson

Study title:	**A study to identify the acoustical characterisation of an Intensive Care Unit**
REC reference:	**15/NI/0106**
Amendment number:	**Non-Substantial Amendment #3**
Amendment date:	**27 December 2017**
IRAS project ID:	**128446**

Thank you for your email of 27 December 2017, notifying the Committee of the above amendment to extend the end date of the study until 30 April 2018 in order to finish the work.

The Committee does not consider this to be a "substantial amendment" as defined in the Standard Operating Procedures for Research Ethics Committees. The amendment does not therefore require an ethical opinion from the Committee and may be implemented immediately, provided that it does not affect the approval for the research given by the R&D office for the relevant NHS care organisation.

Documents received

The documents received were as follows:

Document	*Version*	*Date*
Notice of Non Substantial Amendment [Email Notification - Further Extension to Study from D Dawson]		27 December 2017

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics

Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

15/NI/0106:	Please quote this number on all correspondence

Yours sincerely

[redacted]

Denise Nesbitt
Ethics Administrator

Email: RECA@hscni.net

Business Services Organisation

Office for Research Ethics Committees Northern Ireland (ORECNI)

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HSC REC A

11 April 2018

Miss Deborah Dawson
[redacted]
St George's Healthcare NHS Trust
GICU, St George's Hopsital
Blackshaw Road
LONDON
SW17 0QT

Dear Miss Dawson

Study title:	**A study to identify the acoustical characterisation of an Intensive Care Unit**
REC reference:	**15/NI/0106**
Amendment number:	**Non-Substantial Amendment #4**
Amendment date:	**8 April 2018**
IRAS project ID:	**128446**

Thank you for your email of 8 April 2018, notifying the Committee of the above amendment to extend the end date of the study until 31 December 2018 in order to complete the study.

The Committee does not consider this to be a "substantial amendment" as defined in the Standard Operating Procedures for Research Ethics Committees. The amendment does not therefore require an ethical opinion from the Committee and may be implemented immediately, provided that it does not affect the approval for the research given by the R&D office for the relevant NHS care organisation.

Documents received

The documents received were as follows:

Document	*Version*	*Date*	
Notice of Non Substantial Amendment [Email Notification - Further Extension to Study from D Dawson]		8 April 2018	

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

15/NI/0106:	Please quote this number on all correspondence

Yours sincerely

[redacted]

Lorna Callaghan
Ethics Administrator

Email: RECA@hscni.net

Appendix 2

Sound in Time datasheet

DATE	
TIME OBSERVATION COMMENCED	
AREA OBSERVED	
LOCATION OF OBSERVER	

	TALLY
INTERUPTIONS	
RECORDER INTERUPPTED	
RECORDER INTERUPTS	

SOUND IN TIME STUDY SHEET

Type	Source	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	Occurance	Source	Type
Clinical equipment	Preparing/clearing away equipment																																																													0	Preparing/clearing away equipment	Clinical equipment
	Oscillator																																																													0	Oscillator	
	Oxygen/CPAP/Optiflow																																																													0	Oxygen/CPAP/Optiflow	
	Bed/trolley																																																													0	Bed/trolley	
	Procedure at bedside																																																													0	Procedure at bedside	
	Programming infusion/syring pump																																																													0	Programming infusion/syring pump	
	X Ray																																																													0	X Ray	
	Suction																																																													0	Suction	
	Blood gas machine																																																													0	Blood gas machine	
	Bedside trolley																																																													0	Bedside trolley	
	Clinical trolley																																																													0	Clinical trolley	
Housekeeping equipment	Bedside table																																																													0	Bedside table	Housekeeping equipment
	Bin lid closing																																																													0	Bin lid closing	
	Chair																																																													0	Chair	
	Mobile phone																																																													0	Mobile phone	
	Entrance phone																																																													0	Entrance phone	
	Internal phone ringing																																																													0	Internal phone ringing	
	Doorbell																																																													0	Doorbell	
	Drawers slamming																																																													0	Drawers slamming	
	Keyboard/mouse																																																													0	Keyboard/mouse	
	Sink/taps																																																													0	Sink/taps	
	Towel dispensor																																																													0	Towel dispensor	
	Aprons																																																													0	Aprons	
Miscellaneous	Cacophony of sound																																																													0	Cacophony of sound	Miscellaneous
	Clip file																																																													0	Clip file	
	Sudden loud noise																																																													0	Sudden loud noise	
	Footsteps																																																													0	Footsteps	
	Other noise (see box)																																																													0	Other noise (see box)	
Alarms	Other alarm																																																													0	Other alarm	Alarms
	Mattress alarm																																																													0	Mattress alarm	
	Feed pump alarm																																																													0	Feed pump alarm	
	Syringe/infusion pump alarm																																																													0	Syringe/infusion pump alarm	
	Oscillator alarm																																																													0	Oscillator alarm	
	Vision alarm																																																													0	Vision alarm	
	Ventilator alarm (Evita 4)																																																													0	Ventilator alarm (Evita 4)	
	Aquarius alarm																																																													0	Aquarius alarm	
	Monitor urgent																																																													0	Monitor urgent	
	Monitor alarm																																																													0	Monitor alarm	
Communication	Nurse/nurse																																																													0	Nurse/nurse	Communication
	Nurse/patient																																																													0	Nurse/patient	
	Nurse/doctor																																																													0	Nurse/doctor	
	Nurse/other																																																													0	Nurse/other	
	Nurse/relative																																																													0	Nurse/relative	
	Patient/patient																																																													0	Patient/patient	
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	Relative/relative																																																													0	Relative/relative	
	Patient noise																																																													0	Patient noise	
	Talking on internal phone																																																													0	Talking on internal phone	
No. sources		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		No.sources
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60			
Location	Observed bed space																																																														Observed bed space	Location
	Left adjacent bed space																																																														Left adjacent bed space	
	Right adjacent bed space																																																														Right adjacent bed space	
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	Other bed space																																																														Other bed space	
	Other bed space/not known																																																														Other bed space/not known	
	GICU staff base																																																														GICU staff base	
	GICU entrance																																																														GICU entrance	
	GICU sluice																																																														GICU sluice	
	Clinical room																																																														Clinical room	
	HDU/GICU entrance																																																														HDU/GICU entrance	
	HDU staff base																																																														HDU staff base	
	HDU office/entrance																																																														HDU office/entrance	
	HDU sluice																																																														HDU sluice	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60			

Comments:

Appendix 3

Hearing Test

Department of Audiological Medicine

St George's Healthcare NHS Trust

Tested by: S-KOTTUR

Test Date: 01/07/13

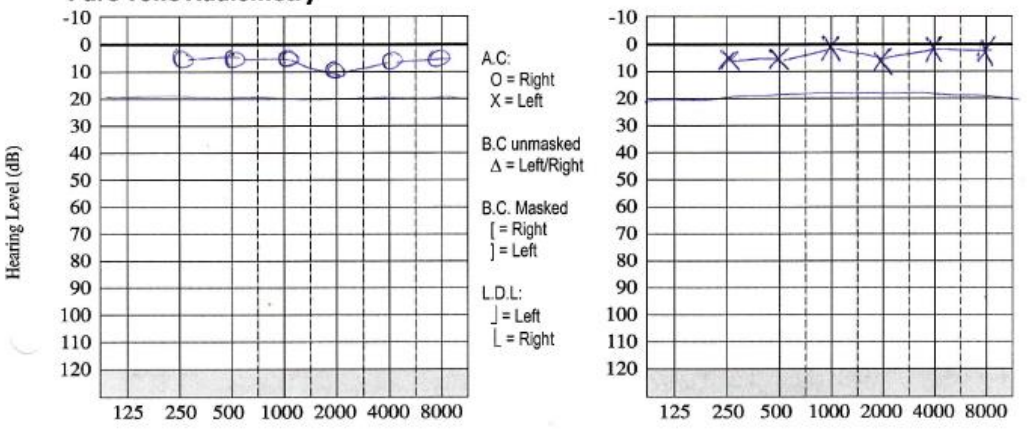
Supervisor: _____ (If student testing)

Name MS. DEBORAH DAWSON

Hospital No _____

DOB 23/07/1963

Pure Tone Audiometry



Masking levels:

AC						
BC						

Masking levels:

AC						
BC						

Comments (incl. test modifications)

Both Ears: Hearing acuity within normal limits

Tympanometry & Acoustic Reflex Thresholds

Y/B/G Probe - Right

	500 Hz	1 kHz	2 kHz	4 kHz
Ipsi (dB)				
Contra (dB)				

Ear canal volume _____ ml

Maximum compliance _____ ml/mho

Middle ear pressure _____ daPa

Comments

Y/B/G Probe - Left

	500 Hz	1 kHz	2 kHz	4 kHz
Ipsi (dB)				
Contra (dB)				

Ear canal volume _____ ml

Maximum compliance _____ ml/mho

Middle ear pressure _____ daPa

Comments

KEY:
→ = Y/B/G probe
▷ = Loudspeaker

Range of adult normal value: Middle ear compliance: mean = 0.7ml (0.3 to 1.6 ml), Middle ear pressure: ± 50daPa

PTA ART Form - RIGHT BOOTH Audiology SGH 2004 v2.3
Modified 11/07/2012

Audiometer Details	
Type	KC50
Serial No.	Audiometer 2

Tympanometer Details	
Type	GSI Tymp Star
Serial No.	Tympanometer 4

Appendix 4

Completed example of a Sound in Time datasheet. Example taken from Observation 3 Bed space 5 from 18.10 – 19.09hrs on 12/7/2015.

SOUND IN TIME STUDY SHEET

DATE	12/07/2015
TIME OBSERVATION COMMENCED	18.1
AREA OBSERVED	Bed 5
LOCATION OF OBSERVER	end of bed 5 by window

INTERUPTIONS	TALLY
RECORDER INTERUPPTED	3
RECORDER INTERUPTS	

Type	Source	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	Occurance	Source	Type
Clinical equipment	Preparing/clearing away equipment							1																																																						1	Preparing/clearing away equipment	Clinical equipment
	Oscillator																																																													0	Oscillator	
	Oxygen/CPAP/Optiflow																																															1	1	1	1	1	1	1	1	1	1	1	1	1	1	14	Oxygen/CPAP/Optiflow (nebuliser)	
	Bed/trolley																														1																															1	Bed/trolley	
	Procedure at bedside	1						1			1			1									1				1			1					1	1	1								1	1		1									1	1	1			1	17	Procedure at bedside	
	Programming infusion/syring pump							1	1			1	1												1		1																																			6	Programming infusion/syring pump	
	X-Ray																																																													0	X-Ray	
	Suction																																																													0	Suction	
	Blood gas machine																																																													0	Blood gas machine	
	Bedside trolley																						1																						1	1											1	1					5	Bedside trolley	
	Clinical trolley																																																													0	Clinical trolley	
Housekeeping equipment	Bedside table																																																													0	Bedside table	Housekeeping equipment
	Bin lid closing			1						1	1	1				1			1				1							1	1	1	1		1	1					1	1	1					1		1	1	1	1		1			1			1	24	Bin lid closing	
	Chair																		1																			1	1				1								1		1									6	Chair	
	Mobile phone																					1																							1																	2	Mobile phone	
	Entrance phone																			1																																1										2	Entrance phone	
	Internal phone ringing	1		1	1				1	1			1		1	1							1	1								1								1	1																						13	Internal phone ringing	
	Doorbell																1			1	1																																									3	Doorbell	
	Drawers slamming																1			1																																										2	Drawers slamming	
	Keyboard/mouse																																																									1				1	Keyboard/mouse	
	Sink/taps										1	1				1																									1							1														5	Sink/taps	
	Towel dispensor										1	1				1																									1	1	1					1											1				8	Towel dispensor	
	Aprons		1					1								1	1			1	1						1		1	1	1				1		1	1														1						1				15	Aprons	
Miscellaneous	Cacophony of sound																																																													0	Cacophony of sound	Miscellaneous
	Clip file												1	1																																																2	Clip file	
	Sudden loud noise																						1																																							1	Sudden loud noise	
	Footsteps																			1		1				1					1		1																		1					1		1				8	Footsteps	
	Other noise (see box)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	61	Other noise (see box)	
Alarms	Other alarm																																							1				1																		2	Other alarm	Alarms
	Mattress alarm																	1																																												1	Mattress alarm	
	Feed pump alarm																																																													0	Feed pump alarm	
	Syringe/infusion pump alarm								1	1										1					1	1			1															1								1	1			1						10	Syringe/infusion pump alarm	
	Oscillator alarm																																																													0	Oscillator alarm	
	Vision alarm																																																													0	Vision alarm	
	Ventilator alarm (Evita 4)	1								1									1		1						1				1							1							1	1	1	1		1								1	1	1		15	Ventilator alarm (Evita 4)	
	Aquarius alarm																																																				1						1	1	3	Aquarius alarm	
	Monitor urgent																																																													0	Monitor urgent	
	Monitor alarm	1																							1		1																																			3	Monitor alarm	
Communication	Nurse/nurse	1	1	1	1									1					1	1									1	1	1			1	1	1	1			1	1			1			1				1	1			1					1		22	Nurse/nurse	Communication
	Nurse/patient		1											1	1	1										1	1	1							1																1			1	1	1		1	1		1	15	Nurse/patient	
	Nurse/doctor	1	1	1	1							1	1	1	1	1	1	1		1											1		1																						1	1	1	1	1	1	1	21	Nurse/doctor	
	Nurse/other									1																																																				1	Nurse/other	
	Nurse/relative			1	1								1											1	1	1									1	1	1	1							1								1		1							13	Nurse/relative	
	Patient/patient																																																													0	Patient/patient	
	Patient/doctor				|1|																																																								1	Patient/doctor	
	Patient/other																																																													0	Patient/other	
	Patient/relative	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1												45	Patient/relative	
	Doctor/ doctor		1	1	1						1	1	1	1	1	1	1	1	1	1													1																										1	1	1	17	Doctor/ doctor	
	Doctor/other																																																													0	Doctor/other	
	Doctor/ relative																																																													0	Doctor/ relative	
	Other/other																																																													0	Other/other	
	Other/relative																																																													0	Other/relative	
	Relative/relative																	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1			1							1	1	1												24	Relative/relative	
	Patient noise																																																													0	Patient noise	
	Talking on internal phone						1	1	1																1																																					4	Talking on internal phone	
No. sources		8	7	8	7	3	3	7	6	7	7	8	8	8	6	10	7	6	8	12	6	5	8	5	8	7	8	5	5	6	10	4	6	4	9	7	7	7	4	5	7	4	5	5	7	5	4	9	4	6	7	7	6	4	7	8	5	11	6	7	8	394		No.sources
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60			
Location	Observed bed space	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	60	Observed bed space	Location
	Left adjacent bed space	1	1	1	1	1	1					1	1	1	1	1							1	1		1	1		1						1	1	1	1	1														1		1					1		24	Left adjacent bed space 4	
	Right adjacent bed space																																																														Right adjacent bed space	
	Other bed space			1						1	1			1					1	1			1								1				1	1	1	1		1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	33	Other bed space 3	
	Other bed space									1																																									1										2	Other bed space 2	
	Other bed space										1	1	1	1	1	1	1	1		1																																										9	Other bed space 8	
	Other bed space																																																										1			1	Other bed space 6	
	Other bed space/not known	1								1								1	1	1						1	1																							1			1							1		10	Other bed space/not known	
	GICU staff base			1			1	1	1		1		1		1	1				1			1	1										1					1	1	1											1			1	1	1	1	1	1	1	23	GICU staff base	
	GICU entrance																			1			1																																1							3	GICU entrance	
	GICU sluice				1	1																																																								2	GICU sluice	
	Clinical room																1																													1	1											1					4	Clinical room	
	HDU/GICU entrance		1					1																		1					1																					1	1	1									7	HDU/GICU entrance	
		3	3	4	3	3	3	3	2	4	4	3	4	4	4	4	3	3	3	6	1	1	4	3	1	4	3	1	2	1	3	1	2	2	3	3	3	3	3	3	3	2	2	1	2	3	3	2	2	3	4	4	5	2	5	3	4	3	4	5	3	178		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60			

Comments: Flotron boots continuous sound/helicoptor 27 (6.36)/21, 44 mobile phone used as calculator/52 relative shouting to another relative/39 (6.48), 43 (6.42) bed alarm

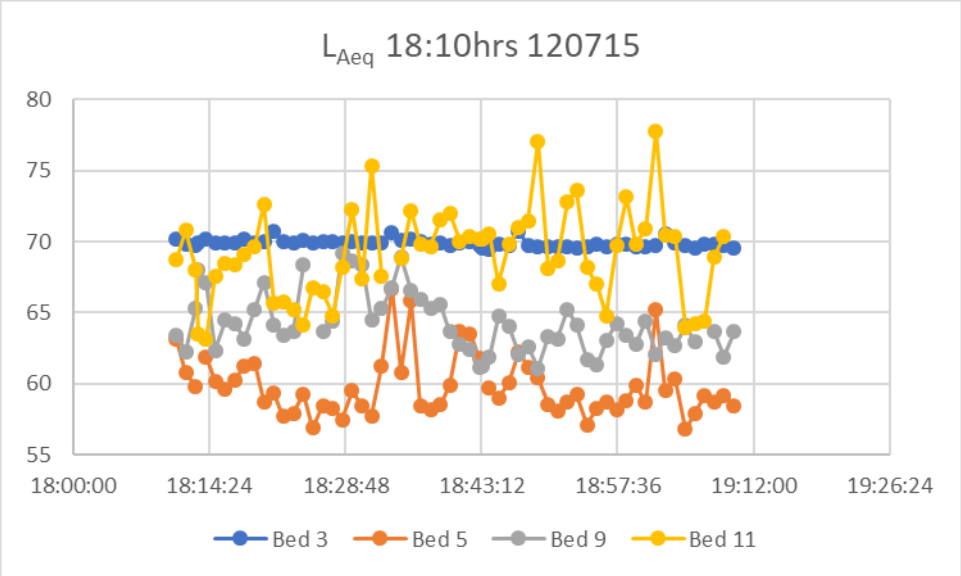
Appendix 5

Example data from a spreadsheet comparing $L_{Aeq1min}$ for the observed and other bed spaces under study. Example taken from Observation 3 Bed space 5 from 18.10 – 19.09hrs on 12/7/2015.

Sunday

	Bed 3	Bed 5	Bed 9	Bed 11
12/07/2015 18:10	70.15625	63.125	63.42578	68.77344
12/07/2015 18:11	69.82031	60.77734	62.26953	70.80859
12/07/2015 18:12	69.75781	59.82031	65.31641	68.02734
12/07/2015 18:13	69.94141		67.97266	63.48438
12/07/2015 18:14	70.14453	61.90625	67.13281	63.10547
12/07/2015 18:15	69.86719	60.16797	62.35938	67.60156
12/07/2015 18:16	69.92578	59.56641	64.46094	68.46875
12/07/2015 18:17	69.92969	60.26563	64.24609	68.41016
12/07/2015 18:18	70.16016	61.21875	63.14844	69.08203
12/07/2015 18:19	69.91797	61.4375	65.21484	69.65625
12/07/2015 18:20	70.01172	58.73828	67.12109	72.66406
12/07/2015 18:21	70.73047	59.29688	64.14844	65.62109
12/07/2015 18:22	69.99609	57.71094	63.43359	65.74219
12/07/2015 18:23	69.89453	57.92969	63.6875	65.21875
12/07/2015 18:24	70.11719	59.25	68.33984	64.125
12/07/2015 18:25	69.94531	56.87109		66.75391
12/07/2015 18:26	69.98438	58.46094	63.63281	66.44531
12/07/2015 18:27	69.98828	58.27734	64.41406	64.79297
12/07/2015 18:28	69.95313	57.44531	69.20313	68.21484
12/07/2015 18:29	70.01563	59.49219	68.62109	72.28125
12/07/2015 18:30	69.89063	58.42188	68.36328	67.37109
12/07/2015 18:31	69.87891	57.71484	64.44922	75.36328
12/07/2015 18:32	69.90234	61.24609	65.28516	67.60156
12/07/2015 18:33	70.66016	66.67188	66.76172	
12/07/2015 18:34	70.12891	60.81641	68.94531	68.84375
12/07/2015 18:35	70.17188	65.83203	66.53516	72.17188
12/07/2015 18:36	70.04297	58.42578	65.92578	69.79297
12/07/2015 18:37	69.85547	58.17969	65.30078	69.66797
12/07/2015 18:38	69.91797	58.5	65.53906	71.57813
12/07/2015 18:39	69.72656	59.88672	63.66016	71.99609
12/07/2015 18:40	69.90234	63.65625	62.79297	70
12/07/2015 18:41	69.97266	63.53125	62.40625	70.32031
12/07/2015 18:42	69.72266	61.78125	61.13672	70.20313
12/07/2015 18:43	69.57813		61.23828	70.21875
12/07/2015 18:44	69.43359	59.74219	61.83203	70.54297
12/07/2015 18:45	69.78906	59.00781	64.72656	67.04297
12/07/2015 18:46	69.76172	60.03906	64.03906	69.81641
12/07/2015 18:47	70.72656	62.26563	62.07031	70.96875
12/07/2015 18:48	69.70313	61.18359	62.61719	71.48438
12/07/2015 18:49	69.68359	60.39453	61.07422	77.08594
12/07/2015 18:50	69.63281	58.55469	63.34375	68.05859
12/07/2015 18:51	69.625	58.10547	63.15234	68.66797

12/07/2015 18:52	69.63281	58.69531	65.23047	72.83594
12/07/2015 18:53	69.51953	59.21094	64.09375	73.59375
12/07/2015 18:54	69.68359	57.10156	61.70313	68.16797
12/07/2015 18:55	69.80469	58.28516	61.32422	66.97656
12/07/2015 18:56	69.63672	58.73438	63.00781	64.79688
12/07/2015 18:57	69.82813	58.15625	64.22266	69.71484
12/07/2015 18:58	69.80469	58.83203	63.39844	73.14453
12/07/2015 18:59	69.66016	59.90625	62.75391	69.82422
12/07/2015 19:00	69.65234	58.66406	64.4375	70.87109
12/07/2015 19:01	69.71875	65.20313	62.05859	77.79297
12/07/2015 19:02	70.54297	59.55859	63.23047	70.48438
12/07/2015 19:03	69.88672	60.32813	62.64063	70.39453
12/07/2015 19:04	69.76563	56.77734	64.10938	63.91797
12/07/2015 19:05	69.58594	57.86328	62.99609	64.26172
12/07/2015 19:06	69.78125	59.19141		64.4375
12/07/2015 19:07	69.78516	58.71484	63.68359	68.89453
12/07/2015 19:08	69.71094	59.19531	61.91016	70.375
12/07/2015 19:09	69.58203	58.47656	63.67578	
dB average	**69.89661**	**60.08961**	**64.4644**	**69.7109**



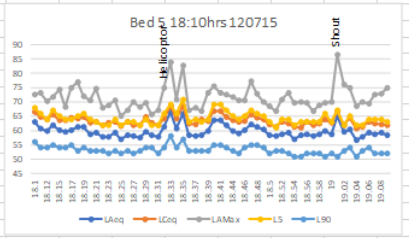
Appendix 6

Completed example of a spreadsheet of a 1-hour observation containing sound pressure levels, source annotation and restorative time. Example taken from Observation 3 Bed space 5 from 18.10 – 19.09hrs on 12/7/2015.

noise emanating from observed bedspace throughout; minimal from adjacent beds spaces; moderate from staff base; observed from window side of bed; patient/relative conversation for a large part of observation; aware of flotron boots throughout

Sunday

		L_{Aeq}	L_{Ceq}	L_{AMax}	L5	L10	L25	L50	L75	L90	R2B	<50	<55	
12/07/2015 18:10	18.10	63.125	66.5625	72.58203	68	67	64	61	58	56	73.7			
12/07/2015 18:11	18.11	60.77734	64.85547	73.24219	66	64	61	58	56	54	71.7			
12/07/2015 18:12	18.12	59.82031	63.86719	70.21094	64	63	61	58	56	54	71.7			
12/07/2015 18:14	18.14	61.90625	65.59766	71.71875	67	65	63	60	57	55	72.7			
12/07/2015 18:15	18.15	60.16797	63.58984	74.46484	65	63	60	58	56	54	71.7			
12/07/2015 18:16	18.16	59.56641	63.69531	68.13672	64	62	60	58	56	54	71.7			
12/07/2015 18:17	18.17	60.26563	64.45313	74.88281	64	63	61	59	57	55	72.7			
12/07/2015 18:18	18.18	61.21875	64.26172	76.89844	65	63	61	58	56	53	70.7			bin lid closing; internal phone ringing; syringe/infusion pump alarm; ventilator alarm; nurse/other; patient/relative
12/07/2015 18:19	18.19	61.4375	64.77344	72.11719	66	65	63	59	56	54	71.7			
12/07/2015 18:20	18.20	58.73828	62.78906	70.66406	64	62	59	56	54	53	70.7			
12/07/2015 18:21	18.21	59.29688	63.17969	74.70703	63	61	58	56	54	53	70.7			
12/07/2015 18:22	18.22	57.71094	62.01172	68.09375	62	60	58	56	54	53	70.7			
12/07/2015 18:23	18.23	57.92969	62.67969	68.82031	62	61	59	56	54	52	69.7			
12/07/2015 18:24	18.24	59.25	63.10156	70.46875	64	63	60	57	55	53	70.7			
12/07/2015 18:25	18.25	56.87109	61.75391	65.01953	62	60	58	56	53	52	69.7			
12/07/2015 18:26	18.26	58.46094	62.92969	67.09766	63	62	59	57	55	53	70.7			
12/07/2015 18:27	18.27	58.27734	61.84375	69.97656	63	60	59	56	54	52	69.7			
12/07/2015 18:28	18.28	57.44531	61.84766	68.14844	62	60	58	56	54	53	70.7			
12/07/2015 18:29	18.29	59.49219	64.6875	69.73828	64	62	60	58	56	54	71.7			
12/07/2015 18:30	18.30	58.42188	62.84375	65.80469	62	61	59	57	55	54	71.7			
12/07/2015 18:31	18.31	57.71484	61.99219	67.125	62	61	58	56	54	52	69.7			
12/07/2015 18:32	18.32	61.24609	64.18359	74.96094	66	64	61	58	56	54	71.7			
12/07/2015 18:33	18.33	66.67188	68.57031	83.94531	69	68	65	62	60	58	75.7			helicoptor; programming infusion/syringe pump; syringe/infusion pump alarm; monitor alarm; nurse/relative; patient/relative; relative/relative
12/07/2015 18:34	18.34	60.81641	64.25391	70.93359	66	64	62	59	56	54	71.7			footsteps; syringe/infusion pump alarm; nurse/patient; nurse/relative; patient/relative; relative/ relative;
12/07/2015 18:35	18.35	65.83203	68.625	82.88281	71	68	66	62	59	57	74.7			helicoptor; procedure at bedside; programming syringe/infusion pump; aprons; ventilator alarm; monitor alrarm; nurse/patient; relative/relative
12/07/2015 18:36	18.36	58.42578	62.57422	67.03125	63	62	59	57	55	53	70.7			
12/07/2015 18:37	18.37	58.17969	62.19922	68.11719	64	61	58	56	54	53	70.7			
12/07/2015 18:38	18.38	58.5	63.89453	66.875	63	62	59	57	55	53	70.7			
12/07/2015 18:39	18.39	59.88672	63.41797	73.21094	64	63	61	58	55	53	70.7			
12/07/2015 18:40	18.40	63.65625	66.67969	75.55078	69	67	64	61	58	55	72.7			bin lid closing; patient/relative; relative/relative
12/07/2015 18:41	18.41	63.53125	66.94141	73.33594	69	67	65	60	57	55	72.7			
12/07/2015 18:42	18.42	61.78125	64.78516	72.47656	67	65	62	59	56	54	71.7			
12/07/2015 18:44	18.44	59.74219	63.71094	71.66016	65	63	60	57	55	53	70.7			
12/07/2015 18:45	18.45	59.00781	62.94141	70.61328	64	62	60	57	54	52	69.7			
12/07/2015 18:46	18.46	60.03906	63.25391	70.53906	65	63	61	58	56	54	71.7			
12/07/2015 18:47	18.47	62.26563	65.55859	77.3125	67	65	63	60	57	55	72.7			chair; internal phone ringing; patient/relative
12/07/2015 18:48	18.48	61.18359	64.60938	72.87109	66	64	62	59	57	55	72.7			
12/07/2015 18:49	18.49	60.39453	63.98047	69.99609	65	64	61	59	56	54	71.7			
12/07/2015 18:50	18.50	58.55469	62.12109	68.69141	63	62	59	56	54	52	69.7			
12/07/2015 18:51	18.51	58.10547	61.44922	66.76172	61	61	59	57	55	53	70.7			
12/07/2015 18:52	18.52	58.69531	63.03516	70.9375	64	62	59	57	55	53	70.7			
12/07/2015 18:53	18.53	59.21094	62.36328	73.08984	64	62	59	56	53	52	69.7			
12/07/2015 18:54	18.54	57.10156	61.17969	69.75781	62	60	58	55	52	51	68.7			
12/07/2015 18:55	18.55	58.28516	61.10938	69.96484	63	61	59	56	53	51	68.7			
12/07/2015 18:56	18.56	58.73438	62.97266	69.80078	63	62	59	57	54	52	69.7			
12/07/2015 18:57	18.57	58.15625	62	66.68359	63	62	59	56	53	52	69.7			
12/07/2015 18:58	18.58	58.83203	62.36328	68.89844	63	62	60	57	54	52	69.7			
12/07/2015 18:59	18.59	59.90625	63.91016	69.75	66	64	60	56	53	51	68.7			
12/07/2015 19:00	19.00	58.66406	62.83984	70.14063	63	62	59	57	54	52	69.7			
12/07/2015 19:01	19.01	65.20313	66.71875	86.54297	67	64	60	56	52	51	68.7			relative shouting; nebuliser; bin lid closing; chair; syringe/infusion pump alram; nurse/relative;
12/07/2015 19:02	19.02	59.55859	61.89453	76.01563	62	61	59	56	54	53	70.7			nebuliser; nurse/patient; aquarius alarm
12/07/2015 19:03	19.03	60.32813	64.44922	74.95313	65	63	59	56	55	54	71.7			
12/07/2015 19:04	19.04	56.77734	60.63672	68.41797	62	60	56	54	52	51	68.7			
12/07/2015 19:05	19.05	57.86328	61.26172	69.91406	62	61	58	56	54	53	70.7			
12/07/2015 19:06	19.06	59.19141	62.92969	69.35156	64	62	60	57	56	54	71.7			
12/07/2015 19:07	19.07	58.71484	62.50391	72.66406	64	62	58	55	53	52	69.7			
12/07/2015 19:08	19.08	59.19531	62.30078	73.03125	64	62	59	56	54	52	69.7			
12/07/2015 19:09	19.09	58.47656	61.77344	74.98828	63	61	58	55	53	52	69.7			
		60.0896145	63.6931796	72.8737421	64.6407683	62.9313342	60.3419483	57.5287455	55.1504329	53.3646344	8.60%	0.00%	0.00%	



Appendix 7

Patient Information Sheet and Consent Form – Study 4

St George's University Hospitals NHS
NHS Foundation Trust

St George's University Hospitals
NHS Foundation Trust
Blackshaw Road
London
SW17 0QT
Tel: 020 8725 1307
Email: deborah.dawson@stgeorges.nhs.uk

Participant Information Sheet (PIS) General Intensive Care Unit

Part 1 -

Study Title: A study to identify the acoustical characterisation of an Intensive Care Unit

Chief Investigator: Deborah Dawson

Invitation to participate in the above study:

We would like to invite you to take part in a research study. Before you decide we would like you to understand why the research is being done and what it will involve for you. Please take time to read the following carefully and discuss it with others if you wish. ***We will go through the information sheet with you and answer any questions you have.*** *We'd suggest this should take about 10 minutes.*

Part 1 of the PIS tells you the purpose of this study and what will happen to you if you take part.

Part 2 gives you more detailed information about the conduct of the study.

Please ask us if there is anything that is not clear. Take time to decide whether or not you wish to take part.

What is the purpose of the study?

The purpose of this study is to measure the sound levels of the general intensive care unit, to identify the sources of noise and how the various noises impact on patients, their visitors and staff. Each bed space has a device located in the ceiling that measures the sound level, it cannot record the individual sounds including any conversation, and therefore the content of any speech that may occur at the bedside cannot be noted or recreated. The individual sounds are being identified during periods of observation; where the researcher will listen for a short period of time, at an individual bed space and record on a chart the many sources of these sounds such as the alarms and speech. This is very valuable information; however we would like to know how the various sounds impact on patients, their visitors and staff. We hope that understanding the actual sound levels, the sources of those sounds and the impact of the sound will enable the future design of more appropriate environments for the benefit of critically patients, their visitors and the staff caring for them. To this end we invite you to participate in completing a sound diary.

Why have I been invited?

You are a patient or a regular visitor of a patient who has required care in the general intensive care unit for 48 hours or more, or member of staff who retains a permanent position on the unit. We wish to understand how annoying the sound levels are for patients, visitors and staff. To understand this we need to ask you what you can hear and how that sound makes you feel. We are asking you to do this at the same time as we are recording the sound levels and observing the individual sources of these sounds. This is why we are asking you to participate over the next few days.

Do I have to take part?

It is up to you to decide whether or not to take part. We will describe the study and go through this information sheet with you. If you decide to take part, you will be given this information sheet to keep and asked to sign a consent form. You are still free to withdraw at any time, without giving a reason. A decision to withdraw

at any time or not take part will not affect the standard of care you or your relative receives or if you are staff, your employment.

What will happen to me if I take part?

You will be asked to complete a sound diary, recording entries on approximately six occasions over a maximum of three days. If you are a patient you may feel too weak to write this down for us. The researcher or one of your visitors can help by doing the writing for you, but you will need to be able to answer some questions on each occasion you decide to complete an entry. All participants, patients, their visitors or staff will be asked the following questions:

- What can you hear?
- How does that sound makes you feel?
- On the last occasion each day we will also ask you to tell us or write down the most reassuring, annoying and frightening sound.

We expect this to take no more than five minutes each time you record your sound diary. The researcher will write the bed space where you are located when recording this information for us, they can then identify the sound levels at the same time as you record or tell us this information.

If you are a patient:

On each occasion before the sound diary is recorded, we will ask you if you are in any pain, if so we will ask you to rate how bad that pain is, we will also record if we have given you any pain medicine in the previous four hours. We are doing this to understand if you have received strong pain killers or are in any pain that may affect your appreciation of the sounds around you.

Expenses and payments

There is no payment for this participation.

What do I have to do?

Should you wish to take part, then we will ask you to complete up to six entries in the sound diary over a maximum of three days. If you are a patient we recognise you may not feel able to do this and sometimes may need some help to write down your entries. These entries ask you to tell us:

- What you can hear
- How that sound makes you feel
- On the last recording each day the most reassuring, annoying and frightening sounds.

It is possible you may be or have been asked to participate in other research studies, as well as this one. This study will not stop you participating in other studies at the same time; however you do not have to do this.

What are the possible disadvantages and risks of taking part?

We do not believe there are any risks in taking part in this study. If you are a patient, the additional work may make you feel tired. If you are too tired you can decide not to complete a diary entry at the time you are asked, but do this at another time when you may feel more able to do this.

What are the possible benefits of taking part?

We do not believe there is any direct benefit to you in taking part in this study. We hope that your participation will help us design a better environment for future patients, their visitor and our staff.

What if there is a problem?

If you have a concern about any aspect of this study, you should ask to speak with the researcher who will do their best to answer your questions (details below). If you remain unhappy and wish to complain formally, you can do this through the NHS Complaints procedure. Details can be obtained from the hospital. You can also contact the Patient Advisory Liaison Service (PALS) telephone 020 8725 2453

Any complaint about the way you have been dealt with or any possible harm you might suffer will be addressed. The detailed information on this is given in part 2

Will my taking part in the study be kept confidential?

Yes, we will follow ethical and legal practice and all information about you will be handled in confidence. The details are included in Part 2.

This completes Part 1. If the information in Part 1 has interested you and you are considering participation, please read the additional information in part 2 before making any decision.

Part 2

What will happen if I don't want to carry on with this study?

You are free to participate or not as you wish and feel able to do so. As patient your care and treatment, or that of your relative will remain the same. For staff there is no effect on your employment if you take part, choose not to take part or withdraw at any time.

If you do not wish to continue with the study then any diary entries already completed will be analysed. If you wish to withdraw your consent completely and for no diary entries to be included in the study then all information previously recorded for this study will be destroyed.

What if there is a problem?

Complaints:

If you wish to complain, or have any concerns about any aspect of the way you have been treated during the course of this study then you may speak with the researchers, Deborah Dawson, Dr Barbara Philips or Dr Mark Hamilton on 020 8725 1307 or the Matrons Lindsey Izard or Susan Reynolds 020 8725 0877 who will do their best to answer your questions or concerns. The normal National Health Service complaints mechanisms are also available to you. If you are still not satisfied with the response, you may contact the Joint Research and Enterprise Office at St George's.

Harm:

St Georges, University of London has agreed that if you are harmed as a result of your participation in the study, you will be compensated, provided that, on the balance of probabilities, an injury was caused as a direct result of the intervention or procedures you received during the course of the study. These special

compensation arrangements apply where an injury is caused to you that would not have occurred if you were not in the trial. We would not be bound to pay compensation where: -The injury resulted from a drug or procedure outside the trial protocol and/or -The protocol was not followed. These arrangements do not affect your right to pursue a claim through legal action.

Will my taking part in the study be kept confidential?

Your confidentiality will be safeguarded during and after the study, all information which is collected about you during the course of the research will be kept strictly confidential. Data collected will be coded so we can identify which bed space you occupied or where working in when the sound diary was recorded. It will also be coded to identify whether you are a member of staff, a visitor or patient. This data is necessary so we can identify the actual sound level in the bed space you were occupying, visiting or working in at the time you recorded your diary entry, this may help to identify whether the sound level or the type of sound is more or less annoying or reassuring.

Initially the information you provide will be recorded on paper, these documents will be surely stored in a locked cabinet of a lockable office. This information will be transferred to a computer for analysis. To ensure we can put all your diary entries together and not muddle them with another person's, we will record your initials, bedspace, age and gender on the form. Your information will not be individually identifiable when the data is presented. We will not make any of the information you have provided available to anyone else. Once the information collected is fully analysed and presented the original data will be destroyed following the Trusts confidential waste policy. Only the researcher and her supervisors will have access to the data, no one caring or working with you will have access to this information.

What will happen to the results of the research study?

The results from this study will provide the data to enable me to submit a PhD Thesis and will therefore be seen by my supervisors and examiners. At the same time the data will be used to inform conference presentations and publications. It is hoped that the data generated from this study will inform further research in

this area and improve the sound environment for patients who are critically ill. You will not be individually identifiable in any report, presentation or publication. If you consent to take part and would like a short overview of the results, we would be very happy to forward this to you. The process of the collecting the data, analysing and writing up the data may take some time, therefore this synopsis may not be available for a couple of years after your participation.

Who is organising and funding the research?

This research is being completed in part fulfillment of a doctoral thesis and is organised by the researcher, Deborah Dawson and supervised by St George's Medical School. No funding for this part of the study has been received,

Who has reviewed the study?

All research in the NHS is looked at by independent group of people, called a Research Ethics Committee (REC), to protect your interests. This study has been reviewed and given favorable opinion by Office for Research Ethics Committees Northern Ireland.

If you should wish to participate in the study you may keep this information sheet and will be given a copy of the signed consent form you signed to keep.

Thank you for taking time to read this.

Deborah Dawson, Consultant Nurse Critical Care St George's University Hospitals NHS Foundation Trust

Dr Barbara Philips, Reader and consultant in Intensive care medicine St George's University of London

Dr Mark Hamilton, Clinical Director and Consultant in Intensive Care Medicine, St George's University Hospitals NHS Foundation Trust

St George's University Hospitals NHS
NHS Foundation Trust

St George's University Hospitals
NHS Foundation Trust
Blackshaw Road
London
SW17 0QT
Tel: 020 8725 1307
Email: [redacted]@stgeorges.nhs.uk

REC Reference Number: 15.0097

Patient Identification Number for this trial: _____

CONSENT FORM

Title : A study to identify the acoustical characterisation of an Intensive Care Unit

Name of Researcher: Deborah Dawson, General Intensive Care Unit, St George's Hospital,

Please initial each box

1. I confirm that I have read and understand the information sheet dated 31/5/2015 version 1.1 of the above study and have had the opportunity to consider the information, ask questions and have these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care (Patients only) or legal rights being affected. ☐

3. I understand that relevant sections of any of my medical notes and data collected during the study may be looked at by responsible individuals from St George's University of London (SGUL) and/or St George's NHS Healthcare Trust (SGHT), the NHS Trust or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to my records. (Patients only) ☐

4. I agree to take part in the above study. ☐

_____	_____	_____
Name of Participant	Date	Signature
_____	_____	_____
Name of person taking consent	Date	Signature

When completed 1 for participant; 1 for researcher; 1 for patient notes

Appendix 8

Example data sheet for the Sound Diary - Study 4

St George's University Hospitals NHS
NHS Foundation Trust

Participant code

Date
Completed at bed space number

CAM-ICU positive/negative (Patients only, one per day)

Time of entry
Average Peak L90 SPL

Pain score (patients' only, record for each sound diary entry)

Sedation/analgesia received in the previous four hours to data entry (Patients only, record for each sound diary entry) Name/dose/time

What can you hear?

How does this sound make you feel?

Describe the most reassuring sound you have heard today (last entry of day)

Describe the most annoying sound you have heard today (last entry of day)

Appendix 9

Transcribed data from Sound Diaries - Study 4

Code	Date	Time	What can you hear	How does this make you feel	Reassuring	Annoying	Frightening
P1	16/03/2017	17.45 - 22.45	lots of beeps and monitor sounds	sometimes I wonder if the beeps are coming from my bed space or not	when it's really silent on the ward and I know everything is OK	the sound of rubbish bins being emptied and loud sound of aprons being pulled out of the holder	the sound of the exit door (by bed 12) being banged- it wakes me when I am sleeping
	17/03/2017	06.45-08.30	the sound of the nebuliser under my neck	It's a bit weird but I know it is clearing my chest	the sound of the nurses walking around when I wake up	loud visitors when other patients are trying to sleep	the sound of the exit door (by bed 12) being banged- it wakes me when I am sleeping
	18/03/2017	08.30-15.30	Banging exit door -very loud	It woke me up and frightened me	no bells or alarms going at all	the sound of nurses chattering loudly, when I am calling for help	
	19/03/2017	07.00-12.00	the sound of the nurses talking loudly	It wakes me up when they are at the bottom of my bed	the sound of nurses coming to my aid	exit door closing loudly	visitors talking loudly
	20/03/2017	07.00-09.00	nurse coming towards me, chatting loudly	wondering what they are going to do to me	no beeps or monitors going off	exit doors again	nurses talking very loudly
P2	27/09/2017		lots of professionals talking, lots of alarms and buzzers, swoosh of aprons being put on, opening closing of bins, airflow from my own oxygen supply	reassured, confident, cared for	two nurses talking in hushed tones about the welfare of another patient	banging of files after lights out, assumed lights out would be volume own	not sure if I heard a frightening sound
P3	06/07/2018	10.45hrs	constantly hearing machines at night	not pleasant, not nice	lunchtime	a machine that goes da, da, da, la ,la (F & P Humidifier)	I have heard one or two bangs, which makes me have flash backs

P4	07/06/2018	15.00hrs	bleeps of monitors, voices	bleeps make me irritable	my nurses voice	bin lids	patient groans
	08/06/2018	11.00hrs	patients iPad	Irritable	my nurse	iPad film	Patient groaning
	09/06/2018	22.00hrs	sounds of cleaner emptying bins, chairs being dragged across the floor	annoyed - trying to sleep	my nurses voice	chairs dragging across floor	n/a
	10/06/2018	9.30hrs	staff/voices	OK	my nurses voice		patient screaming
	11/06/2018	? nightime11.45		voices/staff	Ok	nurses before bed	moving of boxes
	12/06/2018	9.30hrs	voices/staff	OK	nurses voice	moving equipment	patient screaming
P5	16/10/2018	09.20hrs	blinging? noise from the machine	sick and ?	the voice of the nurse asking if I am OK	the noise from the machines I am attached to	the noise of a patient saying she wants to go home and hearing the patient in pain
		09.40hrs	a patient describing his family	it makes me want to be at home	my nurse telling me my results are getting better	my nurse telling me I need to eat more	at night-time when I can hear a patient crying
		09.50hrs	a nurse asking what we want for breakfast	cold and chilled	my mum calling to check I am OK	need to eat more food	at the end of the day a nurse had to get a patient
		10.00hrs	my grandmas voice	it feels like home	my Dads voice telling me it is OK	need to eat more food	anything during the night
		10.10hrs	my nurses telling me to drink and eat more food	it makes me feel calm	the voice of my mother	none	none
P6	28/11/2018	13.00hrs	verbal conversations which are fairly low in volume,	not affected at all			
		13.00hrs	low sound of air pump fixed to the air mattress,	not affected at all	nurses complimenting myself or other patients		

		13.00hrs	other patients sound of agony	feel sympathy for patient	hospital visitor playing beautiful music on harp	not experienced any	not experienced any
		21.00hrs	air pump of air mattress	although sound louder now as silent ward, but still not discomforting, but fine to go to sleep	nurse's encouragement using CPAP	none	none
	29/11/2018	07.30hrs	staff getting ready for the day, movement/stocking of equipment, air pump for air mattress	as it is low level it does not cause any bother or discomfort	none	none	none
		12.00hrs	very low verbal chatter, the air pump for the air mattress, which is low volume	no effect as low volume	nurse words of encouragement and physio's compliments	none	none
P7	28/11/2018	NR	bin lids closing, cupboard doors banging, apron dispenser, squeaking sluice room door all night long,	it makes you jumpy	nurse doing obs	too many people talking at once, over each other	I am used to all sounds now, so none are frightening
		NR	sluice door, bin lids banging	unsettled	when I was left to sleep	apron dispenser	nothing, used to it all now
P8	26/12/2018	14-22.00hrs	everything	annoyed - trying to sleep	my wife	the apron roll	something fell over and made me jump