RELATING ACOUSTICS AND HUMAN OUTCOME MEASURES IN HOSPITALS

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RELATING ACOUSTICS AND HUMAN OUTCOME MEASURES IN HOSPITALS

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To my parents,

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α	Acoustic Absorption coefficient
$\overline{\propto}$	Average absorption coefficient
AI	Articulation Index
ANSI	American National Standards Institute
ASHRAE	American Society of Heating Refrigeration and Air Conditioning Engineers
ASTM	American Standard Test Method
AvgBP	Average blood pressure
B&K	Brüel & Kjær
BP	Blood Pressure
bpm	Beats per minute
BS EN	British Standards European Norm
C_{50}	Clarity (50 ms)
C_{80}	Clarity (80 ms)
CCU	Coronary Care Unit

CD	Compact disc
CPM	Cycles per minute
D	Definition
dB	Decibel
dBA	A-Weighted decibel
dBC	C-Weighted decibel
DiasBP	Diastolic blood pressure
DL_2	Rate of spatial decay
DL_f	Excess sound pressure w.r.t free field
ECG	Electrocardiograph
EEG	Electroencephalagraphy
GMA	Gastric myoelectrical activity
HR	Heart Rate
HRTF	Head related transfer function
HVAC	Heating, Ventilation and Cooling
Hz	Hertz
ICU	Intensive Care Unit
ICUESS	Intensive Care Unit Environmental Stressor Scale
IEC	International Electrotechnical Commission

ISO	International Organization for Standardization
JHU	Johns Hopkins University
jnd	Just noticeable difference
kHz	Kilohertz
L_{Aeq}	A-Weighted average sound level
L_{Amax}	A-Weighted maximum sound level
L_{Amin}	A-Weighted minimum sound level
L_{Cpk}	C-Weighted peak sound level
L_{eq}	Average sound level
L_{MF}	Mid-frequency average
L_p	Sound pressure level
L_w	Sound power level
m	slope of a line
MLS	Maximum length sequence
mmHg	Millimeters mercury
MRT	Modified Rhyme Test
n or N	Sample size
NC	Noise Criterion

NCB	Balanced noise criteria
NRC	Noise reduction coefficient
p	P-value
ρ	Spearman rank correlation
pcf	Pounds per cubic foot
PSG	Polysomnography
QAI	Quality Assessment Index
r	Distance from microphone
R	Room constant
r	Pearson product-moment correlation coefficient
RASTI	Rapid Speech Transmission Index
RC Mark II	Room Criteria Mark II
RC	Room Criteria
REM	Rapid eye movement
Resp	Respiratory Rate
RMS	Root mean squared
RT	Reverberation Time
s_X	Sample standard deviation
SA	Surface area
SE	Standard error
SI	Speech Intelligibility

SII	Speech Intelligibility Index
SIL	Speech Interference Level
SLM	Sound level meter
SO_2	Oxygen Saturation
SPL	Sound Pressure Level
SPL_{500}	Sound pressure level in the 500 Hz octave band
SPO2	Percent Oxygen Saturation
SSDC	Spatial sound distribution curve
STI	Speech Transmission Index
SysBP	Systolic blood pressure
T_{60}	Reverberation Time
THR	Total hip replacement
TKR	Total knee replacement
V	Volume (cubic meters)
WHO	World Health Organization
$\overline{X}$	Sample mean
$z_{\propto}$	Standard score

SUMMARY

Hospital noise has been an area of concern for medical professionals and researchers for the last century. Researchers have attempted to characterize the soundscape of hospital wards and have made some preliminary links between noise and human outcomes. In the past, most of the research has used traditional acoustic metrics. These traditional metrics, such as average sound level, are readily measured using sound level meters and have been the primary results reported in previous studies. However, it has been shown that these traditional metrics may be insufficient in fully characterizing the wards. The two studies presented here use traditional metrics and nontraditional metrics to define the soundscape of hospital wards. The uncovered links, between both sound level metrics and psychoacoustic metrics and patient physiological measurements, are discussed. Correlations and risk ratios demonstrate the presence and the strength of these relationships. These results demonstrate the relationships between hospital acoustics and patient physiological arousal. Additionally, the effects of adding absorption in a hospital ward are presented. Sound level, sound power, reverberation time and other acoustic metrics are directly affected. The speech intelligibility in these wards is evaluated in order to highlight the temporal nature of speech intelligibility. With both studies combined, both traditional and nontraditional acoustic measures are shown to have statistically significant relationships to both patient and staff outcomes.

CHAPTER 1 - INTRODUCTION

1.1 Overview

Fundamentally, hospitals primarily exist as a place to pursue better health and to recover from illnesses. It would seem counterproductive to this basic function of a hospital to expose patients to environmental factors that deter or negatively affect their overall health. Equally concerning is the possibility that the hospital environment can cause a healthy person or staff member to show symptoms of negative health issues due to the environment. Some of these environmental factors for patients and staff members can include infection rates, fall rates, worker footstep/paths, lighting, temperature controls, etc.

One such factor that is increasingly becoming more relevant is the acoustic profile or the "soundscape" of the hospital. Florence Nightingale recognized noise as a potential hazard in the hospital in her book Notes on Nursing in 1859 when she wrote, "Unnecessary noise is the most cruel abuse of care which can be inflicted on either the sick or the well" [1]. Since then, hospital noise research has often been neglected or relegated to unscientific anecdotal stories. Early research, as described in the review portion below, often have a narrow focus, do not use proper acoustical techniques, or do not use rigorous statistics to interpret their findings. However, the research described in this dissertation provides substantive results that combine the fields of acoustics, engineering, architecture, statistics, and environmental medicine.

Specifically, results presented here will relate acoustics to occupant outcomes. In this case, the occupants are the patients and staff that occupy the hospital, and the outcomes include physiological and questionnaire results. The acoustics are defined by a variety of physical measurements and metrics calculations that are described below. The research can basically be broken into two large sections, a) examination of how acoustics relate to patient physiological outcomes, and b) examination of how acoustics relate to staff outcomes. Throughout this research, traditional acoustic metrics are utilized in combination with non-traditional and psychoacoustic metrics to determine these potential relationships. The results will characterize the noise in hospitals, show relevant acoustic metrics that are useful in hospitals, and reveal that statistically significant relationships exist between various acoustics metrics and hospital occupant outcomes.

1.2 Motivation and Hypotheses

As stated briefly in the Overview, the majority of the previous work lacks sufficiently rigorous measurement and analysis of the hospital soundscape. The types of metrics used in previous research and in the World Health Organization (WHO) guidelines written in 2005 [2], in addition to many of the measurement techniques used in previous acoustical studies may give a misleading or incomplete description of the sound environment. This may be because medical professionals with limited experience in engineering, acoustics, noise measurement and noise control have undertaken much of the previous research.

With regard to the types of noise metrics used, several fundamental factors related to ambient noise are thought to influence the response of occupants: 1) the level (or relative-loudness), 2) the potential for task-interference and 3) the quality of the background noise [3]. Level, spectral content, tonality, and temporal pattern are four key components that determine the quality of the background noise. Previous research has shown that these specific quality characteristics of noise can impact human annoyance, concentration, and productivity in indoor office environments [4-12]. Typically, previous hospital noise research reports background noise based only on overall levels—the A-weighted equivalent sound pressure level (L_{Aeq}) [13]. L_{Aeq} provides a single number loudness value but does not provide any information about the other three components of spectral content, tonality, and temporal pattern. Few hospital studies report limited information about the spectral content, but provide little or no occupant outcome results [14]. In this research, all four key characteristics of the background noise will be investigated and related to occupant outcomes.

Other important acoustical characteristics, aside from the background noise, are lacking in detail, as the previous research described below will show. These characteristics include reverberation time (RT) [16], speech intelligibility (SI) [18-23], and psychoacoustic quality. Reverberation time and speech intelligibility are considered important acoustic parameters for buildings [24]. Psychoacoustic qualities, such as the shape of the spectral envelope and temporal variance, have also been shown to be highly correlated to human perception of sound [25]. This research delves into these other important acoustical characteristics to relate the acoustic environment to occupant outcomes in hospitals.

This research is motivated by the idea that noise will affect people in a positive or negative manner. To that end, the natural lines of questioning range from: how does noise affect occupants; what acoustically causes these effects; and how prevalent or strong are these responses to noise?

The research presented pursues the following hypotheses:

- Patient Outcomes (Sweden) Hypothesis
    - Traditional and non-traditional sound level metrics are statistically related to patient physiological outcomes of heart rate, respiratory rate, oxygen saturation, and blood pressure.
- Staff Outcomes (JHU) Hypotheses
    - Traditional sound level metrics and room acoustic metrics (DL_2 (a spatial sound decay metric), reverberation time, clarity, and speech intelligibility) improve with added absorption.
    - Nurse outcomes of perceived annoyance, stress symptoms, specific noise sources, etc. improve with added absorption.

1.2.1 Contribution Breakdown

The research conducted for this dissertation consisted of two projects that both involve large collaborations. The collaborators span the fields of acoustics, engineering, occupational health and medicine. In order to clearly delineate between the creative contribution presented in this dissertation and the collaborator's contributions, Table 1 is presented to provide a breakdown of contributions. The left column presents the teams' contribution to the projects and the right column represents the personal creative contributions made by the author that are presented in this dissertation.

Table 1. Contribution breakdown between team and personal contributions

Team Contribution	Personal Contribution
Metrics affecting patient outcomes (Sweden)	
Initial Measurement Methodology	Data analyses conceptualization and methodology
Patient Measurements	Execution of data analyses
Acoustic Measurements	Developed link between patient physiology and acoustics
	Discussion, interpretation and write-ups
Metrics affecting staff outcomes (JHU)	
Development of panels	Development and conceptualization of measurement methodology
Installation of panels	Development and authorship of the staff questionnaire
	Acoustic measurements with some assistance from a Johns Hopkins University graduate student
	Analyses initiated and executed
	Developed link between staff response and acoustics
	Developed link between noise and room acoustic measures and the installation of absorptive panels
	Discussion, interpretation and write-ups
DL_2 was joint work between the author and Dr. Colin Barnhill	

1.3 Background Literature/Previous Research

1.3.1 Noise in hospitals

1.3.1.1 Overall Levels

A number of articles highlight the importance of appropriate hospital auditory environments or “soundscapes,” with a particular focus in previous work on background noise. The World Health Organization (WHO) has published recommendations for noise levels in an unoccupied room [2]. The recommendations state that L_{eq} in a patient room should not exceed 35 dBA during the day, 30 dBA at night, and that L_{max} should not exceed 40dBA at night [2]. A landmark study tracked published hospital research from 1960 and found that the noise levels have been rising consistently over the years [26]. There have been several studies that have quantified the overall noise levels in different types of hospital wards and care units, with general findings indicating levels ranging from approximately 40 to 77 dB L_{Aeq} [14,15,27-41]. In addition, one study found that doctor’s rounds can exceed 65 dB L_{Aeq} [35]. However, the majority of previous work has focused on overall levels of background noise, with minimal examination of the frequency content, tonality, fluctuations, and other detailed acoustic properties. There are a few hospital studies that analyze spectral information [26] and statistical distributions of level [43]; however, these studies generally do not correlate these detailed properties of noise to occupant response. More recent studies have looked at how the hospital architectural design (i.e., layout) can be contributing factor to hospital noise, reverberation time, and staff response [44]. Please note that for this review section, if no decibel weighting is mentioned or referenced, then the original paper did not specify any weighting.

Researchers have also tried to identify the primary noise sources in the hospital soundscape. Noise sources have been shown to include medical equipment such as cardiac monitors and ventilators, nursing care noises such as patient transfers and moving trolleys, patient noises such as snoring and coughing, and environmental noises such as staff conversation, telephones, and office noises [31]. In one study, nurses were asked to rate how disturbing they perceived certain sources to be. Noises such as beeping monitors, alarms, and telephones were found to be some of the most disturbing noises [46]. The excessive number of alarms in intensive care units (ICUs) were also identified as a concern; for example, it was found that staff could not always accurately identify which alarm they were hearing [49].

Several factors and different types of metrics are thought to be related to the response of occupants. These include—the level (or relative-loudness), the potential for task-interference, and the quality of the background noise [3]. The background noise quality, measured in the above reviews, can be broken into several items: the level, spectral content, tonality, and temporal pattern. General non-hospital-specific previous research with background noise has shown that these specific quality characteristics of noise can impact human annoyance, concentration, and productivity in indoor office environments [4]. The aim of this dissertation is to focus these general ideas into the hospital setting and determine which of these quality factors as well as novel factors will relate to hospital occupant outcomes.

1.3.1.2 Types of metrics and limitations

Most of the previous work in hospital acoustics has focused on overall level. However, previous research in non-hospital domains shows that human perception and task performance are impacted by factors other than level. This section highlights a few of these studies.

Persson et al. found that two signals measured at the same L_{Aeq} can be perceived differently [47]. In that study, two different types of ventilation noise were used as the sound sources—1) the reference noise which was a continuous and relatively even fan noise (noise R) and 2) a similar fan noise with increased low frequency energy (noise L). Each pair of both R and L was played at 40, 50, 55, 60, 65, and 70 dB L_{Aeq}. Subjects were asked to read textbooks for 30 minutes, and then were asked to rate their annoyance. In all case pairs, the low frequency (L) noise was perceived as more annoying than the reference (R) noise. This may imply that L_{Aeq} may not be the best predictor of annoyance, as two noise conditions with similar L_{Aeq} values were judged to be different because of their spectral quality.

Persson Waye and Rylander, in a separate study, reaffirmed that in certain circumstances, L_{Aeq} may not be an adequate predictor of annoyance [48]. This field study focused on long-term term noise exposure in residences. Questionnaires were administered to gather data about annoyance and disturbance of rest and concentration. Subject responses were then compared with in situ noise measurements. Results suggested that low-frequency dominated noise was related to annoyance perception.

Other research has focused on examining how background noise impacts task performance. Some research has looked at how very high levels of noise may affect productivity [51]; however, the research studying how typical office background noise affects worker performance is more limited. Some limited effects have been investigated. For example, the effect of excessive low frequency background noise on task performance has had some attention [4,6,7,54-58]. As described in 1.3.5 on staff effects, some conclusions from these studies are that task performance can be affected by background noise and the spectral content of the noise is important in addition to overall level.

1.3.2 Patient Effects

1.3.2.1 Physiological Principles

Four primary patient physiological factors were examined in this study: heart rate, respiratory rate, oxygen saturation, and blood pressure. The basic physiological principles of each are described in the following sections.

1.3.2.2 Heart Rate

Heart rate is defined to the number of beats per minute the heart beats, or bpm. This physiological measurement can be measured anywhere an artery pulsation exists. Common methods to measure heart rate vary from manual measurements to automated heart rate monitors to electrocardiograph (ECG) measurements. Typically, the resting heart rate for a healthy adult is between 60-100 bpm. Maximum heart rate can be calculated by using stress tests or can be estimated by using various accepted formulas. The maximum heart rate represents the highest safe heart rate an individual should achieve through exercise. However, at rest, the stage of tachycardia is reached when the heart rate surpasses 100 bpm. A higher resting heart rate can be a risk factor for potential health concerns, including heart attacks and cardiovascular stress [59].

1.2.3.3 Respiratory Rate

Respiratory rate is defined to be the number of breaths per minute a human takes. The average respiratory rate in healthy adults falls in the range of 15-20 breaths per minute. Measurement of this metric simply involves counting the number of breaths per minute. However, because of the relatively low number of breaths per minute, measurements are commonly taken over a longer time span to formulate a potentially more accurate average per minute measurement. Some medical conditions such as fever may have a symptom of higher respiratory rate. Additionally, other conditions such as respiratory dysfunction and low oxygen saturation may be related to respiratory rate. Respiratory rate in patients on ventilators can present measurement complications, as the use of respirators can significantly alter the natural resting respiratory rate of the patient [59].

1.3.2.4 Oxygen Saturation

Oxygen saturation is a physiological metric that is determined as the percentage of hemoglobin binding sites that have oxygen bound to it. Measurement of oxygen saturation is generally done with a pulse oximeter. The pulse oximeter clips to a fingertip or earlobe and measures the absorbance of a red light. Typical healthy adults will have oxygen saturation between 97-99%. If oxygen saturation falls below 90%, hypoxemia may occur, and if saturation falls below 60%, blood and oxygen supply to an organ may be reduced, resulting in tissue damage. This can be linked to conditions such as hypoglycemia, tachycardia, hypertension, embolism and other diseases related to low blood supply to organs [59].

1.3.2.5 Blood Pressure

Blood pressure is the pressure that blood exerts on the walls of the arterial vessels. Generally, in one heart beat cycle, the blood pressure will vary. The maximum pressure during this cycle is the systolic pressure, whereas the minimum pressure in this cycle is the diastolic pressure. Blood pressure is often reported as the systolic over the diastolic value, i.e., 114/74 mmHg represents a systolic value of 114 mmHg and a diastolic value of 74 mmHg. Additionally, the averaged pressure during this cycle can be called the mean arterial pressure. The most common method of blood pressure readings is an external measurement made at the brachial artery on the arm. A common device used is a sphygmomanometer. This procedure records the height of a column of mercury; the unit of measurement is given in millimeters of mercury, mmHg. Another blood pressure measurement method is an invasive method where the pressure is measured through an arterial line. These invasive measurements are generally only done in hospital environments.

A commonly accepted value of blood pressure for healthy adults is 120/80 mmHg. Values tend to vary from individual to individual and can even vary from arm to arm or by measurement type. However, studies have shown that risk of cardiovascular disease can rise when blood pressure rises higher than 115/75 mmHg. Prehypertension can be diagnosed when systolic blood pressure is higher than 120/80 mmHg. Stage 1 hypertension occurs at 140/90 mmHg. Hypertension can signify cardiovascular disease that can lead to heart attacks, strokes, and renal failure [59].

1.3.3 Review of Physiological Effects

This section of the review surveys the existing literature on the effects of hospital noise on human occupants. This review specifically tries to address studies of hospital noise and their effects. Studies that described aspects of hospital patient or staff well-being but did not specifically address noise were not considered. For example, studies that investigated sleep disruption and arousals but without addressing noise-induced arousals were eliminated from this review. The main areas of focus of the search were:

- Patient sleep disturbances
- Patient cardiovascular responses
- Length of hospital stay
- Patient pain management
- Patient wound healing
- Staff job performance
- Staff stress
- Staff burnout and annoyance
- Staff hearing loss
- Staff psychosocial environment
- Visitor responses to noise

1.3.3.1 Search Strategy

The literature search originated from two strategies. In the first strategy, references of known papers in the field were located and systematically screened for articles of interest or disinterest. The second strategy employed the use of Internet search engines including academic search engines of PubMed, JSTOR, and JASA, along with the more widespread engines of Google and Google Scholar. Examples of the keywords used were: hospital noise, wound, wound healing, noise wound, noise sleep, and noise pain. Abstracts and articles were methodically screened for relevance. In general, studies were only considered if they were published in peer-reviewed journals. Studies that described aspects of hospital patient well-being but did not specifically address noise were not considered. For example, studies that investigated sleep disruption and arousals but without addressing noise-induced arousals were eliminated from this review.

1.3.4 Patient response

Noise has the potential to negatively affect patients during their stay in a hospital. Previous studies have used experimental results and questionnaire survey data to explore psychological and physiological effects on these patients. One large group of studies has concluded that noise is a major factor in sleep disturbance. Additionally, noise is linked to an altered cardiovascular response—specifically, that hospital noise affects heart rate and blood pressure. Other studies have correlated noise to pain management, healing rate, length of hospital stay, and gastric myoelectrical activity functions. This section will discuss the previous research dealing with patient response to noise.

1.3.4.1 Sleep disturbance

Noise-induced sleep disturbance can be a culprit in negative psychological and physiological effects. The majority of research has focused on how noise affects the length, quantity, and quality of sleep. One method of quantifying sleep quality is by using polysomnography (PSG) [61,62]. A PSG records physiological parameters in sleeping and waking subjects while being able to analyze multiple organ systems such as the respiratory system and nervous system. At least ten of the following twelve parameters are collected—data on the central lead, occipital lead, right eye, left eye, chin, right leg, left leg, electrocardiogram, airflow, thoracic effort, abdominal effort, and arterial oxygen saturation. Other methods often make use of structured questionnaires, interviews, and electroencephalography (EEG). An EEG measures electrical activity in the brain by placing electrodes on specific parts of the head and often is one testing aspect of a PSG.

Using these techniques, researches have been able to track noise-induced sleep disturbances in hospitals [63].

The use of PSG can be a useful tool in studying sleep disturbances. As early as 1976, investigators studied how the quality and quantity sleep in a respiratory intensive care unit was affected by the noise. Investigators used PSG, interviews, and the observations of ten patients of a respiratory intensive care unit (ICU) [63]. The patients were monitored for 48 hours and exposed to noises such as speech sounds, equipment noise, alarms, phones, tapping of chairs and rails, radio noise, construction noise, and heating ventilation and air conditioning (HVAC) noise. None of the ten patients completed one undisturbed sleep cycle, and only one patient had sufficient sleep time for even the possibility of a complete sleep cycle. The study concluded that patients would have difficulty sleeping normally due to interruptions such as noise caused by personal and environmental noises. Other studies complement this result. For example, Aurell and Elmqvist studied nine subjects in a postoperative ICU using both PSG and EEG as well as interviews [64]. The sleep PSG and EEG recordings lasted a maximum of 83 hours or until the patient was discharged. However, in this study, a reduction of environmental noise was also made to compare the quiet environment to the noisy environment at night. The degree of change was unreported, but with these acoustical alterations, all nine subjects experienced sleep deficiencies.

There are also studies that utilize PSG to account for arousals and awakenings due to noise. Although the percentage slightly varies in each study, it can be generally shown that roughly 11-20% of arousals and awakenings are due to noise [65]. In the experiments involving sleep disturbance, researchers have focused on disturbances that occur within three seconds of a measurable increase in noise, e.g., greater than 15dB.

Other studies investigated specific aspects of sleep and disturbances. The interaction between noise and the suppression of rapid eye movement (REM) sleep was studied with a sample of seventy women, comparing quiet conditions with noisy conditions [70]. Although the study took place in a sleep lab, the subjects were exposed to a recording of nighttime coronary care unit (CCU) noise that was calibrated to an alarm at 84 dB. This study concluded that noise does affect the quality of REM sleep compared to patients in quiet conditions. These subjects exposed to noisy (CCU) noise experienced shorter REM periods and less REM activity. The authors concluded that noise acts as a suppressor to REM.

Another study tested five adults to see if acoustic stimulation can cause a sleep disturbance [71]. Additionally it investigated how the presence of electrocortical arousal and inhaled carbon dioxide correspond to sleep arousal. They concluded that an EEG arousal could be evoked in non-REM sleep with an acoustic stimulation. The acoustic signals consisted of two binaural tone bursts: 1) a 0.5-second 4 kHz tone at 85 dB SPL and 2) a 99-second interstimulus interval produced by a tone generator. Furthermore, they found increased respiratory activity after an acoustic stimulation that was independent of general electrocortical arousal.

Aaron et al. sought to determine the level and number of sound peaks of noise needed in order to create an arousal [72]. This study took place in an intermediate respiratory care unit. Sound level information was recorded in 60-second periods. 24-hour polysomnography measurements were made for the sleep analysis. Although this study only had a sample size of six subjects, the researchers concluded that sound peaks greater than 80 dBA can correlate to sleep arousals. Freedman et al. used a larger sample size of twenty-two patients in a medical ICU—20 of these patients were mechanically ventilated [76]. Taking sound level measurements three inches of the patient's head, the mean noise level was 59.1 dBA in the day and 56.8 dBA at night. These were measured in 1-minute intervals in either 24 or 48-hour measurements. They found that environmental noise was not main reason for fragmentation in sleep, but that noise is partially responsible; specifically, 11.5% of the total arousals were related to environmental noise.

However, there is some disagreement about whether the absolute peak levels alone are a factor in sleep disruption or if the differences between peak and background levels are more important. Five subjects were tested and 1178 arousals were recorded using PSG during a study [73]. Subjects were exposed to recorded sounds from an ICU that included sounds from patient-staff interactions, alarms, ventilators, equipment noise, and other background noises. Another recording combined these sounds with white noise. The average level of the ICU noise-only was 57.9 dB and the combined ICU and white noise recording averaged 61.1 dB. The addition of this white noise lowered the number of sleep arousals caused by ICU noise even though the average sound level increased. The authors suggest that this may be attributed to increasing the baseline noise level and reducing the difference between peak levels and noise levels. This essentially decreases the change in ICU noise intensity by raising this baseline sound level with the use of additional white noise.

Another study compared the different contributions of ICU noise and patient-care activity noise to sleep disruption [68]. Six healthy male patients and seven mechanically ventilated male patients were studied using a 24-hour PSG and a structured questionnaire was administered to the healthy subjects. For the mechanically ventilated subjects, the average daytime noise level was 56.2 dB and the average nighttime noise level was 53.9 dB. For the healthy subjects in an open ICU, the average daytime level was 55.6 dB and the average nighttime level was 51.4 dB. The healthy subjects in a single room experienced average daytime levels of 44.3 dB and average nighttime levels of 43.2 dB. They determined that the ICU noises and patient-care activities accounted for less than 30% of the sleep disruptions. Furthermore, the opening and closing of the main door of the ICU, which was close to the room, accounted for the remaining arousals and awakenings. The seven mechanically ventilated patients generally exhibited a higher awakening index and a shorter sleep time as compared to the healthy group—6.2 hours of sleep time for the mechanically ventilated subjects compared to 8.2 hours for the healthy subjects in an open ICU and 9.5 hours for healthy subjects in a single room. They also determined that about half of the patient's sleep occurred during the day.

Questionnaire-only studies have also analyzed the relationship between noise and sleep disturbances without the use of physiologic measurements [64]. The use of questionnaires is one method in describing the effect of noise on sleep. Sixty females were exposed to an eight-hour audiotape of coronary care unit (CCU) noise that consisted of sounds such as equipment noise, monitoring devices, ventilators, suction machines, drains, oscilloscopes and sounds from staff [74]. The subjects reported a general negative impact on sleep, specifically a longer time to fall asleep, more awakenings, and fewer hours sleeping. Another questionnaire survey of 50 general ICU patients used the Intensive Care Unit Environmental Stressor Scale (ICUESS) and revealed that high stressors such as pain and noise were also factors in patients' inability to sleep and the authors suggest that interventions in lowering noise levels could allow for better sleep [75]. Furthermore, a study of 203 patients revealed that patients felt their sleep was significantly worse in an ICU than at home [76]. Specifically, staff communication and alarms were the most disruptive to sleep, whereas telephones, televisions, beepers, and equipment noise were not as disruptive.

An observational study without a questionnaire can also provide insight into how noise affects sleep [77]. The investigators observed these patients in either 24-hour periods or 8-hour periods. All but three of the patients in the ICU participated, but a specific sample size was not given. Patients were interviewed and asked about sleeping patterns at home, in previous hospitalizations, and in the current hospitalization. Additionally, staff members observed the patients as "frequently as possible" without structured questioning, and one final staff observation following the release from the ICU. Each staff observation consisted of logging interruptions, such as identifying discrete events that impacted the patient in a direct manner, such as the taking of blood pressure, noting the nature, duration and response of the interruption. They observed that the main deterrent to sleep was activity and noise.

Other changes that can be made are behavioral changes with the staff. Behavioral modification programs can be developed by studying the factors that can potentially cause sleep disturbance. One such program implemented a non-disturbance period in a neuro-intensive care unit [79]. Additionally, they adopted noise-reducing medical and nursing routines, and afternoon and night non-disturbance periods. This before and after study analyzed two groups: nine patients in the first group and fourteen patients in the second group. The total number of sleep disturbance factors over a one-week span prior to the behavioral modification program averaged 194.3 sleep disturbances. This is contrasted by an average of 162.1 sleep disturbances after the behavioral intervention. Another program studied by Walder et al. implemented five guidelines including the systematic closure of doors, a reduction of intensity of alarms, efforts for low conversation, and coordination and limitation of nursing interventions in sleeping hours [80]. This study showed a lowering of average and peak levels after the changes but reported that sleep patterns could still be disrupted. A similar study by Kahn et al., located in both a medical and respiratory ICU, attempted to reduce peak noise sources [81]. An observer was present in the measurements to note the noise sources. They recorded noise sources such as HVAC noise, medical equipment noise, televisions, telephones, intercoms, beepers and conversational noise. Before behavioral modification, the peak levels for these sources were between 74.8 and 84.6 dBA with the mean peak level as 80.0 dBA. After the program was implemented, the mean peak level was reduced to 78.1 dBA. Analyzing the total number of peaks that exceeded 80 dBA, overall there was significant reduction (p<0.001) in the total number of peaks that exceeded 80 dBA, from 1,363 periods out of 2,880 possible periods to 976 periods out of 2,811 possible periods. Specifically, between 6am and 12am, there was a significant reduction of sound peaks exceeding 80 dBA. Divided into 6-hour blocks, there was roughly a 22% decrease in peaks exceeding 80 dBA between 6am-12pm, a 42% decrease from 12pm-6pm, a 35% decrease from 6pm-12am, and a 30% increase from 12am-6am. The authors suggest that sleep can be improved due to this reduction of sound peaks, but left the topic for a future study. Furthermore, Xie et al. also performed a literature review on the impact of noise reduction strategies in ICUs and their impact on patients' sleep and concluded that staff conversation and alarms are the most disturbing noise sources, that acoustic absorption can be effective for noise reduction, and sound masking could potentially be the most effective technique for improved sleep [82].

Studies show that other factors of the acoustic environment besides noise have also been correlated to sleep disruption [78]. One such study, which took place in a refurbished former surgical ward, focused on the effects of reverberation time on noise-induced sleep arousals using EEG. Twelve subjects were used and the reverberation time was reduced by an average of 0.124 seconds, from originally around 0.47 seconds to about 0.35 seconds after the installation of sound absorptive ceiling tiles. Noise ranged from 27-58 dB(A), coming from both continuous and impulsive sources such as dropped plates, traffic noise, fan noise, machine noise, doors closing, and radios. The researchers were able to show that the installation of the sound absorptive ceiling tiles did not significantly change sound levels, but did significantly reduced the number of arousals during sleep.

In summary, the sleep of patients has been shown to be affected by the presence of and exposure to noise. A number of research methods, including PSG, EEG, patient questionnaires, and observational studies have confirmed the relationships between noise and sleep length, quantity, or quality. Specifically the occurrence rate of sleep arousals tend to rise with the exposure of heightened background or peak levels. Attempts to make reductions in the background noise, through acoustical modifications or behavioral program changes have shown to be effective in raising the quality of sleep.

1.3.4.2 Cardiovascular response

Cardiovascular response is also related to the acoustical environment. Some of the earliest studies have revealed that heart rate, blood pressure, and other cardiovascular measures can be affected by noise levels greater than 70 dB [15]. Falk et al. studied the relationship between vasoconstriction and noise intensity and bandwidth. At noise levels greater than 70 dB, there exists a linear relationship between increases of sound intensity and increases in vasoconstriction [15]. Further, an exposure to 90 dB of white noise can cause an immediate vasoconstriction with the recovery time of about 25 minutes after the white noise was turned off. The severity of vasoconstriction, as stated in this research, is a function of bandwidth of the noise—as the bandwidth increases, the vasoconstriction worsens. In another study by Cartwright and Thompson, an increase in diastolic blood pressure and change in heart rate was observed when humans were subjected to loud industrial noise of 85-90 dB [84]. Furthermore, Andren tested 18 males, exposing them to 20 minutes of 40 dBA recumbent noise and 20 minutes of 95 dBA noise [85]. Diastolic blood pressure had a significant increase although systolic blood pressure had no change. Although these studies did not specifically use hospital noise as the source, the cardiovascular response to loud noises may provide insight into the sounds experienced in hospitals.

Another study by Conn related heart rate, frequency of arrhythmias and state of anxiety during quiet and noisy periods in a CCU [86]. Twenty-five male patients in a CCU were exposed to one-minute noise recordings between 3-4 pm and 7-8 pm. The results showed that anxiety was heightened and the number of ventricular arrhythmias rose significantly during the “noisy” periods, defined to be periods of noise greater than 55 dB.

Further research has related changes in heart rate with types of noise source [87]. One study sampled heart rate every two minutes for six hours to attempt to relate cardiovascular response to human and non-human sounds in a typical CCU. The average heart rate increased due to the presence of human sounds. In 1992, another study of 28 patients in a surgical ICU showed that there was an increase in heart rate due to talking inside a patient’s room [32]. The average sound levels ranged from 49.1 to 68.6 dBA recorded in six-hour noise measurements taken three feet above the patient’s head. When there were noise events that caused an increase of 3 dBA or greater in overall level, 89% of the tests showed an increase in heart rate more frequently than a decrease in heart rate. For 46% of the tests, this increase was statistically significant. When sound pressure levels showed a 6 dBA increase, the heart rate also rose from two to twelve beats per minute. Additionally, they found a statistically significant increase in heart rate for impulse noise sources, from 91.5 beats per minute before the impulse to 93.3 beats per minute during the impulse, back to 91.2 beats per minute two minutes following the impulse. A similar study compared ambient stressors of equipment sounds to social stressors like conversation in a CCU [88]. Measurements were taken three times a day over two days with twenty subjects. 55% of the hospital noise was conversation in the room, 20% of the noise originated from background sound, 15% from hall conversation, and 10% from environmental sound. They found that the noise did not significantly affect blood pressure. However, heart rate was elevated during conversations compared to quiet ambient conditions. Also, they found that the heart rate was about three beats per minute faster during conversational sounds than during environmental sounds.

Similar to the sleep study with variable acoustics described earlier [78], a study was performed to examine blood pressure and heart rate in a "good" and "bad" acoustical environment [89]. The group studied contained 94 patients in an intensive coronary heart unit. The change in environment was due to the addition of absorptive acoustical ceiling tiles that decreased reverberation time from 0.8 to 0.4 seconds in the main work area and from 0.9 to 0.4 seconds in the patient rooms. Also, the absorption allowed for a decrease in overall sound level of 5-6 dB in the patient rooms. Even though there was no significant difference across the entire group in heart rate, blood pressure, or pulse amplitude, there were significant differences when analyzing the data by degree of disease. In acute myocardial infarction and unstable angina pectoris groups, the heart pulse amplitude was higher with the "bad" (i.e., less absorptive) acoustical setting at night. Additionally, patients in the "bad" acoustic setting were re-hospitalized more frequently at one and three month follow-up ($p<0.01$).

A study by Sonnenberg examined the link between cardiovascular response, mental stress, gastric acid secretion, and noise [90]. There were two parts to this study, one tested ten male subjects and exposed them to 90 dBA of broadband noise for one hour. Blood pressure, heart rate and respiratory rate were measured. The second part of the experiment tested 14 male subjects. The subjects' gastric response was tested after exposing them to 90 dBA of broadband noise and a gastric stimulation. Gastric acid was sampled and analyzed. This study showed that both diastolic and systolic blood pressure increased by 4 and 8 mmHg, but heart rate and respiratory rate were not affected.

However, the noise did not affect gastric acid secretion. The authors also reported previously unpublished results by J.F. Erckenbrecht that found that noise significantly increased small bowel transit time, stool frequency, and stool volume.

Cardiovascular responses are shown to be related to the patient's noise exposures. These studies above give examples of occurrences of vasoconstriction, increases in heart rate and blood pressure due to the presence of acoustical stimuli. Additionally, tachycardia, anxiety, and arrhythmia episodes are more frequent in these noisy scenarios. The addition of acoustic absorption can help offset the levels of noise and reduce the negative effects of noise on heart pulse amplitude and incidence of re-hospitalization. However, as a whole, results are not entirely consistent with each other, with some studies showing changes in heart rate or blood pressure due to the exposure to noise, while other studies claiming no changes.

1.3.4.3 Length of hospital stay

Noise in the hospital can affect the average length of hospital stay [91]. One report compared the hospital stay length of 416 cataract patients during periods while the hospital was and was not under construction. They showed that the hospital stay was longer for patients who endured construction noise than for the patients that were free of construction noise, with average length of hospital stay increasing about one day in the noisy construction periods.

1.3.4.4 Pain

The pain experienced by patients can also be affected by the noise encountered by the patient. A study by Minkley related the range of sound levels to the number of patients requiring pain medication, such as narcotics, in a ten-bed recovery room [92]. It was found that an increase in noise caused an increase of necessary pain medication. The noise, reaching 60-70 dB, included crying, laughing, groaning, snoring, telephones and jocular comments. They hypothesized that these jocular comments led to a feeling of resentment by the patients. Contrarily though, noise can be used into reduce pain sensations when the patients can control the noise [93]. One-thousand dental patients were exposed to ordinary dental office sounds such as dental drills. The patients wore earphones and they were able to adjust the level of either orchestral music or white noise. 65% of the patients were able to use this audio analgesic effectively for procedures that usually elicit the use of nitrous oxide or local anesthesia.

1.3.4.5 Wound healing

Wound healing and noise has thus far primarily been studied in animals. One experiment exposed rats to 80 dB of rock music for a 22-hour time period and then measured changes of leukocyte function [94]. The rock music was turned off for 90 minutes every two hours to prevent habituation. Additionally, a radio station with varied programming was used. This experiment showed that lymphocyte function remained unchanged in the presence the noise. However, short-term noise exposure of noise stress induced on rats did cause an alteration of superoxide anion and interleukin-1 secretion of neutrophils and macrophages, thus decreasing wound healing. Further studies investigated wound healing in rats exposed to intermittent noise. By measuring wound surface area, they found that the wounds healed slower in the group that was exposed to random white noise at 85 dB [95]. The noise was played intermittently for 15 minutes for 19.5 days. Additionally, the average weight of the exposed group of rats was lower even though food intake was the same between the exposed and unexposed group. In yet another study, 119 mice, exposed to temperature and noise stressors, were inflicted with a small wound [96]. The noise stressor consisted of 99 dBC white noise. Healing rate was measured by the reduction in wound area per day. They found that noise slowed down healing, but this noise also affected the healing rate less than temperature stressors. Healing rate, measured by the hormone secretion of the suprarenal cortex, can also be used [97]. 124 albino rats had a patch of skin removed from part of the back. Healing rate was measured by two methods at the end of the experiment: the size reduction of the wound and by the weight of the suprarenal gland. The rats were exposed to certain environmental stressors that included flashes of light, the impulsive sounds of a ringing bell, and the continuous sounds of scraping metal wheels. Sound levels were not reported. They concluded that these stressors slowed the healing of wounds in male rats but not female rats. Within the male group, the average difference in total healing between the exposed rats and the control rats was about eight days.

1.3.4.6 Other Responses

Noise has also been shown to have unclear effects on gastric myoelectrical activity (GMA) and the autonomic nervous system function [98]. GMA controls the motility of the stomach and the contraction of the stomach muscles. The normal GMA in humans is about three cycles per minute (CPM). In one study, twenty-one male subjects were exposed to a 110-minute recording, played through headphones, that simulate different noise sources—hospital noise at 87.4 dBA, conversational noise at 91.3 dBA, and traffic noise at 85.6 dBA. It was shown that although GMA normally changes with age, hospital noise and traffic noise exposure can significantly decrease the percentage of

3 CPM activity. There was also a decrease in percentage of 3 CPM activity with respect to conversation noise, but this was not statistically significant.

An experiment with conflicting results showed no relationship between gastric secretion and noise [99]. Fifty dyspeptic subjects were exposed to 95 dB pink noise for 15 minutes. Gastric juice samples were taken in thirty-minute intervals. This study was not able to find any link between gastric secretion and noise. Some of their results showed an increase in secretion levels, some showed a decrease, while other results showed unchanged levels.

Additionally, patient disturbance due to noise was studied by Akansel and Kaymakci. Using 25 coronary artery bypass graft surgery patients and a questionnaire, they aimed to measure noise levels in the ICU and record the disturbance levels of patients. They found that noise levels (between 49 and 89 dBA) did not change much between different ICU locations and that other patient noises, as well as alarms and staff conversations were the most disturbing noises. Other disturbing noises came from nurse shift changes and sudden unexpected noises [100].

Noise levels have also been used as an indicator for potential infections after a surgery. Kurmann et al. measured 35 open abdominal procedures, took noise measurements throughout the surgeries, evaluated the operation using a questionnaire, and looked at the surgical site infection rate within 30 days of the surgery. They found that noise volume was a linked to a higher surgical site infection rate. The median sound levels for the patients who developed a surgical site infection were reportedly 43.5 dB versues 25.0 dB. The authors suggest this may be due to lack of concentration, a stressful environment, or even difficultly performing surgery [101].

1.3.5 Staff response

In addition to patient response, there is a general concern over the exposure of staff to hospital noise. Staff members occupy the hospital for extended periods and can be exposed to occupational health hazards due to the noise. Some of the hazards include impaired job performance, inducement of stress that can cause burnout, hearing loss, and a change in the psychosocial environment of the hospital. This section details some of these effects.

1.3.5.1 Job performance

Job performance is a priority among hospital staff. Any impairment of job performance that can cause mistakes to occur may negatively impact patient care. Thus, an understanding of how noise affects job performance is necessary.

Noise in an operating theater and the effects on the productivity and effectiveness of the workers has been examined in a few studies. In a study by Hodge and Thompson, intermittent noises reached 108 dB in an operating theatre [102]. Noise measurements were taken in representative 5-minute segments. Overall levels met recommended levels for a satisfactory working environment according to the Standards Association of Australia, with occupied L_{Aeq} = 51 dBA and background noise levels of 13 dBA. However, the recommended speech levels were exceeded, thus making communication challenging. Thus, the authors concluded that the concentration of the physicians is put at a direct risk by the levels of noise in the operating theater. A similar study concluded that noise levels up to 96 dB can occur in operating rooms, thereby causing similar problems [103].

The effect of noise in an operating room on anaesthetists has also been studied [104]. An operating room was measured to have a noise level of 77 dBA. By exposing twenty anesthesia residents to recorded operating room noise equivalent to 77 dBA, the residents experienced deterioration of both their mental efficiency and short-term memory due to the exposure to this noise.

Contrarily, there have also been studies showing noise does not affect staff performance [105]. Twelve anesthetist trainees were tested on psychomotor performance while being exposed to music, silence, white noise, and classical music [105]. Sound pressure level was not reported, rather the volume was adjusted to a “comfortable” level. There was no experimental effect of any of these noise sources on the trainees’ psychomotor performances. Moreover, a study involving twelve laparoscopic surgeons showed they also were not affected by noise or music [106]. They were given three scenarios for this experiment: 1) exposure to white noise at 80-85 dB or representative background noise, 2) music that was at their own preferred level, or 3) a quiet condition. These surgeons had the task of placing three laparoscopic sutures on a suture pad. The researchers theorized that the surgeons were successfully able to “block out” disturbances.

1.3.5.2 Stress & burn-out

To understand the effects of noise on stress, it is important to understand some of the effects of stress independent of noise. Later in this subsection, the connection of noise and stress will be made.

1.3.5.3 Stress studies (non-noise)

Stress can drastically change the way workers feel about their overall job satisfaction and psychological health. Using a questionnaire study of 180 critical care nurses, one study showed that higher levels of perceived stress were related to lowered job satisfaction and a larger occurrence of psychological symptoms [107]. Stress therefore can be seen as having a negative impact on the staff. Ways to measure stress become imperative in any experiment dealing with stress.

A common method of stress testing involves measuring salivary cortisol. Cortisol has been coined the "stress hormone" because the human body releases higher levels of cortisol during periods of stress. One study examined 112 nurses and 27 physicians and their cortisol levels [108]. Subjects consisted of neonatal and pediatric critical care unit staff. Salivary samples were taken every two hours and after 15-20 minutes after stressful events. As expected, there were high rates of cortisol increases in the "stress-exposed healthcare environment." However, researchers discovered that these cortisol increases occurred even during routine events. Furthermore, they showed that professional experience of less than eight years does not reduce the amount of cortisol released. These increases occurred regularly, frequently, and even happened without the perception of stress by the worker. The authors of this study also conclude that this increase of psychological stress may lead to an increased rate of burnout.

Another study dealing with cortisol levels sampled 84 nurses from pediatric ICU, oncology wards, and children's medical wards [109]. Researchers targeted cortisol levels to help identify the most prevalent stress factors, in an effort to develop possible organizational changes to reduce stress. Cortisol levels can also be used to measure endocrine activity. Salivary samples were taken every two hours. They observed that this endocrine activity, resulting in changes in cortisol levels, could be used as an indicator of stress when simple questionnaires may not be conclusive. They also found that some organizational interventions such as a shift in the nurses' hours and delayed ward rounds for doctors could help reduce cortisol levels and therefore potentially reduce stress.

A self-administered questionnaire test of 73 female emergency department nurses and 50 general ward nurses was used to study how perceived stress relates to salivary cortisol levels [110]. By taking a sample in the morning and one in the afternoon, they found that the morning salivary cortisol concentration is a better indicator of stress as opposed to the afternoon sample.

The established link of stress and the release of cortisol is a concern for hospital staff. One of cortisol's detrimental effects is the possible impairment of memory. This could directly hinder the job performance of the hospital staff [111]. In a non-human study, investigators exposed rats with a footshock and tested their abilities to get through a water-maze [111]. Those rats exposed to the footshock thirty minutes before testing experienced impaired performance. A human study, done in two stages, tested the link between stress and memory [112]. The first study had 13 subjects, and the second study had 40 subjects. In the first study, the subjects underwent a psychosocial laboratory stress test and a declarative memory test. The psychosocial laboratory test consisted of a public speaking task and a public mental arithmetic task. The declarative memory task consisted of a presentation of a list of 24 nouns and the task of writing down all the words that start with certain letters. In the second stage, the subjects were orally given 10 mg of either cortisol or placebo and they were administered declarative and procedural memory tests.

The first stage showed a significant negative relationship between memory task performance and cortisol levels induced by stress. The second stage showed that those subjects who received cortisol had impaired performance on the tests.

1.3.5.4 Noise and Stress

As evidenced by the studies above, salivary cortisol measurements are commonly used in stress testing. Bigert et al. further demonstrated that salivary cortisol measurements can be used to relate stress to non-hospital noise [113]. Their study focused on people living near airports. In each individual case, five samples of salivary cortisol were taken a day, with at least 3 days being sampled. In a group analysis, three samples a day across just one day were found to be sufficient. Although cortisol can be obtained from different sources, the use of saliva offers the option of a noninvasive procedure to collect samples.

There have also been some preliminary studies linking noise-induced stress to health problems such as headaches on the job [114]. This questionnaire study consisted of 100 critical care unit nurses. They rated the hospital sounds on a five-point scale. The rated sounds included telephones, televisions, conversational noise and visitors. There was also preliminary evidence that these noise-induced stressors alter a person's characteristics and health. Noises such as beeping monitors, alarms, and telephones were found to be some of the most disturbing noises. Furthermore, they showed that a noise-sensitive nurse was not at increased risk for burnout.

Another study used a questionnaire, salivary amylase analyses, and heart rate measurements to see if noise could be related to nursing stress and annoyance among 11 tertiary care pediatric ICU nurses [115]. Daytime sound levels averaged 61 dBA and nighttime levels averaged 59 dBA. Saliva samples were taken every thirty minutes over a three-hour period. The noise was not shown to have a correlation to salivary amylase, but was shown to have a significant effect on heart rate, time spent in tachycardia, stress levels, and annoyance levels. As stated earlier, tachycardia is the state of elevated heart rate. They concluded that average heart rate increased 6 beats per minute for every 10 dBA increase in average sound level. Subjective stress and annoyance levels were tested using the Specific Rating of Events Scale. This scale ranges from 0 to 100, with 0 being "not at all stressful" to 100 being "most stress possible." The increase of 10 dBA in average sound level caused a 30-point increase in annoyance ratings and a 27-point increase in stress ratings. Effect on tachycardia was tested by the total amount of time spent in tachycardia. An increase in 10 dBA in average sound level resulted in a 20% increase in time spent in tachycardia. This increase though may be offset by work experience, with a 12% decrease in time for each additional year of nursing experience.

1.3.5.5 Hearing loss

Perhaps the most obvious effect of noise is the hearing loss of workers exposed to high levels of noise. Levels during five orthopedic surgeries, of both total knee replacement (TKR) surgery and total hip replacement (THR) surgeries, were found to have transient, peak sound levels exceeding 140 dB on multiple occasions [116]. Average noise levels were between 74.8 and 82.1 dBA. In addition, maximum levels were 108.3 dBA for THR and 107.6 dBA for TKR. On average, the THR procedure lasted 77.28 minutes and the TKR surgery lasted 69.76 minutes.

Another study by Holmes et al. focused on workers dealing with orthopedic surgical equipment that reached levels of 95-106 dBA at a distance of four feet from the source [117]. This study used five cast technicians to test for noise-induced hearing loss. There was not only an association between the use of these orthopedic tools and hearing loss; but also, the hearing loss was more prominent on the side of the dominant hand of the worker.

Similarly, a study tested twenty-two members of an orthopedic staff and found evidence of noise-induced hearing loss in half of these staff members due to the use of the orthopedic air powered and electric tools [118]. Evidence of noise-induced hearing loss was present in 11 of the 22 subjects. The peak hearing loss occurred at 6 kHz, with a 12.3 dB average loss. Interestingly, this hearing loss differs in frequency from typical factory noise hearing loss, which usually occurs at approximately 4 kHz.

1.3.5.6 Psychosocial environment

The psychosocial environment relates to the psychological and social conditions experienced at workplaces. Studies have shown that the psychosocial environment among workers in a hospital can also be affected by noise. One study examined how the acoustic environment correlates to changes in the work environment and staff perception [50]. This study, linked to the Hagerman paper that researched cardiovascular response in patients [89], altered the acoustic environment in a CCU by changing the reflective ceiling tiles to absorptive ceiling tiles. Fifty nurses were given questionnaires with a psychosocial focus. They were asked about their pace of work, their quantity of work, their decision latitude, their own competence, the atmosphere at work, the quality of care, the social support at work, and other work situational questions. As stated before in the Hagerman study [89], the added absorption reduced the reverberation time from 0.8 to 0.4 seconds in the main working area, and from 0.9 to 0.4 seconds in a patient room. An overall sound level drop of 5-6 dB occurred in the patient rooms—where 3 dB could be accounted for by the shorter reverberation time. Speech intelligibility was also improved by the Rapid Speech Transmission Index (RASTI) method, with standard qualitative measurements improving from “good” to “excellent.” The RASTI method is a speech intelligibility measurement that uses an modulated signal to determine how well speech can be understood. With the addition of these acoustic tiles, the staff reported that they noticed the better speech intelligibility and that they felt more relaxed and less irritable. Specifically, these positive work effects were more prominent in the afternoon shift of workers.

1.3.5.7 Annoyance & other reactions

A study of 295 volunteer hospital workers tested subjective response to noise using a structured questionnaire [33]. The noise levels in this study were categorized into external and internal sources. External sound levels from street noise, aircraft noise, and sirens averaged 66.9 dBA and about 26% of these noise measurements surpassed 70 dBA. The internal noise averaged 64.1 dBA and about 16% of these measurements surpassed 70 dBA. Most of these internal sources were human voices, vehicles and hospital service noise. This study found that most workers felt that noise was a negative environmental factor, with 61% of workers considering themselves to be “very annoyed.” However, most workers also believed that noise levels could be reduced by using several noise reduction methods such as improving working conditions, controlling the sources of noise, enhancing acoustic insulation, and educating workers and visitors to reduce unnecessary noise.

1.3.6 Non-hospital staff potential outcomes

Several studies may be applicable to hospital research even though the studies were not performed with hospitals in mind. In general, these non-hospital outcomes can be used to hypothesize how hospital staff members may react to noise. The following studies focus on how different types of noise can relate to human response and on which acoustic metrics may or may not be appropriate.

Landström et al. examined the effects of three different ventilation noise signals on non-hospital occupant performance, wakefulness, and annoyance [54]. Three signals were tested: a) broadband signal of 40 dBA; b) a 100 Hz tonal broadband signal at 40 dBA; and c) the same 100 Hz tonal broadband signal with the addition of a 41 dBA low frequency pink masking noise. Each subject was exposed to 50 minutes of each noise signal. During the 50 minutes, the subjects performed a specific task for the first 40 minutes and then rested for the final 10 minutes. No significant differences in performance were observed between signals a) broadband and b) tonal noise. However, performance on figure identification tasks tended to be lower during the 100 Hz tonal noise as compared to the masked 100 Hz tonal noise. Thus, the types of noises can influence the results; specifically, tonality can impact performance outcomes.

A study by Holmberg et al. used five different ventilation noise exposures: a) broadband noise from 31.5 to 500 Hz with a slope of -5 dB per octave band at 40 dBA; b) the same broadband noise as above but reduced to 35 dBA; c) the same as the first signal but with raised levels around 43 Hz (40 dBA); d) the same as the first noise but now adding a superimposed tone at 43 Hz (40 dBA); and e) naturally occurring background noise at 20 dBA [7]. Each noise was played for 60 minutes while the subjects completed proofreading tasks. No statistically significant differences between cases were found on the performance tests; however, the overall trends showed that spectral characteristics should be considered when evaluating the effects of ventilation noise on annoyance sensation and performance.

Additionally, two NC-35 ventilation signals, one with predominantly mid-frequency content, and one with predominantly low frequency content were studied by Persson Waye et al. in a study to evaluate the effect on performance and work quality [7]. Each noise source lasted one hour. The study found that low frequency noise interfered more strongly with performance on three cognitive tasks than the mid-frequency noise. The difference between productivity scores in this study indicates that NC curves do not represent the negative impact of low frequency noise on task performance. Furthermore, there was an indication that the effects of noise developed over time. Persson Waye et al. [7-8] followed up the previous study and found that low frequency noise negatively impacted demanding grammatical proofreading tasks; however, the effects on more routine tasks were not as conclusive. Additionally, in the low frequency noise scenario, demanding verbal reasoning tasks showed a slower subject response time. The results indicated that low frequency noise may be more difficult to adapt to.

In open-plan offices, Bradley investigated the effects of noise on performance and speech intelligibility [119]. Across the span of a workday, participants were exposed to simulated ventilation noises in combination with simulated telephone conversations emanating from nearby workstations. Subjects underwent memory-based clerical tasks and answered questions about the background noise. They concluded that overall satisfaction with the work environment decreased as speech intelligibility worsened.

Additionally, worker satisfaction was influenced by the spectral content of the ventilation noise, as determined by the difference between high and low frequency components. Other studies have taken a more in-depth look at the differences between broadband noise verses speech noise and the corresponding effects on performance [120].

1.3.7 Speech intelligibility in non-hospital settings

Speech intelligibility (SI) has a direct impact on communication between hospital staff members. Speech intelligibility has been well defined by several metrics, such as Articulation Index, Speech Intelligibility Index, Sound Transmission Index and Articulation loss. However, these standards provide insight on generalized situation, and not in critical conditions, like a hospital. These critical conditions may or may not need higher speech intelligibility. One similar area of research that can potentially provide better insight into critical environments may be military applications of SI. The following papers look at military applications of speech intelligibility.

One study focused on the communication between military tank crews [124]. Six five-person tank crews were asked to position their tanks to some specified location. The communications speech intelligibility was varied from 100% to 25%, using the Modified Rhyme Test (MRT) scale. They found that decrements in task performance occurred at higher levels of intelligibility for more complex tasks than for less complex tasks. Furthermore, tasks took longer to complete and probability of completion decreased. The most severe decline occurred between the 50% and 25% intelligibility levels and the study also found that workload increased as intelligibility decreased. By studying the transcripts of the communication, even the communication structure between the crews were altered as SI was varied. The authors hypothesize that the decrements in performance may cost more money in terms of time, errors and workload when compared to the cost of potentially trying to fix the intelligibility problem.

The military has also researched how speech intelligibility levels can affect visual task performance [125]. Using 28 civilian students as subjects and the Modified Rhyme Test, they found that speech intelligibility impacted performance levels in a visual task that required use of short term memory and decision making. However, intelligibility did not affect performance in a visual tracking task. Additionally, the data suggested that the impact of degraded speech intelligibility was greatest at intelligibility levels of less than 40%. Above 50%, there was relatively little impact on task performance.

Furthermore, radio studies have been performed to try to improve military communication [126]. The aim of one particular study was to improve naval aircraft radio communications and determine how intelligibility was affected by cockpit noise. Standard word lists and the MRT method were employed in testing 20 Navy enlisted men. Simulated and recorded cockpit noises were used. They found that the Modified Rhyme Test was the most acceptable speech intelligibility test and that 95% of the standard test sentences were understood with a MRT score of 80%. The authors also equate MRT of 80% to an articulation index (AI) rating of 0.35 because standard sentence scores exceeding 95% correspond to AI=0.35.

1.3.8 Visitor response

Currently, there have been no published studies that have dealt with visitor response to hospital noise using the search criteria described in the methodology. If the criteria of noise are expanded to include music, there has been one study looking at the use of music in hospital surgery and ICU waiting rooms [127]. Conducted in a waiting room of a large hospital with no televisions present, the investigators played music of various speeds and styles. They analyzed 162 questionnaires and concluded that the visitor's stress levels were lowered by the presence of music.

Several studies suggest that the visitors themselves cause a significant portion of the overall hospital noise [27]. Some noise reduction programs have suggested that the number of visitors be limited and also proposed that unnecessary or loud conversation at the patient bedside be eliminated [81]. Contrarily though, other research listed a ranking of the "most disturbing" noise sources and it placed visitor noise twenty-second out of twenty-four sources [128].

1.4 Discussion

This literature review surveyed the existing research on the effects of hospital noise on patients, staff, and visitors to determine the areas in need of research and improvements. It is clear from the review that the noise in hospitals is a serious issue and can potentially cause acute and chronic damage to hospital occupants, but there are gaps in the research.

The effects of hospital noise on patients can range considerably. Table 2 summarizes the studies that have been published by author and type of potential effects. It appears that sleep studies have traditionally been well studied, but other health effects have not been as comprehensively researched. It has been shown that quality of sleep can be disturbed, heart rate can be increased, blood pressure can be elevated, healing rates can be slowed and hospital stay can be lengthened. There have been many studies conducted on the number of sleep arousals within different levels of sleep caused by the presence of noise. Several researchers have used these results heavily, if not exclusively, in their characterization of noise in hospitals [26]. They have determined which noise sources, such as staff conversation and telephone noise, arouse the patients most frequently and these sources become the targets for noise reduction programs. One of the major concerns with these studies is that generally small sample sizes are used in the initial experiments (as few as five patients in some studies). The validity of these results must be scrutinized due to these small sample sizes, but the overall trend clearly shows that noise negatively impacts patient sleep to some extent.

Cardiovascular response has been tested primarily by blood pressure and heart rate measurements. These measurements are generally reliable and are noninvasive in nature. Early studies have shown that there is more strain on one's cardiovascular system due to the presence of noise. However, it is not known yet whether the presence of noise is directly linked to the onset of heart disease or other cardiovascular problems. Furthermore, adding acoustic absorption to the space, thereby changing the acoustic soundscape, can be successful in reducing potentially negative cardiovascular response. Due to these potential cardiovascular responses, there has been a demand by some to develop an acoustic index that will attempt to directly link the acoustic soundscape to the cardiovascular response.

Research on other health effects has been limited. There have been no known studies of healing rate in humans with respect to noise. The few studies in the field of wound healing have dealt only with rodents. Ultimately, studies will want to show a correlation between noise and healing rate in not only rodents, but also humans. The ramifications of increasing healing rate can potentially translate into benefits such as shorter hospital stays and fewer medications, all of which potentially correlate to financial benefits.

The effect of noise in pain management also appears to be a research area with relatively direct applications. The few preliminary studies that exist have been somewhat inconclusive on whether noise can reduce the amount of medication needed. The possibility for conclusive results can potentially improve the way patients are medicated, the way doctors use anesthetics, and thus warrant further investigation.

The results dealing with the staff response generally concluded that noise increased stress, lowered productivity, caused annoyance and burnout, and caused long-term noise-induced hearing loss in certain cases. The largest area of this staff research has dealt with stress levels and noise. This area can be broken down into two sub-areas—1) the general effects of stress on the body and 2) the relationship between noise and stress. Different indicators, such as salivary cortisol, have been used to measure stress levels. Fast, reliable, and noninvasive procedures would ideally be used in any test and the previous development of the salivary cortisol method now allows stress levels to be monitored by a procedure as simple as using a cotton swab. Heightened stress levels can contribute to effects such as a lowered productivity and an increased chance of burnout.

Additionally, surgeons may be at risk for noise induced hearing loss due to the presence of loud sounds during orthopedic surgeries, for example. These loud sounds can also change the psychosocial environment and create a sense of annoyance. As non-invasive procedures continue to develop, the use of structured questionnaires becomes an important tool that can be used to understand how the staff perceives the stress of the working environment.

Table 2. Categorical breakdown of papers reviewed.

Patient Response

Sleep Studies

Hilton [63]	1976
Aurell & Elmquist [64]	1985
Parthasarthy & Tobin [65]	2004
Freedman et al. [67]	2001
Gabor et al. [68]	2003
Cooper et al. [69]	2000
Topf & Davis [70]	1993
Carley et al.[71]	1997
Aaron et al. [72]	1996
Stanchina et al. [73]	2005
Topf et al .[74]	1996
Novaes et al.[75]	1997
Freedman et al.[76]	1999
Dlin et al.[77]	1971
Berg [78]	2001
Monsen & Edell-Gustafsson [79]	2005
Walder et al. [80]	2000
Kahn et al. [81]	1998
Xie et al. [82]	2009

Cardiovascular Studies

Falk & Woods	1973
Cantrell [83]	1979
Cartwright & Thompson [84]	1975

Staff Response

Job Performance

Hodge & Thompson [102]	1990
Ray & Levinson [103]	1992
Murthy & Malhotra [104]	1995
Hawksworth et al. [105]	1998
Moorthy et al. [106]	2004

Stress studies (non noise)

Norbeck [107]	1986
Fischer et al. [108]	2000
Fischer et al. [109]	2000
Yang et al. [110]	2001
de Quervain et al. [111]	1998
Kirschbaum et al. [112]	1996
Bigert et al. [113]	2005

Stress and noise

Topf [114]	1988
Morrison et al. [115]	2000

Hearing Loss

Love [116]	2003
Holmes et al. [117]	1996
Willett [118]	1991

Andren et al. [85]	1980
Storlie	1976
Conn [86]	1981
Marshall [87]	1972
Baker	1992
Baker et al. [88]	1993
Hagerman et al. [89]	2005
Sonnenberg et al.[90]	1984

Hospital Stay

Fife & Rappaport [91]	1976

Pain

Minkley [92]	1968
Gardner[93]	1960

Wound Healing

McCarthey et al. [94]	1992
Wysocki [95]	1996
Cohen [96]	1979
Toivanen et al. [97]	1960

Other Responses

Castle et al. [98]	2007
Tomei et al. [99]	1994
Akansel et al. [100]	2008
Kurmann et al. [101]	2011
Okcu et al. [44]	2011

Psychosocial environment

Blomkvist et al.[50]	2005

Annoyance/other reactions

Bayo et al. [33]	1995

Visitor Response

Routhieaux & Tansik [127]	1997
Allaouchiche et al. [27]	2002
Bentley et al. [34]	1977
Topf [128]	1985
Kahn et al. [81]	1998

With regards to other staff responses, the link between productivity and noise is still relatively inconclusive. Determining how noise affects a doctor or nurse's job performance is potentially imperative. Doctors and nurses should have a consistent level of job performance in order to provide the best care for the patients. Any proposed methods to reduce the deterioration of job performance could have many potentially positive outcomes.

There have virtually been no studies on visitor response. Visitors can often spend considerable amount of time in hospitals under high levels of stress and the noise can have important effects on them. It is counterproductive for a hospital to potentially harm healthy visitors. A more comprehensive understanding of visitor response is needed to ensure that hospital noise does not negatively affect them.

In all of this previous research, a major underlying concern stems from the number of people studied and the selection of the participants. For example, some staff studies used as few as five participants. The validity of studies that utilize so few participants must be scrutinized. These studies provide preliminary results that should be validated in future research that utilizes more subjects. Patient and staff access can sometimes be difficult to obtain; however, in order to truly confirm these preliminary results, larger subject populations are absolutely needed.

Additionally, as a comment, upon first glance it may appear that the number of studies that have attempted to link hospital noise and occupant outcomes have not been as prevalent in the last few years. However, considering that the previous studies discussed in this dissertation range from the 1970s to the 2010s and they are distributed relatively evenly across the decades, there actually is not such a great difference in the number of studies that have been published in the last few years. Indeed, there have been numerous special sessions on hospital noise-related topics over the last few years at meetings of professional societies such as the Acoustical Society of America and the Institute of Noise Control Engineering, indicating continued interest in the topic.

The literature taken as a whole can be organized in a way that studies the entire research chain: from the acoustic metrics being tested through the mechanism being tested to the occupant outcomes. For example, if a study focused on how a change in reverberation time affects staff stress, the metric is reverberation time, the mechanism is the addition of absorptive tiles, and the occupant outcome is that “staff stress was reduced.” Table 3 highlights these relationships. The disparity between the numbers of papers in Table 2 and Table 3 (Table 3 is populated with only 27 papers whereas Table 2 contains 66 papers) highlights that the majority of the previously mentioned research does not use any mechanism in their studies. Additionally among those 27 papers, only six papers actually complete the entire chain from metric to mechanism to occupant outcome. Of those six papers, three use a change of the physical environment to study the effects of absorptive tiles, and another three papers use administrative behavioral changes. All other papers in Table 3 use the mechanism of noise exposure (signal type A versus signal type B) or change in noise level (increase or decrease in noise) to study potential effects. Specifically, the mechanism column in Table 3 has a four letter coding system. The code “A” signifies that the study exposed the subject to noise. The “B” code means that the study involved a change in noise level—with “B+” indicating an increase in noise level and “B-“ indicating a reduction in noise. “C” corresponds to the researchers adding absorption to the hospital ward with no other mechanisms for reduction, and “D” symbolizes that initiation of administrative behavioral changes. Comparing Table 2 and Table 3 highlights the dearth of studies that study the entire chain, from metric, to mechanism, to outcome.

To highlight certain aspects of this chain, the main metrics that have been studied are average sound level, reverberation time, and/or speech intelligibility metrics. The particular mechanisms used are stated above and are coded with letters A, B(+/-), C or D in Table 3. The occupant outcomes were generally considered negative when the subjects were exposed to noise; i.e., sleep quality was reduced, cardiovascular response was heightened, and healing rates were lowered. When environmental changes or behavioral changes were made to reduce noise or reverberation time, the outcomes were generally positive, with lower stress and better speech intelligibility.

It is important to note that Table 3 contains several blank acoustic metrics under the “Metric” column. This does not mean that acoustics were not considered in the studies; rather, it reveals that specific acoustic metrics were not controlled. For example, in Carley et al [71], 85 dB tones were used in the study for noise exposures. The decibels themselves were not the acoustic metric studied; instead, it is the exposure to the noise that is of interest. Similarly, in the Hagerman study, the acoustic metric that was altered and controlled for was reverberation time. The mechanism was that they added absorptive panels, and the outcome showed that incidence of patient re-hospitalization was reduced. The acoustic metric they drew their conclusions from was specifically

Table 3. Papers that fully or partially highlight the research chain of metrics, mechanisms, and outcomes. A=Exposure to noise; B(+ or -)=Increase or decrease in noise level; C=Installed absorptive panels; D=Administrative behavioral changes

PATIENT		**Metrics**	**Mechanism**	**Outcomes**
Sleep				
	Hilton 1976 [63]		A	No undisturbed sleep cycles.
	Aurell & Elmquist 1985 [64]		B-	Sleep deficiencies seen in all subjects
	Parthasarthy & Tobin 2004 [65]		A	11-20% of arousals and awakenings due to noise.
	Topf and Davis 1993 [70]		A	REM sleep quality changed--shorter REM periods and less REM activity
	Carley et al. 1997 [71]		A	EEG arousal evoked in non-REM sleep. Respiratory activity was increased.
	Stanchina et al. 2005 [73]	Peak Levels	A	Increased number of sleep arousals
	Topf et al. 1996 [74]		A	Reported a negative impact on sleep
	Berg 2001[78]		C	Significantly reduced the number of arousals during sleep
	Monsen & Edell-Gustafsson 2005		D	Reduced number of sleep disturbances

	Walder 2000 [80]	L_{Aeq} and Max Levels	D	Sleep patterns altered
	Kahn et al. 1998 [81]	Peak Levels	D	Number of sound peaks reduced but no physiological component to study
Cardio-Vascular				
	Storlie 1976		A	Determined that change in heart rate possible.
	Conn 1981[86]		A	Anxiety was heightened and arrhythmias rose.
	Marshall 1972 [87]		A	Heart rate increased by 2-12 BPM.
	Baker et al. 1993 [88]		A	Heart rate increase ~3bpm primarily during in conversations only.
	Hagerman et al. 2005 [89]	Reverberation Time	C	Speech intelligibility improved. Patients re-hospitalized at higher incidence in "bad" acoustics.
	Sonnenberg et al. 1984 [90]		A	Blood pressure increased
Hospital Stay				
	Fife & Rappaport 1976		A	Hospital stay length increased
Wound Healing				
	McCarthy et al. 1992 [94]		A	Leukocyte function altered
	Wysocki 1996 [95]		A	Weight loss
	Cohen 1979 [96]		A	Slower healing area rate

	Toivanen et al. 1960 [97]			Healing rate lowered
Others				
	Castle et al. 2007 [98]		A	Decreased gastric myoelectrical activity
	Tomei et al. 1994 [99]		A	No link to physiology
STAFF				
	Hawksworth et al. 1998 [105]		A	No effect
	Moorthy et al. 2004 [106]	L_{Aeq}	A	No effect
	Blomkvist et al. 2005 [50]	Reverberation Time	C	Speech intelligibility improved / staff more relaxed and less irritable
	***All other papers covered in this review did not measure the complete research chain (acoustics related occupant outcome)**			

reverberation time, as opposed to Carley et al that drew their conclusion from the exposure itself, not from an acoustic metric.

In summary, this structured review reveals that very few studies examine the entire research chain and acoustic metric information is still generally lacking. Staff studies in particular are sparse. The studies that measure environment changes that affect the acoustics are not comprehensive and cannot paint a full picture of occupant outcomes. Additionally, metrics that have been historically used may be overly simplistic since these fundamental metrics may not provide a complete enough picture of the acoustic environment. To this point, as shown in this review, several studies show conflicting results and these traditional fundamental metrics may not be sufficient to show hypothesized occupant outcomes. Thus, further investigation is needed to fill these holes in the research chain.

The ultimate goal of the hospital acoustics field should be to identify ways to improve the acoustic environment, but only rudimentary measures, primarily sound levels, have been studied and are reported. Effectiveness of noise reduction programs and acoustic design changes in rooms can help reduce the overall noise in rooms. Additional studies that involve changes in the acoustic environment are necessary in order to optimize the effectiveness of acoustic alterations. Already, the use of absorptive ceiling tiles has been shown to shorten reverberation time, reduce room noise, and provide beneficial occupant outcomes. Other acoustical design decisions such as room shape, equipment selection, and equipment design can be investigated to gauge their effectiveness in reducing overall noise and reducing the negative effects on people. Hospital acoustical design and equipment selection is vital in reducing overall noise.

With a further understanding of how design and selection directly affect overall hospital noise, strides can be made in providing a healthier atmosphere for patients, staff, and visitors.

1.5 Patient and Staff Effects Summary

The topic of hospital noise is a crucial issue in the overall environment of hospitals. Some correlations have been made between patient sleep disturbance, higher heart rate, slower healing rate, higher stress and higher annoyance rates with hospital noise. Furthermore, staff responses to noise include potential reductions in productivity, psychomotor skills, noise-induced hearing loss as well as negative changes in the psychosocial working environment. Yet, the effects of hospital noise are not yet fully understood, due to holes in acoustic methodology for example, and more research is needed to determine the severity and importance of these correlations. The ultimate goal in hospital design is to create a space that is healthy for all occupants and to provide the best environment for a patient to recover and a staff member to work. Additionally, the hospital should not foster an unhealthy environment that can potentially cause harm to healthy staff members and visitors. This review above provides a basis for additional research in order to achieve a healthier environment.

1.6 Research Goals and Contributions

Clearly, there are still many unresolved questions and areas of future research in the hospital acoustics domain. This dissertation project specifically addresses the following holes that were identified during the review of previous research. These goals and contributions try to:

- More fully characterize the hospital soundscape using acoustic metrics that build upon traditional fundamental metrics and use nontraditional metrics such as occurrence rates and psychoacoustic metrics. Previous research has shown that the current acoustic methodology is insufficient.
- Determine more complete relationships, if they exist, between acoustic metrics and patient physiological response, in generalized patient populations. These physiological responses, such as heart rate, respiratory rate, oxygen saturation, and blood pressure will be statistically linked to acoustic metrics through correlations, regressions, curve estimations and risk ratios.
- Apply novel absorptive panels to an existing hospital ward and measure changes in acoustic soundscape metrics, such as reverberation time, noise levels, spatial acoustic metrics, and speech metrics. Whereas average sound level may show marginal differences between acoustic conditions, these other aforementioned metrics can provide a clearer picture of the acoustic changes provided by the panels.
- Measure staff perceived outcomes due to the installed absorptive panels using questionnaires.

CHAPTER 2 - ACOUSTIC PRINCIPLES AND DATA ANALYSIS TECHNIQUES

The studies described in the Chapter 1 literature review generally utilized traditional acoustic metrics. This Chapter will describe the acoustic principles and metrics used in the dissertation study. This dissertation will present not only results stemming from the traditional sound level metrics, but also will investigate the uses of more novel, non-traditional acoustic metrics. These non-traditional metrics include spatial sound decay metrics, speech intelligibility metrics, psychoacoustic metrics, and statistical occurrence rates. All of these non-traditional acoustic metrics are outlined in the following section.

Additionally, the data analysis techniques and principles will be discussed in this Chapter. The Chapter 1 literature review has revealed that only a few studies link the entire research chain together. Using statistical models, the hypotheses presented earlier will be tested. Statistical models used in this research consist of correlations, regressions, curve fits/estimations, and risk ratio analyses. A brief explanation and implication of each type of statistical analysis is included in this Chapter.

2.1 Metrics Derived from Sound Level Meter Measurements

Sound level meters (SLM) have traditionally been used to measure how loud something is—either to determine how many decibels a noise source is, or to measure the background levels of a soundscape. Sound level meter metrics are defined here to be metrics that are directly calculated through a sound level meter or through simple postprocessing of sound level meter data. Some metrics such as equivalent sound pressure level (L_{eq}) and A-weighted equivalent sound pressure level (L_{Aeq}) may be exported from a sound level meter through its built-in functionality. Indirect measurements use these direct measurements and calculate new metrics, such as the statistical occurrence rate. These direct and indirect metrics will be described briefly.

2.1.1 Background Noise

The background noise is defined to be the characterization of all the noise sources occurring over a specified period of time. For example, if a person were to walk into a grocery store, any and all noise that this person experiences, excluding sound produced by the person, would be the store's background noise. In the case of this research, the hospital's background noise level is measured. In an intensive care unit (ICU), primary noise sources may include: heating, ventilation, and air conditioning (HVAC), staff conversation, overhead pagers and announcements, rolling carts, medical equipment noise, alarms, patient noise, telephone noise, among others. The levels, spectral content, frequency of occurrence, and temporal distribution over a specified period of time are the main acoustic factors in background noise [3]. These metrics, although not all directly exported from a sound level meter, can be easily derived from the output from a sound level meter.

Background noise measurements are made over a specified time period. Typical measurements in this dissertation are either 24-hour measurements or 30-minute measurements. The choice of length depended on site access and measurement logistics, such as number of sound level meters available. Additionally, some meters have a "logging" function that allows the meter to store measurements in smaller user-specified increments. For example, if a meter were set up for a 30-minute measurement with 5-minute logging intervals, there would be a total 30-minute output for the entire measurement period in addition to the logging outputs given for every 5-minute interval; thus, there would be seven total outputs. This allows for a detailed time-distribution description of the background noise. In this dissertation, 1-minute intervals were used. This increment of time was chosen due to the storage capacity of the sound level meters and to provide short-term sound level data [129].

2.1.2 Fundamental SLM Metrics

The fundamental sound level metrics analyzed in this study consists of several built-in metrics that a Larson Davis 824 sound level meters can output: A-weighted equivalent sound pressure level (L_{Aeq}), A-weighted minimum sound pressure level (L_{Amin}), A-weighted maximum sound pressure level (L_{Amax}), and C-weighted peak sound pressure level (L_{Cpk}) [129].

L_{eq} can be described as an equivalent sound level. Over a specified time period, the noise levels can fluctuate—simplistically speaking, L_{eq} averages the fluctuations through the time period and calculates the average sound level for that period. The total sound energy of the fluctuating signal will be equivalent to the energy of the calculated equivalent continuous level (L_{eq}) through that same time period. Figure 1 shows a schematic representation of the definition of L_{eq}. This metric is the most commonly used metric to measure hospital noise based on the literature review above.

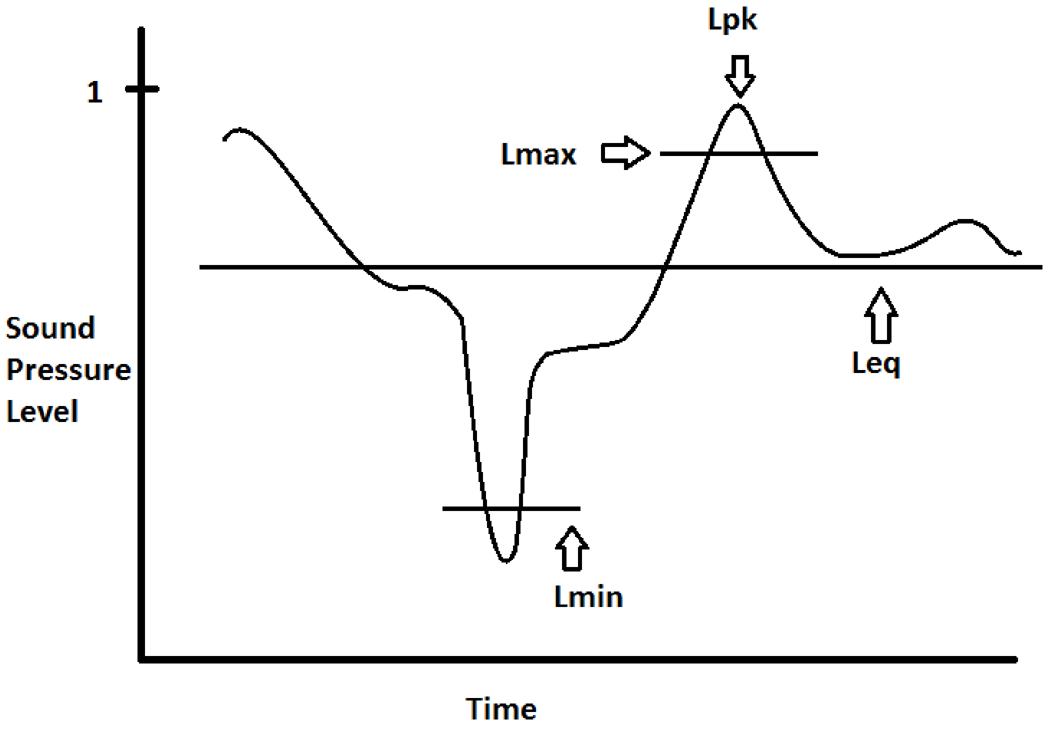

Figure 1. Schematic highlighting L_{eq}, L_{min}, L_{max}, and L_{pk}

L_{min} is defined to be minimum root mean squared (RMS) sound level that is measured in the specified time period. This can be interpreted as a baseline level of the space where the sound sources accumulate upon this minimum level. Similarly, L_{max} is the highest RMS sound level that is measured in the specified time period. L_{pk} is the highest absolute sound pressure that is measured in the specified period. Since L_{max} is an RMS level and L_{pk} is the absolute maximum amplitude of the fluctuations, L_{pk} will be a higher value than L_{max}. To help illustrate the difference between L_{max} and L_{pk}, one period of a sine wave can have a unitless arbitrary amplitude of 1. The peak value would be 1, whereas the max value would be 0.707. A schematic visualization of minimum, maximum, and peak levels is illustrated in Figure 1.

2.1.3 Time Response

One feature built-in to sound level meters is the response time [123]. Meters typically have three settings: slow, fast, and impulse. In modern digital sound level meters, the slow response uses a 1 second time integration period. Fast response corresponds to 125 ms and the impulse settings have a 35 ms response. The slow setting is typically used in HVAC or steady state noise situations. Many previous studies in hospital acoustics have used this slow setting. However, the types of noise sources of interest in hospitals, such as alarms or staff conversation, are not steady state; thus a fast setting is more appropriate for these SLM measurements and is used in this dissertation.

2.1.4 Weighting Networks

When taking sound level meter measurements, several frequency weighting network options exist—with the most popular options being a) flat/Z-weighted, b) A-weighted, or c) C-weighted. These networks are defined in the IEC 61672:2003 standard. The flat weighting option is a spectrally neutral weighting, where no penalties are assigned to any frequency band. The A-weighted option attempts to simulate the human ear's frequency response at a loudness level of 40 phons, with less sensitivity in the low and high frequencies, and greater sensitivity in the speech intelligibility range. At higher sound levels, the C-weighted option may be more appropriate as it was designed for human hearing at 100 phons. Other weighting curves such as B or D are used for various applications; specifically the D-weighting can be used for aircraft noise. Figure 2 shows a graphical representation of these weighting curves. For measurements involving spaces where human occupy, such as schools or offices, A-weighted measurements have traditionally been used. For an average background noise measurement, the A-weighted average level may be reported as L_{Aeq} [130].

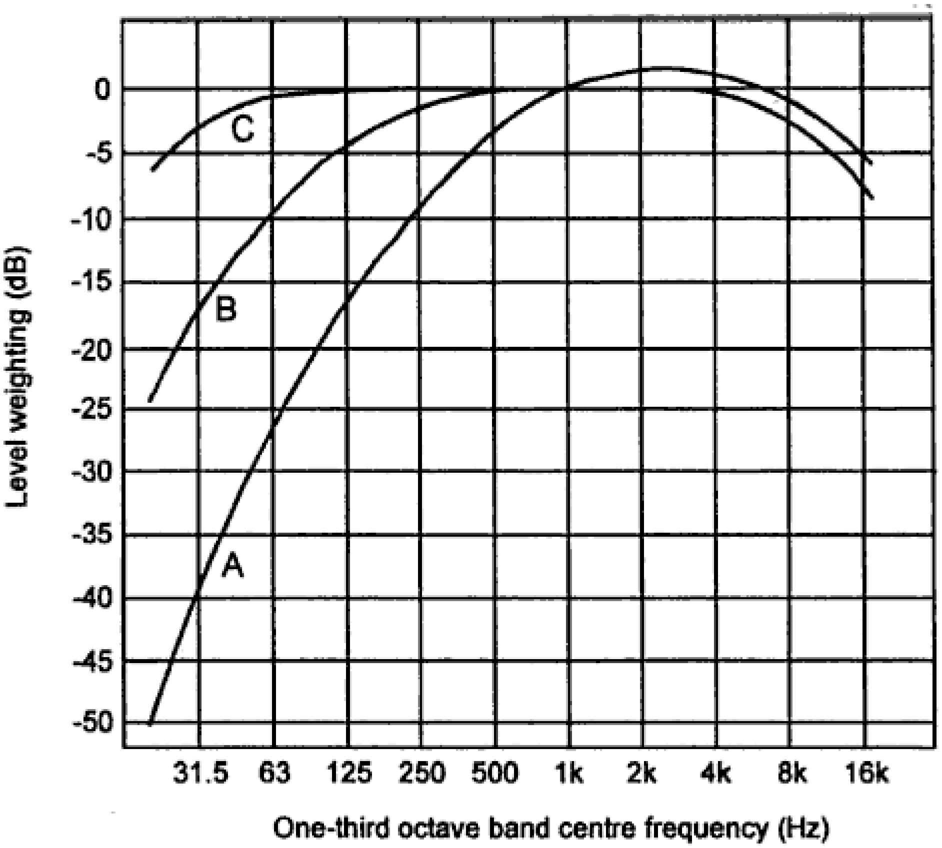

Figure 2. Decibel weighting networks [130]

2.1.5 Occurrence Rate

The occurrence rate is a graphical metric that was developed first by Ryherd and Persson Waye in 2008 as a way to describe the temporal activity in space [39]. The occurrence rate shows what percentage of time the selected metric exceeds a certain threshold value. It is related to percentile level metrics (e.g., L10, L90) in that it looks at a statistical distribution of sound; however, the occurrence rate is typically calculated specifically for maximum and peak sound pressure levels. However, the occurrence rate can also be analyzed for L_{Aeq} to show a graphical time distribution of average sound energy at specified thresholds in lieu of or as an accompaniment to percentile measurements. In order to calculate the occurrence rate metric, the sound level meter device must log measurements at specified periods. These logged results are compared with one another to determine the occurrence rate over the entire measurement period. If peak and maximum levels are analyzed through this analysis, the fluctuating nature or "peakiness" of the space may be ascertained. "Peakiness" here refers to how often peak levels occur and how loud these peak levels are. As an example, the occurrence rate graph may show that in one space the peak levels exceeded 90 dB 50% of the time. This first space would be more "peaky" than a second space where the peak levels exceeded 90 dB 10% of the time. Stated otherwise, peak levels exceeded 90 dB more often in the first space, so it is more "peaky" than the second space.

2.1.6 DL_2

The DL_2 metric has been previously used for open office floor plans, but has not yet been tested in hospitals [132]. The DL_2 measurement involves measuring the decay of sound over distance in specific directions, which may be most applicable in situations where listeners will only be in particular areas of a room or at particular heights. In offices, workers are typically seated, whereas in hospitals, workers are often standing, especially in corridors and patient rooms. Additionally, in cases where absorption is not equally distributed, DL_2 may be a more informative measure then reverberation time because reverberation is the overall acoustic response of a space to a sound source regardless of the placement of acoustic treatments. Typically, in hospitals, sound absorption is not equally distributed and is primarily applied to the ceilings. In a free field, due to the inverse square law, for every doubling of distance sound level attenuates by 6 dB. In an enclosed space, the decay will generally be slower.

The ISO 14257:2001 standard defines the procedures to quantify the spatial decay of sound over a distance via the spatial sound distribution curve (SSDC). In this method, a series of measurements are made with increasing distance from the sound source. The standard derives two quantities from the spatial sound distribution curve: DL_2 and DL_f. DL_2 is given either as a single number across all frequencies or divided into frequency bands and indicates the rate of sound decay per doubling of distance. It is defined as Equation 1 [132]:

$$DL_2 = -0.3 \frac{z\sum_{i=n}^{m}\left[D_i \lg\left(\frac{r_i}{r_0}\right)\right] - \sum_{i=n}^{m} D_i \sum_{i=n}^{m} \lg\left(\frac{r_i}{r_0}\right)}{z\sum_{i=n}^{m}\left[\lg\left(\frac{r_i}{r_0}\right)\right]^2 - \left[\sum_{i=n}^{m} \lg\left(\frac{r_i}{r_0}\right)\right]^2} dB \tag{1}$$

where D_i is the difference between the sound power level at the source and at location, and r_i is the distance from the source, r_0 is the reference distance (1m).

DL_f is the excess sound pressure level of the SSDC from the free field line. In other words, the DL_f quantifies the excess decibels per distance as compared to a free field. In a free field, the DL_2 should be 6 dB; however, in an indoor environment, DL_2 can have a shallower decay slope can occur if reverberation is sufficiently high. In rare circumstances, due to sufficient absorption and floorplan geometry, DL_2 can have a steeper decay.

Though the DL_2 and DL_f are informative, the SSDC can be a more informative measure of the room’s response because the DL_2 and DL_f are based on the regression line fitting to the SSDC. The ISO standard distinguishes three regions: near, middle, and far with typical values being 1-5m, 5-16m, and 16m+ respectively. The standard also offers flexibility in these regions and they may be better defined by the sonic content. The near region should be dominated by the direct sound. The far region should be dominated by the reverberant or reflected sound and the middle region would be defined as the region where both are present.

2.2 Impulse Response

The impulse response of a space is sometimes referred to as the acoustic "fingerprint" of the space. The impulse response measures the direct sound and all reflections for a specific source/receiver pair in a space [24]. If one considers that the source is stationary and the receiver is variable in location, then at each receiver location, the impulse response will be unique. Thus, for any given space, the impulse response needs to be measured at many unique location pairs in order to understand the acoustical characteristics of a space. Typically, metrics derived from the impulse response include reverberation time (RT), frequency response, definition (D), Clarity ($C_{50 \text{ or } 80}$), and speech transmission index (STI). Figure 3 shows an example of an impulse response.

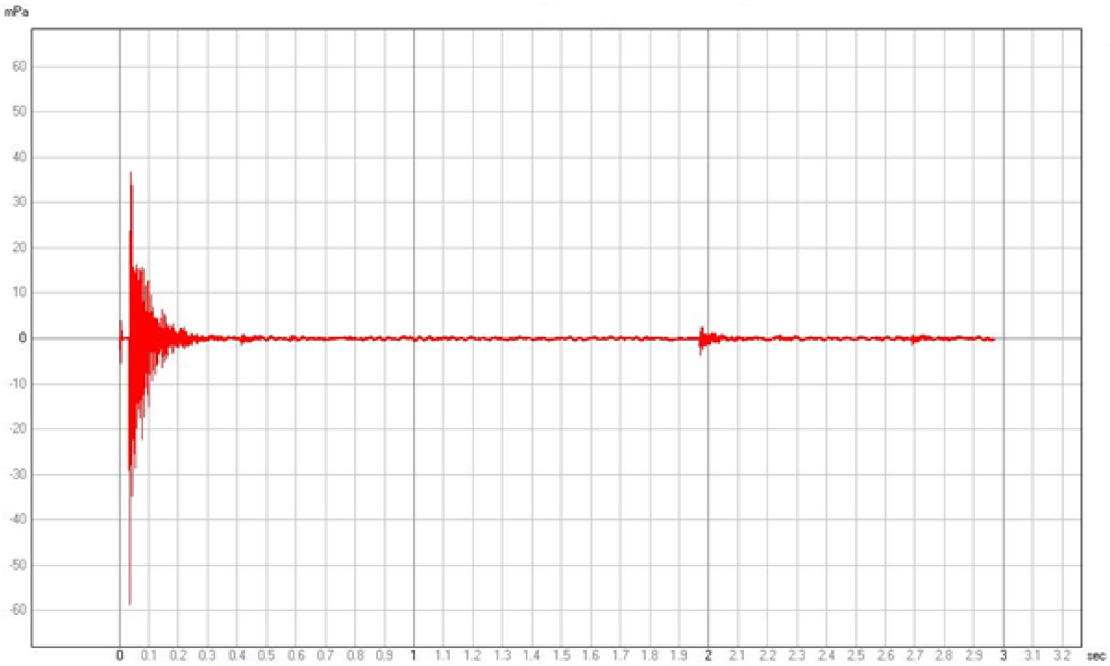

Figure 3. Example impulse response measurement

2.2.1 Measurement Techniques

The impulse response is a common measurement where an active noise source is necessary [17,24,133,134]. Amongst the multiple methods to measure impulse response, three specific ways to measures the impulse response are the a) impulse method or sound cut-off method, b) sine sweep method, c) maximum length sequence (MLS) method.

The impulse method is the traditional way to measure impulse response in a room. The active signal needed is defined to be a loud short burst, simulating a Dirac Delta function—infinitely short in time and inherently broadband. In practice, this source may be a bursting balloon, a starter's pistol shot, or any other type of simulation of a loud short burst. The burst will propagate and reflect off the surfaces and reach the microphone where the impulse response will be recorded. One advantage of this technique is the simplicity—no mathematical processes are needed to extract the impulse measurement. A disadvantage of this technique is the difficulty of using an impulse source, e.g., the signal may not be loud enough, adequately repeatable, or the starter's pistol may be startling to occupants.

The sine sweep method is another popular way of measuring the impulse response. Instead of using a loud short burst, this method uses a swept sine wave signal to measure the impulse response. As the time response and the frequency response are directly related through the Fourier transform, the time domain impulse response can be directly back-formulated from the frequency response of the room. This measurement technique provides potentially a cleaner, more precise impulse response measurement in practice than the impulse method. However, in some situations, the sine sweep may be unpleasant or be deemed an inappropriate test signal for certain spaces. For example, hospital occupants may interpret the sine sweep as an alarm.

The maximum length sequence (MLS) method uses a pseudo-random noise that is spectrally flat, thus sounding similar to white noise. This signal is played through a speaker and a microphone measures the room response. The impulse response can be extracted by circular cross correlating the MLS signal with the measured microphone signal output. This measurement technique can be useful in live working environments because the source is spectrally neutral, sounds like white noise, and may therefore be less bothersome to people. For these reasons, the MLS signal was used for the measurements in this dissertation.

2.2.2 Metrics derived from the impulse response

Reverberation time (RT or T_{60}) is a fundamental metric that is related to the impulse response [24,133]. Reverberation is defined as the time it takes a signal to drop 60 dB in level, or by a factor of 1,000,000. In a measurement, if 0 dB is considered the steady state level, the 60 dB drop time can be measured as the time the sound decays from -5 to -65 dB. In practice, 60 dB is difficult to achieve. Thus, T_{10}, T_{20} and T_{30} can be used with 10 dB, 20 dB, and 30 dB drops, respectively. Each of these measurement times begins measuring at -5 dB and the times are extrapolated to the 60 dB drop. An additional property of reverberation time is that it is frequency dependent and thus can be reported by frequency bands.

One way to measure reverberation time is to excite a room using white noise and measuring the decay after shutting the noise source off. For example, a high-level white noise signal can be activated for several seconds at which point it is abruptly stopped and the first twenty decibels of decay can be measured; from this data, the reverberation time (T60) can be extrapolated.

Reverberation time is directly proportional to the volume of a space and inversely proportional the amount of absorption present. If the volume increases, but absorption is constant, then reverberation time will be increased. This relationship was discovered by Wallace Clement Sabine in 1895 [135]. By adding or removing absorptive seat cushions in lecture halls, he found that the decay time would change. Acoustic absorption, α, is defined as the amount of sound that is absorbed, rather than reflected, off a material. A material with α=1.0 will perfectly absorb all the sound energy that hits it, whereas a material with α=0.0 will perfectly reflect the sound energy. The surface area (SA) multiplied with the absorption (α) gives the absorptive area in sabins. W.C. Sabine developed for an estimation for reverberation time is based and other formulations such as the Norris-Eyring equation can also be used to estimate reverberation time [133]. The Sabine equation for reverberation time is defined as Equation 2:

$$RT = \frac{0.161V}{(SA)(\alpha)} \tag{2}$$

where V= volume in cubic meters, SA= Surface area, and α =Acoustic Absorption coefficient.

2.3 Noise Metrics

Different metrics have been developed to describe the background noise in a space. The great advantage and disadvantage of these noise metrics is that they are generally single-value ratings. The nature of a single-value rating allows for ease of understanding and comparison; however, the single number can sometimes oversimplify and therefore ignore important specific aspects of the background noise. Different metrics are described in the following paragraphs.

2.3.1 Noise Criteria (NC)

The Noise Criteria method quantifies room noise in a single-number rating, determined by comparing the spectrum of background sound levels to a set of defined NC curves [136]. The rating is graphically determined using a tangency method—the NC rating is the lowest defined NC curve under which all the measured background noise data falls. NC only considers octave bands from 63 Hz to 8000 Hz. The NC curves, as seen in Figure 4, were developed from examinations of a variety of office environments and from the equal loudness contours [136].

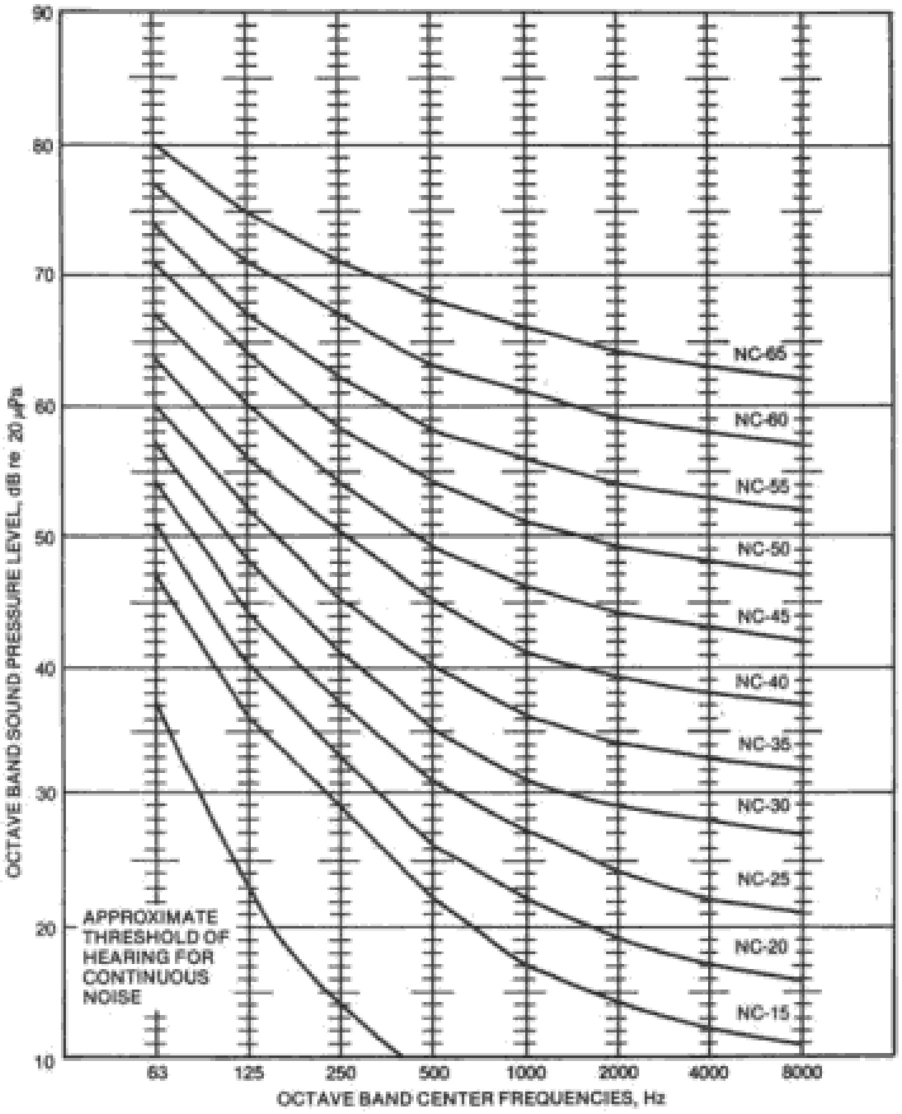

Figure 4. Noise Criterion curves [137]

Many acoustical consultants, mechanical engineers, and architects use NC in a variety of applications [138]. However, problems with NC can occur because of a lack of specific information on spectral quality. Thus, the NC rating can be problematic. The NC procedure can yield similar NC ratings for two spaces with vastly different sound spectra. The noise spectrum is not bound to the shape of any of the NC curves, and the presence of a strong tonal component in any one band can dictate the overall rating. Goodfriend notes that many room noise spectra have shapes that are quite varied from the NC curves [139].

2.3.2 Balanced Noise Criteria (NCB)

Beranek developed the Balanced Noise Criterion System [140] to more accurately reflect potential sound coloration or spectral properties of the background noise. Additional information about NCB is available in several of Beranek’s papers [140-142]. Like its NC predecessor, NCB is a single-number sound level rating but it also gives a qualitative descriptor for the frequency content of the sound. “Rumbly” ratings indicate excessive low frequency content, while excessive high frequency content is described as “hissy.” In addition to “rumbly” and “hissy” ratings, NCB also includes the possibility of noise-induced vibration in the low frequencies (16 Hz to 63 Hz octave bands).

The NCB system additionally extends from its NC predecessor by including the 16 Hz and 31.5 Hz octave bands and by having steeper slopes at high frequencies that correspond to lower curve values than NC. Also, unlike the NC method, the NCB sound level rating is not found using a tangency method, but rather, it is based on the Speech Interference Level [143] as defined in Equation 3:

$$SIL = \frac{1}{4}(SPL_{500} + SPL_{1000} + SPL_{2000} + SPL_{4000}) \tag{3}$$

where SPL_{500} = the sound pressure level in the 500 Hz octave band. The SIL is rounded to the closest decibel and compared to the appropriate given NCB curve. This method results in the NCB rating.

2.3.3 Room Criteria (RC)

The RC methods provide an entirely different prediction scheme, in both development and application. Use of these curves has been most popular in evaluation of spaces where the mechanical system is the primary noise source. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) sponsored a survey of office buildings and determined the perceived optimal slope for background noise as being approximately -5 dB per octave band [3]. The RC methodology was developed to reflect these results. The RC curves, as shown in Figure 5, follow this optimal slope, and extend from the 16 Hz to 4000 Hz octave bands.

The original RC method provides a single-number sound level rating and was the first criteria to include indicators of spectral quality such as rumbly, hissy, and vibrational ratings [3]. RC also includes the possibility of noise-induced vibration in the low frequencies (16 Hz to 63 Hz octave bands). The RC level rating is found by calculation of the mid-frequency average, L_{MF}, as defined in Equation 4:

$$L_{MF} = \frac{1}{3}(SPL_{500} + SPL_{1000} + SPL_{2000}) \tag{4}$$

where SPL_{500} = the sound pressure level in the 500 Hz octave band.

2.3.4 Room Criteria Mark II (RC Mark II)

The next generation of RC was the development of Room Criteria Mark II [145]. The RC Mark II curves are taken almost directly from the RC curves, with the modification that the Mark II curves are 5 dB lower in the 16 Hz octave band than the original RC

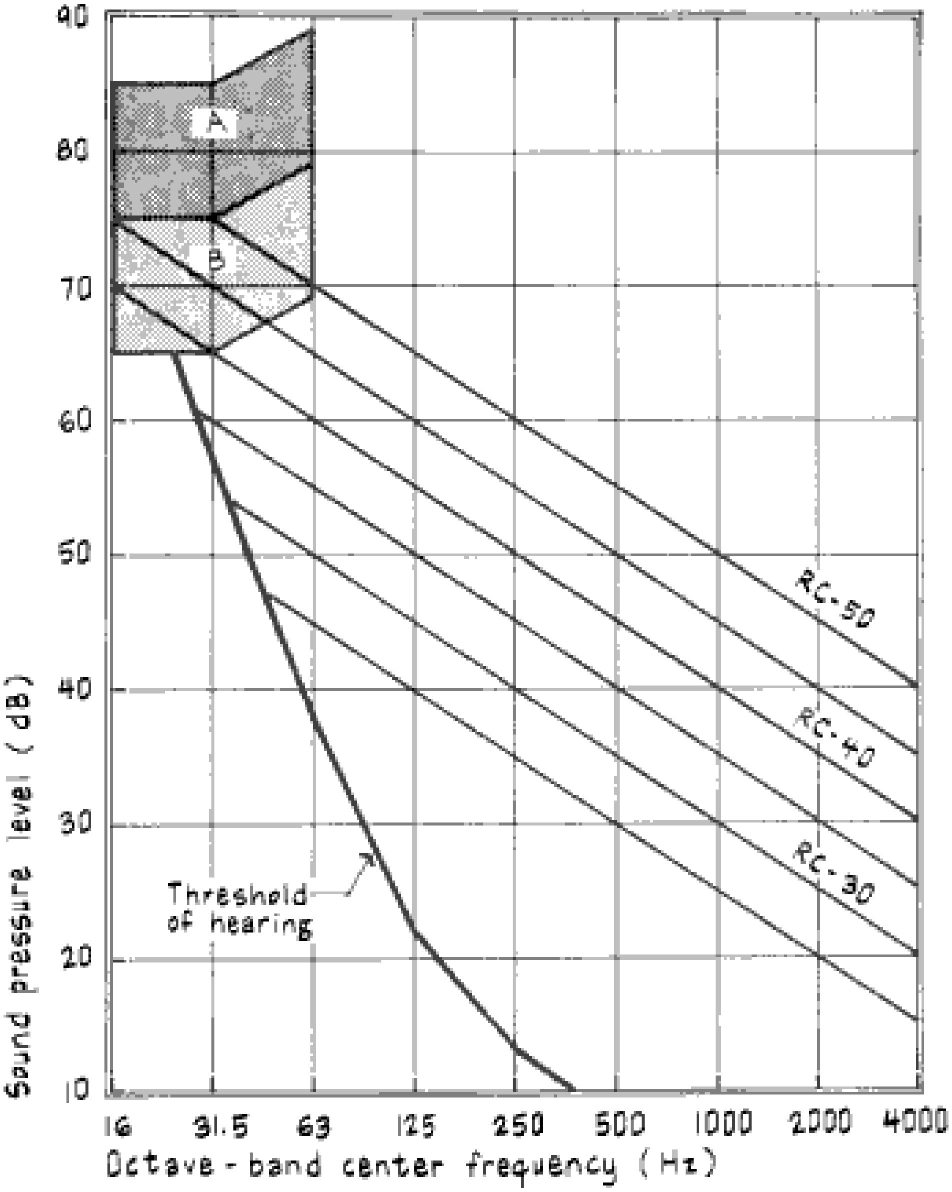

Figure 5. Room Criteria Curves [144]

curves. This is illustrated in the RC Mark II graphs shown in Figure 6. The L_{MF} level rating calculation remains the same as the RC method, but the actual quality descriptors are based on spectral deviations between the measured levels and the RC contour levels. Further, an additional quality descriptor of “roaring” is included for excessive mid-frequency noise. RC Mark II also includes a Quality Assessment Index (QAI) that qualitatively estimates the occupant evaluation, ranging from acceptable to objectionable. The QAI is also based on spectral deviations between the measured levels and the RC contour levels. RC Mark II also includes the possibility of noise-induced vibration in the low frequencies (16 Hz to 63 Hz octave bands).

2.4 Speech Intelligibility

Speech intelligibility is the measure of how well a listener can understand speech [24,133]. Speech intelligibility is dominated by two main factors, signal-to-noise ratio and reverberation time. Signal-to-noise ratio in this case is given by the ratio of the speech of interest to the background noise in the room. The idea is that excessive background noise can mask a speech signal. Reverberation time is the other factor that can affect speech intelligibility—as reverberation time increases, the energy of each speech phoneme will decay into the next phoneme, thus making the speech more difficult to understand. The different metrics used to describe speech intelligibility analyze signal-to-noise ratio, reverberation time, or both of these factors.

2.4.1 Articulation Index

Articulation Index (AI) was first defined by ANSI S3.5-1969 and determined speech intelligibility by considering only background noise [24, 146]. Across the five

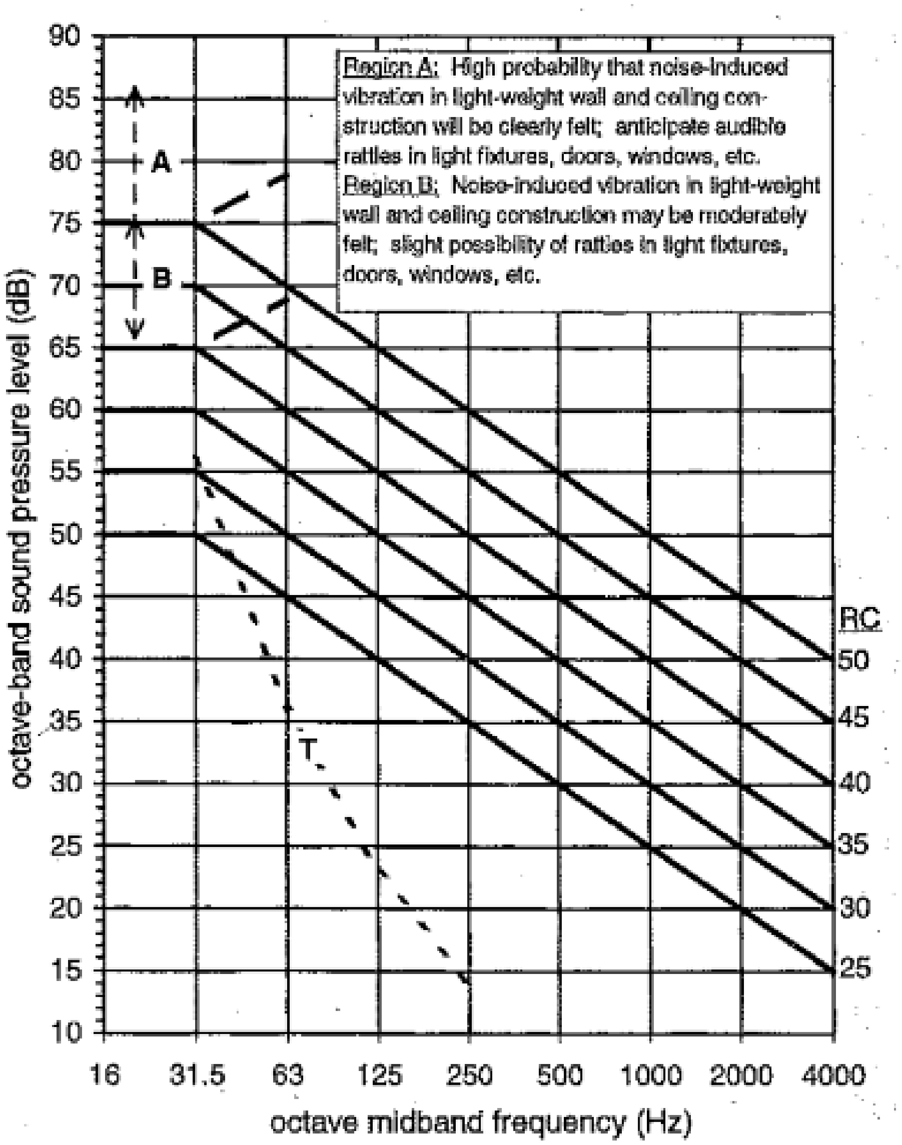

Figure 6. Example of RC Mark II Graph [145]

octave bands covering 250-4000Hz, the signal-to-noise ratio is measured. At each octave band, a weighting factor is multiplied by the signal-to-noise ratio, and the summation of these products determines AI, as defined in Equation 5:

$$AI = \sum Signal - to - Noise\ Ratio\ \times Weighting\ Factor \qquad (5)$$

Articulation Index ranges from 0 to 1, where 0 corresponds to no intelligibility and 1 corresponds to perfect intelligibility. The standard also defines qualitative modifiers for different levels of speech intelligibility as seen in Table 4.

Table 4. Articulation Index Qualitative Modifiers [140]

Articulation Index Rating	**Speech Intelligibility Qualitative Modifier**
>0.7	Very Good
0.5-0.7	Good
0.3-0.5	Marginal
0-0.3	Poor

2.4.2 Speech Intelligibility Index

Speech Intelligibility Index (SII) is described and defined by the ANSI S3.5-1997, R2007 standard [20, 133,134]. SII serves as an update to the AI method described above. Similarly, to AI, SII only accounts for signal-to-noise ratio and does not directly account for reverberation time. This standard also defines standard speech levels, with normal, raised, loud, or shouting levels. SII updates AI by including distortion, masking, and frequency band broadening in the calculations [134]. The SII, like AI, is a single number value between 0 and 1, with 1 representing perfect intelligibility. The standard defines qualitative regions as seen in Table 5.

Table 5. Speech Intelligibility Index Qualitative Modifiers [20]

Speech Intelligibility Index Ratings	**Speech Intelligibility Qualitative Modifier**
0.75-1.0	Good
0.45-0.75	Marginal
0-0.45	Poor

2.5 Audio Recordings

2.5.1 Digital and Binaural Recordings

Digital audio recordings are another tool that can be utilized to characterize hospital noise [147]. Digital audio recordings are digitally continuous recordings—analog signals that are sampled and quantized into a digital signal. The sampling rate and bit depth are the two main properties of a digital recording. The sampling rate, through the Nyquist frequency, determines the highest frequency the digital recording can accurately reproduce without aliasing. The number of bits determines the quantization of amplitude. Audio CDs typically have a sampling rate of 44.1 kHz and a 16-bit depth, corresponding the 22.05 kHz for the highest frequency the recording can reproduce without aliasing. The recordings made in this dissertation use the standard CD sampling and bit depths. The advantage of using these recordings is that where the sound level meter gives the averages, maximums, peaks, and minimum sound pressure levels across a specified period of time, the digital audio recording offers a digital continuous signal to allow for short term analysis possibilities.

Binaural recordings are two-channel recordings made with a mannequin head and microphones placed in the ears of the mannequin [25]. The concept of these recordings is to record what a human would hear inside the ear. These recordings natively incorporate the head related transfer function (HRTF)—a naturally occurring filter that occurs due to reflections and interferences that occur from the shape of the head, the ear lobes, and ear canal. These recordings give a better representation of what happens inside the human ear and create an acoustic “3-D” recording.

2.6 Psychoacoustic Principles

Psychoacoustics is the study of the human perception of sound [25]. Previous research in this field has yielded several metrics, including Speech Interference Level, Loudness, Sharpness, Fluctuation Strength, and Roughness. These metrics are representative of the psychological and physiological responses of the human auditory system. Although they have been used widely in sound product evaluation, they are less commonly used in architectural acoustics and have not yet been tried in hospitals, specifically.

2.6.1 Speech Interference Level

Speech Interference Level (SIL) is a metric derived from sound pressure levels at different frequency octave bands [24-25]. It is an intelligibility metric that focuses on the background noise in the frequency range where the human ear has the highest sensitivity. As noted earlier in the NC method, SIL is defined in Equation 3 above. SIL is the arithmetic average of sound pressure levels at the 500 Hz, 1000 Hz, 2000Hz, and 4000 Hz octave bands. SIL can be interpreted at specified decibels. For example, in a "normal" voice level at 1 meter distance from the speaker, at 57 dBA, 60% of the words are understood. However, at 88 dBA, it takes a "maximum" effort from a speaker for 60% of the words to be intelligible at 1-meter distance.

2.6.2 Loudness

Loudness is the psychoacoustic metric that describes the sensation of sound volume that is defined in ISO 226:2003 [25,148]. The loudness curves are derived from the Fletcher-Munson equal loudness curves. The initial experiments were repeated using loudspeakers in an anechoic chamber by Robinson and Dadson. The equal loudness curves derived by Robinson-Dadson are shown in Figure 7 [133]. Along the contours of this figure, the human ear perceives equal loudness. The unit of phon is defined to be the loudness of a 1 kHz plane wave tone. For example, 40 phons is equal to the loudness of a pure 1 kHz tone at 40 dB on the equal loudness curve.

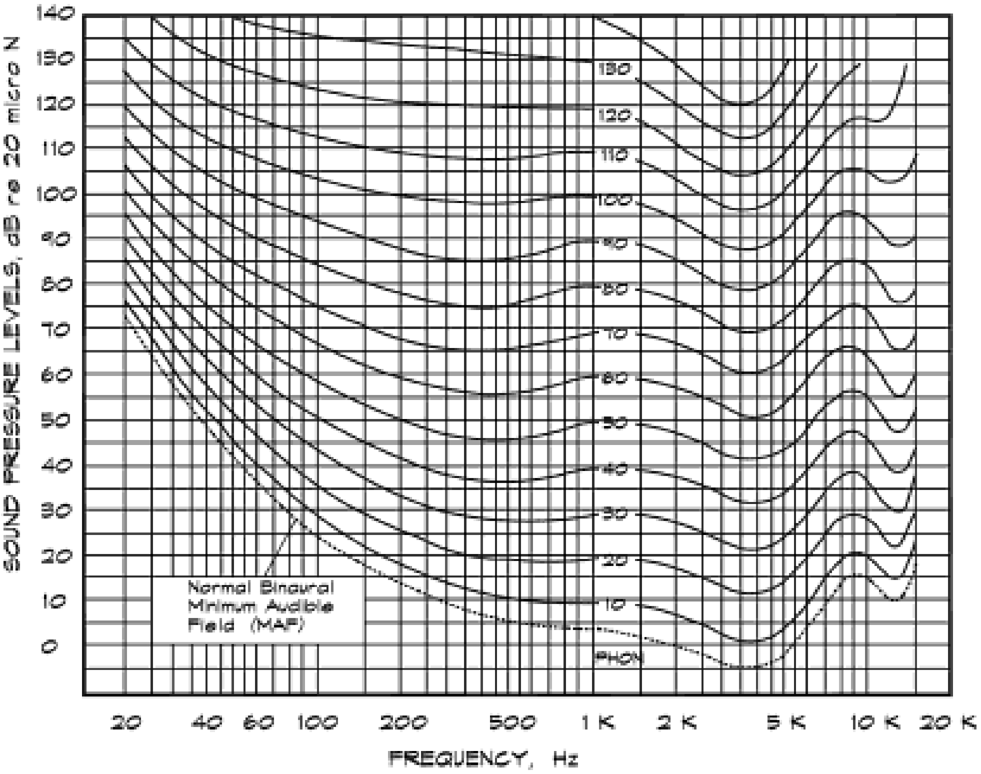

Figure 7. Robinson-Dadson Equal Loudness Curves [133]

Another unit of loudness is the sone. The sone measures relative loudness where 1 sone equals the 1 kHz pure tune at 40 dB on the equal loudness curve. One property of the unit of sones is that a doubling of sones represents a doubling of perceived loudness. To interpret this metric, values of one to four sones can represent a typical conversation and values of five to fifteen sones can sound like a passing car.

2.6.3 Sharpness

Sharpness is the psychoacoustic metric that analyzes the amount of high frequency energy there is in a sound [25]. The unit of sharpness is the acum. As acums increase in value, the sharpness increases which represents an increase of high frequency energy in proportion to the low frequency energy in the sound. Sharpness is measured from 0 to 10 acums, where 10 is the sharpest sound possible. For example, a musical recorder or a flute has a sharpness of around 5 acums, but jingling bells measure close to the maximum 10 acums.

2.6.4 Fluctuation Strength

Fluctuation strength is the metric that describes the temporal signal variations of low frequency modulation [25]. The unit of fluctuation strength is the vacil and it is defined that 1 vacil is equal to a 60 dB 1 kHz tone with 100% amplitude modulation at 4 Hz. The maximum value is 1 vacil and the minimum is 0 vacils, representing no fluctuation. For certain sounds, like speech, a higher fluctuation strength is desired, but for other sounds like wind turbines, higher fluctuation strength can potentially lead to more annoyance.

2.6.5 Roughness

Roughness is a metric that is similar to fluctuation strength. It also measures the temporal changes in a signal but at a higher modulation frequency [25]. The unit of roughness is the asper, where 1 asper is equal to a 60 dB 1 kHz tone that is 100% amplitude modulated at 70 Hz. Roughness can describe how different or similar audible tones sound when compared to each other.

2.6.6 Just Noticeable Difference for Psychoacoustic Metrics

There is somewhat limited data on the just noticeable differences for psychoacoustic metrics. The just noticeable difference is the minimum change in the metric that is typically noticeable by humans. One study of refrigeration noise by You and Jeon measured the just noticeable difference (jnd) for the previously mentioned psychoacoustic metrics [149]. This study in refrigeration noise yielded just noticeable differences as shown in Table 6.

Table 6. Just Noticeable Differences for psychoacoustic metrics [149]

Psychoacoustic Metric	**Just Noticeable Difference**
Loudness	0.5 sones
Sharpness	0.08 acums
Fluctuation Strength	0.012 vacils
Roughness	0.004 aspers

2.6.7 Just Noticeable Difference for Reverberation Time

Just noticeable difference (jnd) for reverberation time is the smallest change in reverberation time that humans can detect. Meng et. al carried out jnd tests for reverberation time on 34 subjects and they tested both white noise and music reverberation time situations [150]. They report that a change of 20-30% of reverberation time is the jnd for music situations. Furthermore, changes of 5-10% constitute the jnd for reverberation time using a white noise stimulus signal.

2.7 Statistics Principles

Statistical analysis has been lacking in the existing hospital acoustics literature as previously stated in the review. This dissertation aims to utilize statistics as a way to identify both statistically significant and meaningful relationships between acoustics and occupant outcomes. Statistical methods such as correlations, linear regression, curve estimation, and risk ratio are standard tools that can be utilized in this type of research. Additionally, a test for statistical significance can be calculated for a specified probability value, or p-value. Commonly used p-values are $p<0.05$ or $p<0.01$. The p-value is the probability that the null hypothesis (or no relationship between variables) is true. For example, if the calculated p-value is 0.05, then the probability of validating the null hypothesis is 5%.

2.7.1 Correlations

In statistics, correlations measure the strength of linear dependence between two variables [151]. Values range from -1 to 1. Two standard correlation types exist: the Pearson product-moment correlation coefficient (r) and the Spearman rank correlation (ρ). For both r and ρ, if the value is 1, then a linear equation perfectly encapsulates the relationship between two variables in a positive direction— i.e., when one variable increases in value, then the other variable also increases in a linear relationship. If the value is -1, the linear relationship is negative—i.e., if one variable increases, the other variable decreases. A value of 0 implies there is no linear relationship between the variables. The Pearson correlation coefficient, r, is defined as the covariance between two variables (X,Y) divided by the product of the standard deviations. It can be calculated using Equation 6 as defined by:

$$r=\frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{X_i-\bar{X}}{s_X}\right)\left(\frac{Y_i-\bar{Y}}{s_Y}\right) \tag{6}$$

where, $\left(\frac{X_i-\bar{X}}{s_X}\right) = \text{standard score}$, $\overline{X} = \text{sample mean}$, and s_x is the sample standard deviation for a given sample size *n* or N. The Pearson method is suitable for parametric statistic scenarios. Nonparametric situations arise when the researcher cannot estimate the parameters of the study, such as the mean and standard deviations. Parametric correlations, for example, use the mean and standard deviation in the calculations.

The Spearman coefficient, (ρ), uses ranked variables (x,y) instead of the raw variables (X,Y). ρ is found by calculating the Pearson correlation coefficient using these ranked variables as seen in Equation 7.

$$\rho=\frac{\sum_i (x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_i (x_i-\bar{x})^2 \sum_i (y_i-\bar{y})^2}} \tag{7}$$

One property of using ranked variables rather than raw variables is that the Spearman method is less sensitive to outliers. Additionally, the Spearman method is used as a non-parametric test.

Both Pearson and Spearman correlation coefficients can be tested for significance for a given *p*-value. Significance tests can be calculated and often determined through table lookups. If the values of *r* or ρ are significant, then the null hypothesis is rejected. It is noteworthy that both these correlations do not imply causation; but rather, significant results of these tests can only show the existence of the relationship between two variables.

2.7.2 Linear Regression

Linear regression is a method of modeling the potential linear relationship between an independent variable (x) and a dependent variable (y) [151-152]. One of the key assumptions in this analysis is a normally distributed sample set. The result of a linear regression analysis is a fitted line that describes the correlation between x and y. The linear relationship can be summarized by Equation 8:

$$y=y_0 + mx$$

$$m = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sum(x-\bar{x})^2}$$

$$y_0 = \bar{y} - m\bar{x} \tag{8}$$

where $y_0$is the y-intercept and m is the slope of the relationship. The variables m and y_0 are calculated using the least-squares method. Additionally, it is possible to extend this procedure to several independent variables relating to the dependent variable.

Statistical significance is calculated using the F-test—the F-variable is defined as the explained variance divided by unexplained variance. Using a defined table, the F-variable can determine if the linear regression is statistically significant or not. If it is, then the regression line can meaningfully describe the linear relationship between the independent and dependent variables.

2.7.3 Curve Estimation

Curve estimation is a method that models different regression relationships between independent and dependent variables [151-152]. A generalization of the linear regression method, curve estimation can attempt to apply nonlinear relationships between the variables, such as quadratic, cubic, logarithmic, or power-curve relationships.

Similarly, to the linear regression method, this method calculates the F-statistic to determine whether or not the curve estimation is statistically significant or not.

Several types of curve fitting are considered: inverse, quadratic, cubic, and logarithmic. The linear relationship in curve estimation uses identical equations as linear regression. Sample curve estimation equations are defined in Equation 9:

$$y = y_0 + \frac{m}{x} \quad \textit{Inverse Relationship}$$
$$y = y_0 + m_1 x + m_2 x^2 \quad \textit{Quadratic Relationship}$$
$$y = y_0 + m_1 x + m_2 x^2 + m_3 x^3 \quad \textit{Cubic Relationship}$$
$$y = y_0 + m \ln x \quad \textit{Logarithmic Relationship} \tag{9}$$

The equations detail the general structure for these potential relationships. Curve estimation can provide another level of understanding between the independent and dependent variables if the linear model is not appropriate. Specific curve models used in this study will be discussed in Chapter 3.

2.7.4 Risk Ratio

Risk ratio or relative risk is the risk of a specified outcome relative to exposure [153]. It is often used to determine the risk of a particular outcome in clinical trial data, such as the risk of developing lung cancer for a smoker. When calculating risk ratio, a risk ratio of 1 means that there is no greater or less risk for an outcome; a risk ratio greater than 1 reveals that there is a greater risk of an outcome; and conversely, a risk ratio less than 1 shows a lowered risk of an outcome. For example, a risk ratio of 1.25

indicates that there is a 25% increased risk of an outcome due to exposure. Risk ratio is defined in Equation 10:

$$\text{Risk Ratio} = \frac{p_{exposed}}{p_{non-exposed}}$$

$$\text{Confidence Interval} = \log(\text{Risk Ratio}) \pm \text{SE} \times z_{\propto} \quad (10)$$

where SE is the standard and $z_{\propto}$ is the standard score. Risk ratio is calculated by dividing the probability of occurrence due to exposure divided by probability of occurrence in a non-exposed environment. If the calculated confidence interval includes 1, then the risk ratio is not statistically significant. If the confidence interval excludes 1, then the risk ratio is statistically significant to a specified *p*-value.

2.8 Conclusion

This chapter summarizes the acoustic and statistical principles that will be utilized in Chapters 3 and 4. These chapters build on the basic acoustic metrics described, such as the sound level meter metrics and psychoacoustic metrics. This research aims to determine if any of these metrics are statistically related to patient or staff responses. The models described above are the primary tools used to find relationships in this research. Correlations, linear regressions, curve estimation and risk ratios will be used to find how the noise can affect patient physiology. Additionally, speech metrics discussed above can shed light on how noise in the wards can affect staff communication. These tools and metrics lay the groundwork for this dissertation.

CHAPTER 3 - METRICS AFFECTING PATIENT OUTCOMES (SWEDEN STUDY)

3.1 Introduction

Ideally, the hospital functions as a location where patients can recover from illness. Environmental factors that are not conducive to patient recovery are counterproductive to the primary function of the hospital. The soundscape is one of these potentially negative factors that can affect the patient's physiology as discussed in the previous chapters. However, the nature of these effects and the even the particular acoustic metrics that relate the sound environment to the patient physiological responses have not been researched to great depth. This research aims to define and clarify these metrics and effects. The hypothesis, presented in Chapter 1, for how metrics affect patient outcomes is:

- Patient Outcomes (Sweden) Hypothesis
  - Traditional and non-traditional sound level metrics are statistically related to patient physiological outcomes of heart rate, respiratory rate, oxygen saturation, and blood pressure.

The chapter discusses a patient study, the first of two major studies presented in the dissertation, that aims to determine which acoustic metrics, traditional and non-traditional, best relate to patient physiological outcomes. The measurements were conducted in a large community hospital near Gothenburg, Sweden and the medical-surgical intensive care unit (ICU) ward was specifically selected for the wide variety of patients there. For the 19 patients that were observed, both acoustic and physiological measurements were made. This study is part of a larger collaboration that also considers other environmental factors and utilizes researchers from the fields of acoustics, environmental medicine, engineering and statistics. The results of the larger collaboration are not presented in this chapter.

In this section, acoustic results are presented in order to characterize the acoustic soundscape of the ICU. Both traditional sound level metrics and non-traditional metrics such as psychoacoustic metrics are utilized. Statistical methods demonstrate the relationships between the patient physiological measurements and acoustical measurements. Additionally, speech intelligibility metrics are considered in this ward.

3.2 Methodology

The methodology and measurements were not initiated or conducted by the author. The other members of the research team developed these initial phases of this study. The methodology is presented here in order to provide background and understanding to the project and the results. All analyses and post-measurement studies were instigated and completed by the author.

3.2.1 Environment

As stated above, the research was conducted at a medical-surgical intensive care unit (ICU) at a community hospital in western Sweden. The patients required continual monitoring in this critical care setting. The ICU examined has several individual rooms, containing two to three patients each. Privacy curtains exist around each patient bed, but are typically left open to allow for better visual access for nurses. Each room contained a nursing work station where one to three nurses monitored patients. Additional staff where often present in the room during procedures and shift change periods. The patient rooms have linoleum tile flooring, gypsum board walls, and a lay-in acoustical tile ceiling. All rooms in the ICU were occupied during the study period and reverberation time measurements were not allowed.

The demographic of the patients varied as there was no “typical” patient amongst the 19 patients, with nine male patients, nine female patients, and one patient with incomplete information. The average age was 61 with the youngest patient at 37 years of age and the oldest at 81. The conditions of these patients included, but were not limited to, infection, embolism, pneumonia, aneurysm, and pancreatitis. Due to the range of conditions, the average stay was 12 days with the range of staying being from 1 day to 76 days.

3.2.2 Types of measurements

To characterize the ICU soundscape, two different types of measurements were taken—sound level meter or stationary measurements and digital audio recordings made with a single channel audio recorder. For the physiological measurements, each patient was monitored and four vital measurements were logged—heart rate or heart frequency (HR), respiratory rate (Resp), percent oxygen saturation (SPO2), and blood pressure (BP).

3.2.3 Acoustic Measurements

The acoustic measurements were carried out in each of the 19 patients’ rooms. For each patient, generally 22-hours were observed, from 4:30pm on the first day, to about 2:30pm on the next day. In the two remaining hours in the 24-hour day, the data was downloaded from the measurement devices, batteries were replaced, microphones and other equipment were moved to the next patient location, etc. It was paramount that the research staff members not interfere with the normal functioning of the ICU. Therefore, there were certain instances when the exact period of observation differed slightly, as it was impossible to access the room, hang microphones, etc., due to the treatment going on within the space. For each patient the two aforementioned types of instruments were used: a) a stationary sound level meter and b) a stationary single-channel recorder. During all measurements, patients, staff, and visitors continued with their normal activities.

3.2.4 Acoustic measurements

Stationary sound measurements were conducted to measure the ambient noise in the room at the patient location. Microphones were suspended approximately 18” below the ceiling at a location near the patient. Sound level meter data was collected with a Brüel & Kjær (B&K) type 2260 sound level meter and corresponding analysis was conducted using B&K Evaluator 7820 software and Excel. The B&K data was collected continuously for approximately 22 hours per patient. One-minute averaging intervals, a fast response time, and a range of 30.8 – 110.8 dB were used. The one-minute averaging intervals were time-synced with the physiological measurements described below. A-weighted equivalent, minimum and maximum sound pressure levels (L_{Aeq}, L_{Amin}, L_{Amax}) and C-weighted peak sound pressure levels (L_{Cpk}) were obtained from the sound level meter measurements. One-third octave band un-weighted frequency data were also measured per minute for the 22-hour collection period.

Digitally continuous single-channel recordings were made with the HEAD SQuadriga system and corresponding analysis was conducted with HEAD ArtemiS v.7.00 software. The digital recordings were made continuously for one hour during three or four different time intervals, using a 16-bit quantization rate and a 44.1 kHz sampling rate. These time intervals were scheduled to sample a representative hour from the morning, afternoon, and night periods—approximately 7:00-8:00 am, 4:30-5:30 pm and 1:30-2:30 am. A fourth measurement was sometimes collected in the late morning/early afternoon. The exact time interval for the afternoon measurement differed slightly from patient to patient due to some of logistical issues involved with accessing the patient rooms during treatments as described earlier.

3.2.5 Patient physiological measurements

Patient physiological data was measured for 19 subjects. The medical apparatuses already in place in the ICU were used for the data collection. Heart rate, respiratory rate, oxygen saturation, and blood pressure (systolic, diastolic and median) were recorded and logged at every minute during the same 22-hour period the stationary acoustic data was taken. Each minute was time-synced with the one-minute logging of the sound level meter setting. For example, from 3:00 to 3:01, the sound level meter measured the average, minimum, maximum, and peak sound levels for that minute. During the same time interval, the physiological medical apparatuses recorded the heart rate, respiratory rate, oxygen saturation, and blood pressure for the 3:00 to 3:01 minute. An additional alarm log was kept for the 22-hour period that included both the time and type of alarm that was triggered. Each patient’s medical observation charts and medication logs were also collected as a part of the complete data set.

3.3 Results

3.3.1 Traditional acoustic metrics

Traditional average, minimum, maximum, and peak sound level metrics provide a view of the fundamental characteristics of the background noise of the ICU. In this section, the results of overall L_{Aeq}, L_{Amin}, L_{Amax} and L_{Cpk} are presented for the entire acoustic data set and for the different work shifts. Overall spectrums of occupied and unoccupied rooms are compared with each other. The relatively newly introduced metric called “occurrence rate” is used to show the temporal distribution of peak and maximum levels for the ICU.

The sound level meter measurement logs were plotted to see how sound levels vary for different parts of the day. In this analysis, only the hours that correspond to the digital audio recording hours are plotted. Figure 8 shows a representative subject room’s average sound levels (Subject 2) during the four measurement hours. The graph shows widely varying sound levels through all four of the hours. A visual inspection of the graphs may provide some initial indication of which hours of the day may be the loudest. For example, noise in the early-to-mid morning hours may be associated with physician rounds and a higher incidence of patient care activities. However, the trends were not the same for all patients.

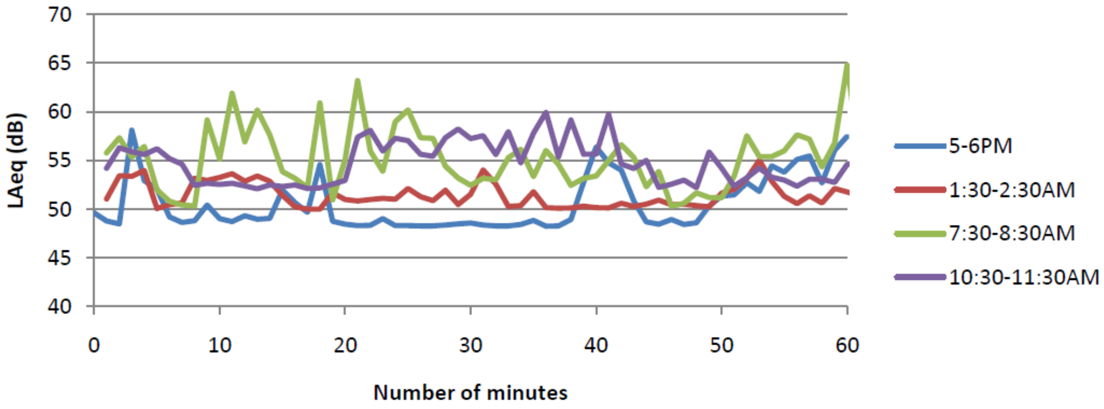

Figure 8. Time history/log of L_{Aeq} sound level.

Visual inspection of the graphs was insufficient and thus more thorough and robust analyses are necessary to understand the soundscape. Determining the average sound level from the data set can begin to reveal the soundscape characteristics of the ICU. Using the entire data set from 19 subjects, the equivalent A-weighted sound level was calculated to be 52.3 dB L_{Aeq}. When presenting the A-weighted minimum, A-weighted maximum, and C-weighted peak levels, the results indicate the absolute maximum or minimum across the data set, i.e., these are not averaged values. The results for the minimum, maximum, and peak acoustic levels are presented in Table 7. These average sound levels exceed World Health Organization recommendations and even though the peak levels are short in duration, values of 113 dBC are considered to be high. Peak levels this high have been attributed to hearing loss and sleep disturbances as shown in Chapter 1. These overall results provide a general scope of the noise levels in the ICU; however, a more detailed breakdown of these measurements is needed.

Table 7. Sound level meter results for all 19 subjects.

Overall Values for complete data set (22 hours per subjects, 19 subjects, 418 hours)

L_{Aeq}	L_{Amin}	L_{Amax}	L_{Cpk}
52 dBA	31 dBA	101 dBA	113 dBC

The work shifts in this medical-surgical ICU are split into three shifts: 7am-2pm, 2pm-9pm and 9pm-7am. Table 8 reports the overall average equivalent, minimum, maximum and peak levels for each of the three work shifts. It can be seen that the morning and afternoon shifts are the loudest, with the night shift possibly being noticeably quieter. The night shift is more than 3-4 dB L_{Aeq} quieter than the morning and afternoon shifts, which is just at the jnd for noise (3 dB L_{eq}; [25]). Although there is also some reduction in L_{Amax} and L_{Cpk} at night, it is arguable how noticeable these differences would be since by definition the L_{Amax} and L_{Cpk} are single event, absolute maximum levels (and not averages).

Table 8. Sound levels separated by work shifts.

Work shift sound results for complete data set (22 hours per subjects, 19 subjects, 418 hours)			
	L_{Aeq}	L_{Amax}	L_{Cpk}
Morning 7am-2pm	55 dBA	101 dBA	113 dBC
Afternoon 2pm-9pm	54 dBA	91 dBA	111 dBC
Night 9pm-7am	51 dBA	88 dBA	108 dBC

Similar measurements of overall levels and work shift levels were made in an unoccupied room. The unoccupied measurements were made in the same manner and over a 22-hour period as well. The results are presented in Table 9. Additionally, each subject's data is separated out as seen in Table 10. Of note, subject 11 is split into two days because the subject was moved from one room to another. When comparing Table 7 and Table 9, the unoccupied room is 9 dBA quieter than the average sound level for the occupied rooms. This corresponds to approximately half the perceived sound level as the occupied rooms. Additionally, in the unoccupied rooms, the morning and afternoon levels are 12 dBA louder than during the nighttime. This may be attributed to the noise that occurs in the corridors and in the nurse stations during the daytime hours. This difference suggests that sound transmission from the outside of the room to the inside of the patient room is an area that could be strengthened.

The results in Table 10 reveal that the patients generally all experience similar average sound levels and similar maximum and peak levels. Considering that these patients have varying conditions and treatments, the sound levels do not differ widely from one room to another. These results provide baseline noise measurements for this general ICU patient population.

Table 9. Unoccupied room sound levels

Unoccupied sound results (22 hours)			
	L_{Aeq}	L_{Amax}	L_{Cpk}
Overall	43 dBA	83 dBA	94 dBC
Morning 7am-2pm	45 dBA	83 dBA	94 dBC
Afternoon 2pm-9pm	45 dBA	82 dBA	94 dBC
Night 9pm-7am	33 dBA	70 dBA	93 dBC

Table 10. Sound levels as separated by subject (~22 hours per subject)

Subject	L_{Aeq}	L_{Amin}	L_{Amax}	L_{Cpk}
Sub2	54	47	88	111
Sub3	52	37	91	108
Sub4	55	42	89	107
Sub5	54	47	88	111
Sub6	54	42	88	104
Sub7	53	31	111	113
Sub8	54	45	89	110
Sub9	53	45	97	113
Sub10	53	40	88	111

Sub11a	51	41	87	109
Sub11b	47	31	87	104
Sub12	52	39	88	104
Sub13	52	41	94	112
Sub14	52	39	84	101
Sub15	53	42	94	108
Sub17	53	43	94	109
Sub18	53	40	97	112
Sub19	53	38	93	114
Sub20	51	44	82	101

Spectral data in the patient rooms allow a frequency comparison between the occupied and unoccupied situations. The overall spectral data was averaged across the 19-subject room data set. Figure 9 shows the spectral measurements for the averaged data as well as for the unoccupied room. The unoccupied data represents the mechanical ventilation noise, which is generally low frequency energy. This unoccupied spectral graph matches the profile of typical HVAC building noise. The occupied room does not roll off in the high frequencies, thus revealing the energy that corresponds to occupant noise, alarm noise, talking, and other noise sources in a patient room. In typical office noise spectrums, the high frequency energy potentially rolls off faster than this ICU data set does, potentially because the ICU has more conversations, alarms and occupant noises than an office would have.

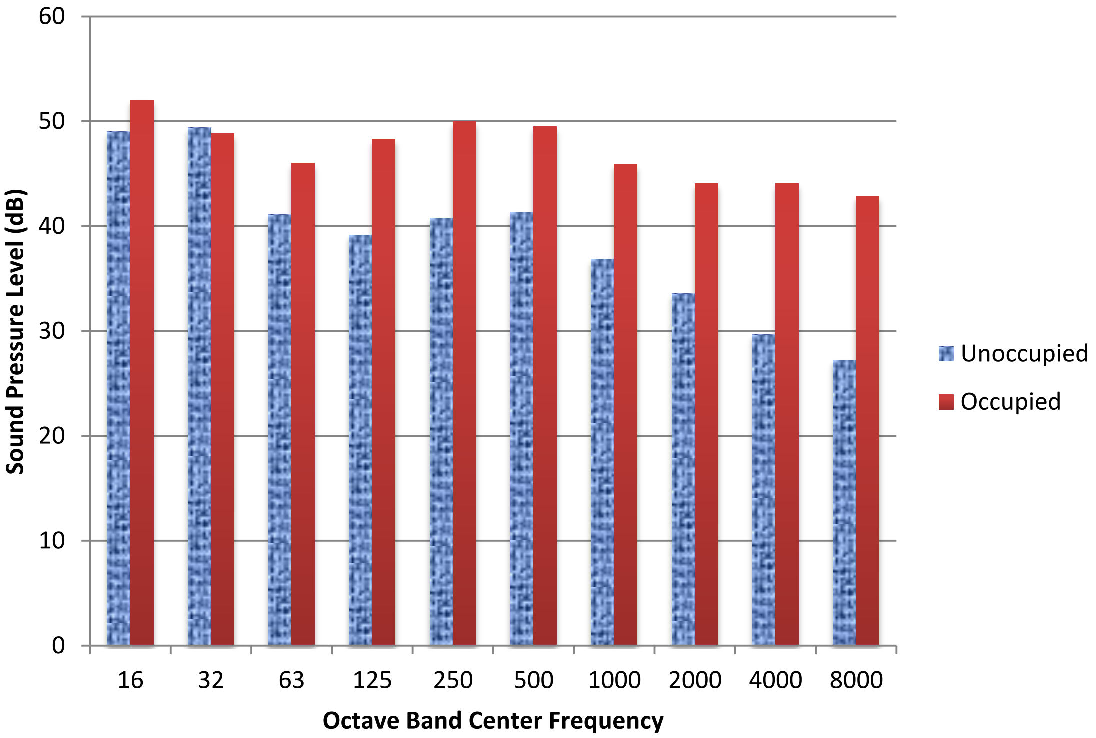

Figure 9. Unoccupied and Occupied spectral measurements

In this study, as stated above, the total measurement time per subject was approximately 22-hours and the logging interval was set to 1-minute. The sound level metrics that were analyzed were L_{Amax} and L_{Cpk}. The occurrence rate analysis was performed on the entire 22-hour recording and the times that corresponded to work shifts.

This overall L_{Cpk} occurrence rate graph for the unoccupied room is shown in Figure 10. It shows that the night shift is the least “peaky”. However, for each minute of the night shift, there exists some peak value within that minute that exceeds 60 dBC.

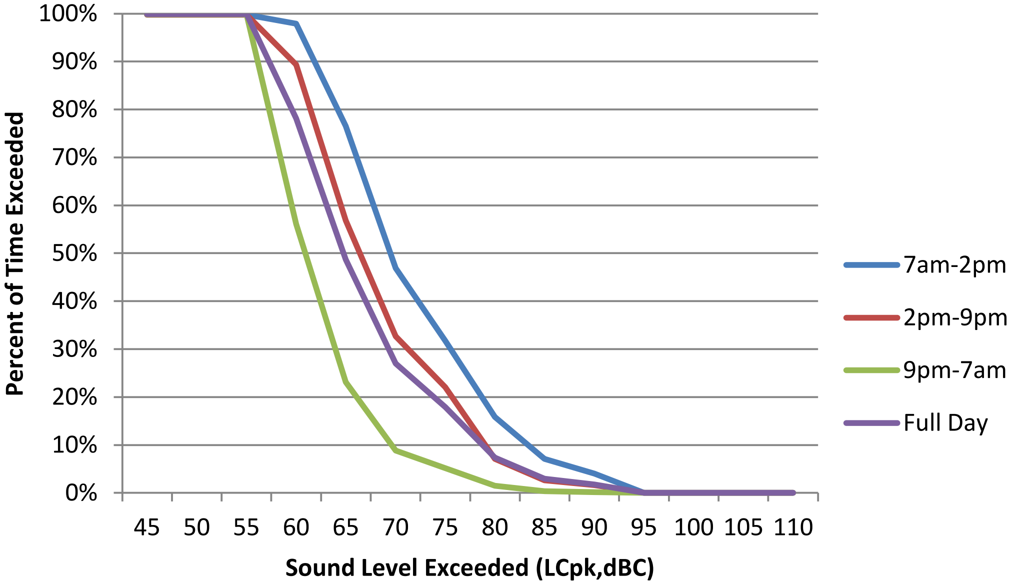

Figure 10. Unoccupied Room L_{Cpk} Occurrence Rate

As a representative sample of the all the subjects, Figure 11 shows the occurrence rate for overall L_{Aeq} for the combined data set. The overall L_{Aeq} is a good representative sample for all the L_{Aeq} occurrence rates and there are few discrepancies between the patients. The only discrepancies are: the afternoon shift is louder than the morning shift in four of the subjects; and the varying curves have different degrees of steepness across subjects. Some general trends could be observed, however. The morning shift is generally louder than the afternoon shift and the overnight shift is the quietest of the three shifts. Again, this may be because physician rounds and numerous patient care activities were conducted by in the morning. As a specific example, overnight, L_{Aeq} exceeds 50 dBA only 30% of time, compared with the morning shift where L_{Aeq} exceeds the same 50 dBA about 63% of the time.

The occurrence rate for L_{Aeq} is shown in Figure 10 and the overall L_{Amax} and L_{Cpk} occurrence rates are shown in Figure 12 and Figure 13. These graphs show the representative trends for the combined data set. It can be seen that all the shifts have the same general S-shaped curve. It is notable that the morning and afternoon shift have a convex type of S-shape to the curve, whereas the overnight shift has the opposite concave-type of S-shape to the curve. This is consistent with some of the other occurrence rate work [38]. Also, the morning shift is slightly louder than the afternoon shift, as seen consistently with this soundscape data. The reasoning for this is likely the same as for the L_{Aeq}; physician rounds and many patient care activities are conducted during the mornings. All the patients show the overnight shift as being the quietest. For example, in Figure 13, during the two daytime shifts L_{Cpk} exceeds 75 dBC approximately 80% of the time. During the overnight shift, L_{Cpk} still exceeds 75 dBC approximately 55% of time. Although nighttime levels are less peaky, these results show that there still exists a high number of peak events all throughout the day.

Figure 14, Figure 15 and Figure 16 show the occurrence rate graphs for a randomly selected subject (Subject 9). This essentially shows what one subject may experience throughout the day and gives a typical temporal representation of sound levels that the subject may experience in his/her room. Similar to above, there are clear differences between shifts.

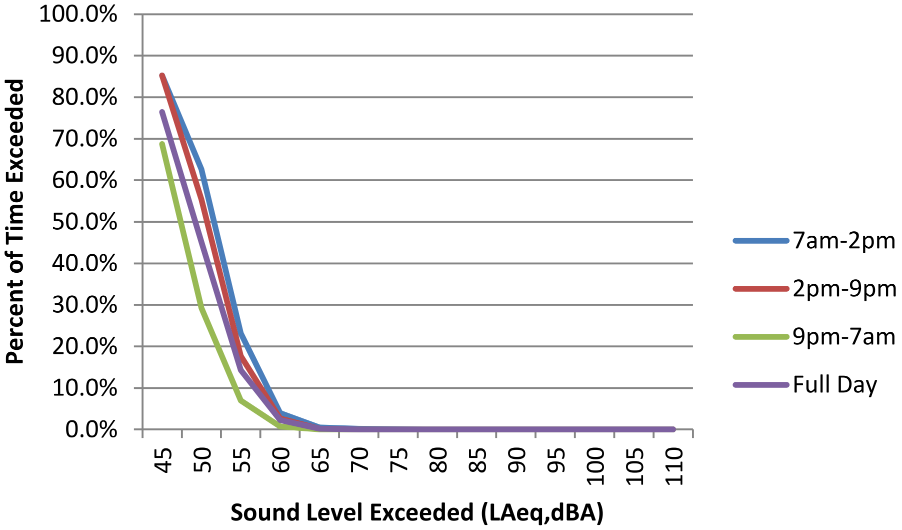

Figure 11. Overall L_{Aeq} Occurrence Rate

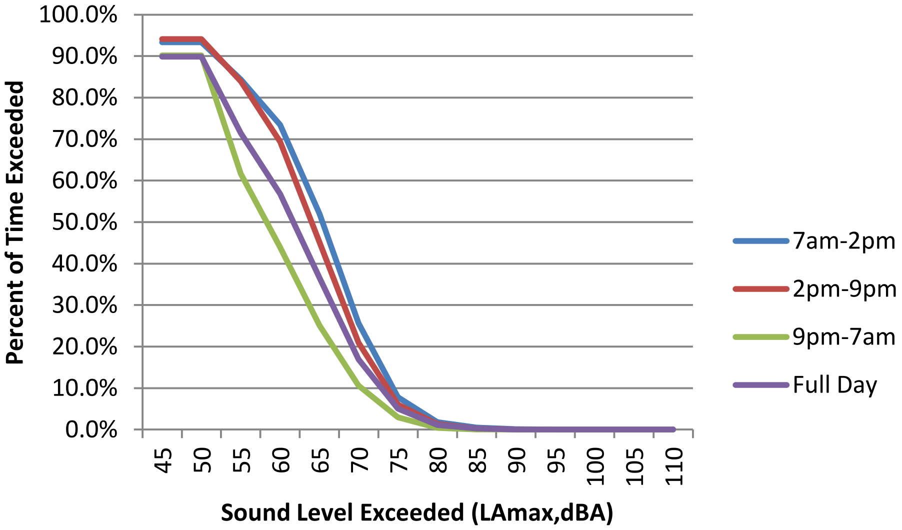

Figure 12. Overall L_{Amax} Occurrence Rate

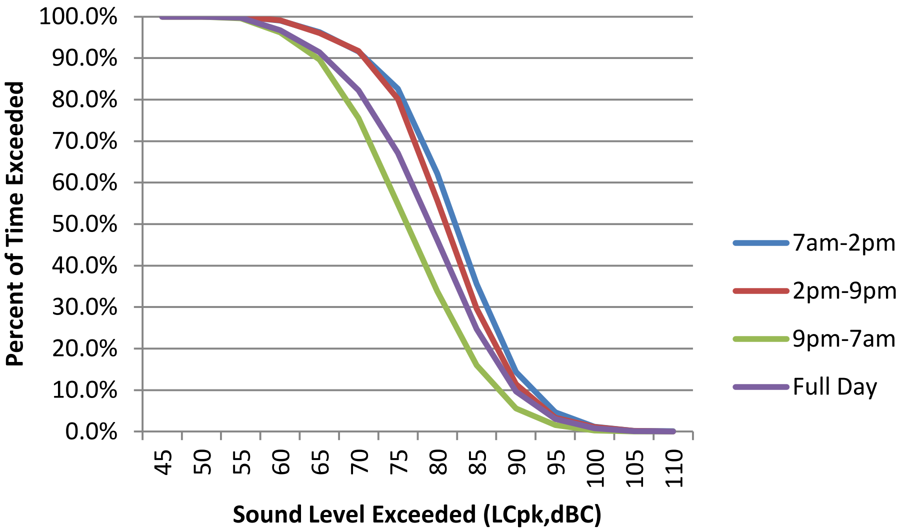

Figure 13. Overall L_{Cpk} Occurrence Rate

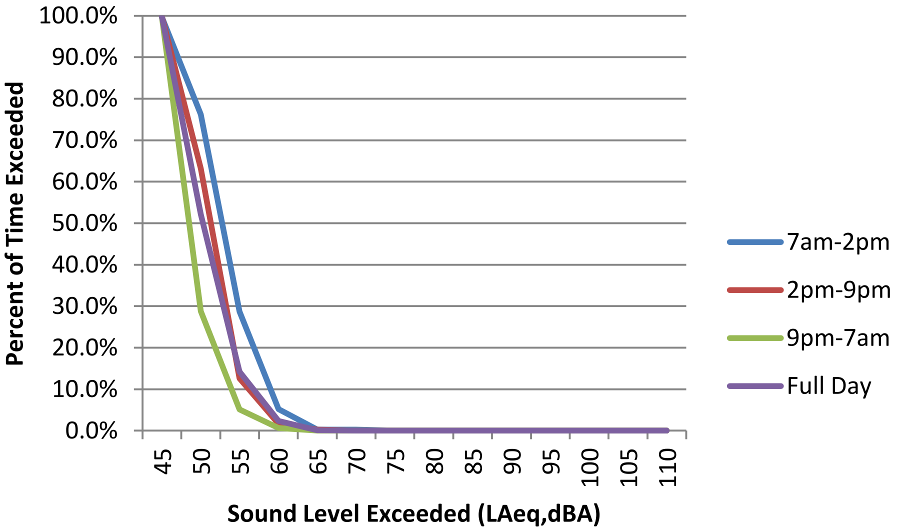

Figure 14. Subject 9 L_{Aeq} Occurrence Rate

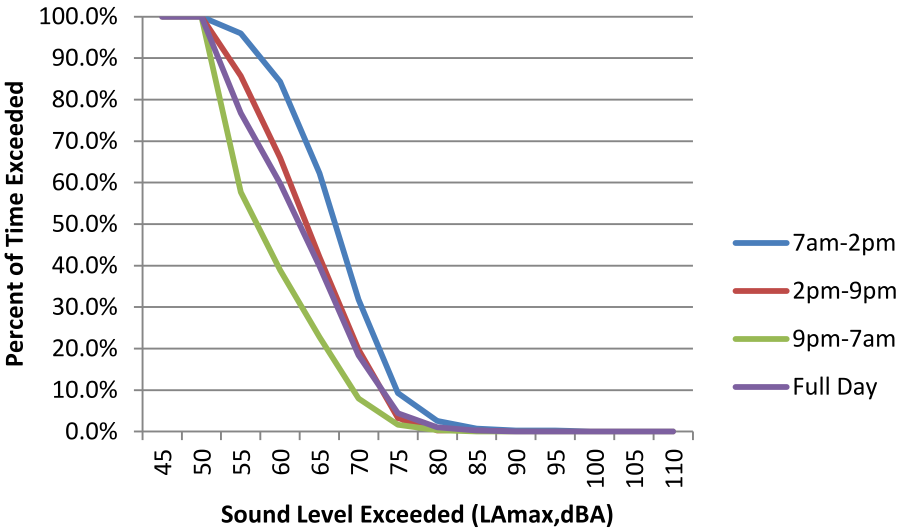

Figure 15. Subject 9 L_{Amax} Occurrence Rate

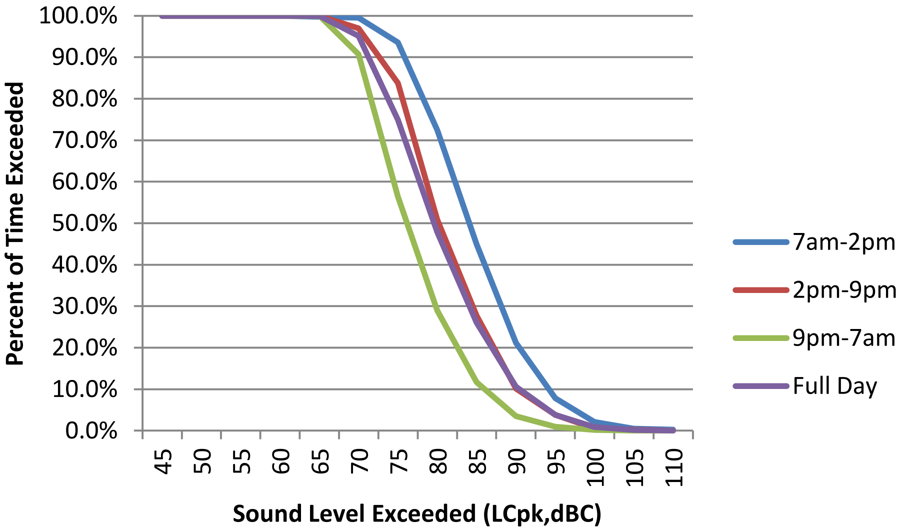

Figure 16. Subject 9 L_{Cpk} Occurrence Rate

3.3.2 Psychoacoustic Metric Results

Beyond traditional sound level meter measurements, non-traditional metrics can potentially allow for a more detailed understanding of the hospital soundscape. Psychoacoustic metrics can offer insight into sound qualities that relate directly to human perception of noise. For these metrics, digital audio recordings were made with a SQuadriga single-channel audio recording system. These audio recordings allow for psychoacoustic analysis that may not necessarily be possible through the sound level meter measurements. The metrics in these analyses were described in Chapter 2—speech interference level (SIL), loudness, sharpness, roughness, and fluctuation strength. As with the sound level meter results, the psychoacoustic soundscape results are presented by complete set, by staff work shift, and for a random subject. These results can provide baseline characteristics of psychoacoustic metrics in medical-surgical ICUs.

SIL was calculated for the data set and the results are shown in Table 11. Average, maximum, and minimum SIL as well as standard deviations were calculated. The average SIL for the entire data set is 41 dB and the range is approximately 33 dB. Whether or not these levels are acceptable is dependent on the level of intelligibility acceptable and the level of vocal effort desired, as described in the Psychoacoustic Metrics Discussion section below.

Loudness was analyzed for both individual patients and across the entire population. Table 12 shows the average, maximum, minimum and standard deviation of loudness. The average loudness for the entire data set was 6 sones with a range of approximately 17 sones. These levels are greater than typical talking or television sounds, and in a range roughly equivalent to automobile sounds at 5 to 15 sones [25].

Sharpness results are shown in Table 13 where the average, maximum, minimum, and standard deviation are shown for each patient. For the entire data set, the average sharpness is 2.0 acums, with a range of approximately 3.3 acums. In accordance to the example above, the sharpness of this data set may not be considered very sharp, as five acums is roughly equivalent to a flute or music recorder.

Results for fluctuation strength are shown in Table 14. The average, maximum, minimum and standard deviation of the data collected for each patient reveal that, for the entire population, the average fluctuation strength is 0.028 vacils, and the range is approximately 0.18 vacils. These are relatively low values for fluctuation strength showing that the ICU does not show much temporal low frequency modulations.

The results for roughness are shown in Table 15. The average roughness was 0.93 aspers with a range of approximately 1.9 aspers. These are relatively high values of roughness indicating that the time varying nature of the noise in the room tended to be of higher frequency amplitude modulations.

Table 11. Speech Interference Level results

Subject #	Average SIL (dB)	Max SIL (dB)	Min SIL (dB)	Standard Deviation. SIL (dB)
2	41.8	50.9	38.5	2.7
3	41.3	51.6	35.1	3.6
4	41.5	52.8	36.0	5.1
5	42.8	52.8	37.5	4.2
6	41.2	56.0	35.8	5.1
7	38.4	47.5	30.3	4.1
8	43.2	53.6	39.4	2.9
9	41.4	52.3	37.2	3.6
10	42.0	54.1	36.0	3.6
11	39.5	48.0	32.5	2.9
12	41.1	49.7	33.5	3.3
13	41.5	50.8	35.6	3.6
14	41.4	50.9	35.0	3.8
15	40.5	50.7	35.1	3.4
17	41.9	53.4	34.9	3.9
18	41.4	63.3	33.6	5.0
19	39.2	54.5	31.7	4.6
20	41.2	54.8	35.2	4.4
Average	41.2	63.3	30.3	4.1

Table 12. Loudness results

Subject #	Average Loudness (sones)	Maximum Loudness (sones)	Minimum Loudness (sones)	Standard Deviation Loudness (sones)
2	6.5	10.1	5.2	1.0
3	6.2	12.5	3.7	1.8
4	6.3	14.2	4.4	1.9
5	6.6	12.0	4.8	1.5
6	6.2	13.5	4.3	2.2
7	4.5	8.2	2.2	1.5
8	7.1	14.4	5.5	1.5
9	6.2	10.9	4.6	1.4
10	6.4	14.5	4.4	1.5
11	5.3	9.5	3.2	1.0
12	5.8	9.8	3.5	1.2
13	6.3	10.7	4.4	1.3
14	6.1	9.9	4.2	1.3
15	5.9	11.9	4.2	1.2
17	6.1	14.9	3.7	2.0
18	6.3	19.4	3.6	2.5
19	4.9	15.3	2.8	1.9
20	6.0	15.1	3.9	2.0
Average	6.0	19.4	2.2	1.8

Table 13. Sharpness results

Subject #	Average Sharpness (acums)	Maximum Sharpness (acums)	Minimum Sharpness (acums)	Standard Deviation Sharpness (acums)
2	1.9	2.3	1.7	0.1
3	2.5	4.5	1.8	0.4
4	2.2	3.8	1.8	0.3
5	2.3	3.0	2.1	0.1
6	1.8	3.7	1.5	0.4
7	1.9	2.6	1.6	0.2
8	1.9	3.5	1.7	0.3
9	2.1	2.8	1.7	0.2
10	1.9	3.6	1.5	0.4
11	1.8	2.9	1.4	0.2
12	1.9	2.9	1.5	0.3
13	1.9	2.6	1.5	0.2
14	1.9	2.6	1.5	0.2
15	2.0	3.5	1.6	0.2
17	1.8	3.7	1.3	0.4
18	1.8	3.2	1.2	0.4
19	1.8	3.3	1.2	0.4
20	2.0	3.6	1.5	0.4
Average	2.0	4.5	1.2	0.3

Table 14. Fluctuation Strength results

Subject #	Average Fluctuation strength (vacils)	Maximum Fluctuation Strength (vacils)	Minimum Fluctuation Strength (vacils)	Std. Dev. Fluctuation Strength (vacils)
2	0.019	0.073	0.002	0.017
3	0.028	0.066	0.006	0.014
4	0.033	0.107	0.002	0.029
5	0.034	0.107	0.002	0.027
6	0.028	0.124	0.003	0.027
7	0.027	0.090	0.003	0.018
8	0.022	0.065	0.004	0.014
9	0.027	0.096	0.003	0.021
10	0.031	0.104	0.004	0.018
11	0.029	0.093	0.004	0.020
12	0.036	0.109	0.006	0.018
13	0.026	0.069	0.004	0.015
14	0.031	0.100	0.004	0.021
15	0.022	0.099	0.003	0.016
17	0.028	0.120	0.001	0.026
18	0.031	0.146	0.002	0.028
19	0.029	0.167	0.001	0.029
20	0.027	0.188	0.002	0.025
average	0.028	0.188	0.001	0.022

Table 15. Roughness results

Subject #	Average Roughness (aspers)	Maximum Roughness (aspers)	Minimum Roughness (aspers)	Standard Deviation Roughness (aspers)
2	1.22	1.49	1.08	0.09
3	1.07	1.90	0.64	0.22
4	1.10	1.72	0.73	0.27
5	1.26	1.76	1.04	0.17
6	1.13	1.86	0.85	0.25
7	0.81	1.63	0.31	0.32
8	1.27	1.82	1.08	0.15
9	1.21	1.78	0.99	0.17
10	1.15	1.93	0.86	0.20
12	0.97	1.46	0.57	0.22
13	1.17	1.79	0.85	0.20
14	1.06	1.64	0.69	0.20
15	1.14	1.94	0.85	0.18
17	0.64	0.92	0.51	0.07
18	0.67	0.94	0.45	0.12
19	0.16	0.56	0.04	0.11
20	0.22	0.83	0.07	0.15
Average	0.94	1.94	0.04	0.39

3.3.3 Psychoacoustic Metrics Discussion

The psychoacoustic data presented here begins to define or characterize the hospital environment in a more comprehensive and rigorous manner rather than just by using the traditional sound level meter metrics. As little to no psychoacoustic data exists for hospital soundscapes, this data set can provide a novel baseline characterization of medical-surgical ICUs. The use of psychoacoustic metrics opens up many possibilities of new ways to characterize hospital soundscapes. Pyschoacoustic metrics are well known to be related to human perception to sound, thus this data set of hospital psychoacoustic averages allows for a characterization of the soundscape that is directly pertinent to human perception.

SIL was measured as an average of 41.2 decibels. This value may be acceptable as it is less than 57 dB, the SIL threshold where one would have to raise their voice to be intelligible. This threshold of acceptability is based on a score that 60% of the speech in intelligible. Whether not this 60% threshold is satisfactory / acceptable is left for future research, as the author has found no research that has explored SIL in mission critical environments. The maximum SIL was 63 dB, corresponding to needing a raised voice to have 60% of the speech intelligible.

Loudness measured averaged 6.0 sones—levels greater than talking or television sounds, and in a range roughly equivalent to automobile sounds at 5 to 15 sones. Further research is needed to determine if these loudness levels may be perceived as too loud where a person is recovering or trying to sleep. In fact, the minimum loudness measured was 2.2 sones, still in the loudness range of a conversation noise. The just noticeable difference for loudness is 0.5 sones, and the standard deviation measured in this study of

1.8 sones is approximately 3.5 times the jnd value. This implies that for the majority of the time, perceptible changes in loudness are occurring.

As presented above, the average sharpness was 2.0 acums and the maximum was 4.5 acums. That is less than the typical sharpness level of a flute or recorder. This average in the ICU is likely dominated by alarm noise, as alarms are present and contribute to high frequency energy. Other than alarm noise and short-term, high frequency metal-to-metal contact or other impact noises, the typical sound sources in a patient room do not tend to accentuate sharpness, based on generalized spectral qualities of typical sounds such as HVAC, conversation, or respirator noise. Further investigation of alarms and how these alarms may affect the psychoacoustic metrics results are presented below.

For fluctuation strength, there is no typical convention of what is considered acceptable or not because fluctuation strength is a more subjective metric—a higher fluctuation strength can be considered better for speech, and a lower value may be better for mechanical noise issues. In this case, the average fluctuation strength was 0.03 vacils and it may be hypothesized that the HVAC noise in the rooms will not be very annoying to patients because of this relatively small measured fluctuation strength. However, the standard deviation of 0.12 vacils is higher than the just noticeable difference of 0.012 vacils, thus a patient would likely be able to perceive these variations in fluctuation strength.

Roughness over 0.10 aspers is considered to be rough, and the average roughness for this data is 0.94 aspers. This implies that the patient rooms have relatively high rates of temporal amplitude variations. Fluctuation strength was relatively low on average, but roughness values were relatively high—indicating that the time varying nature of the noise in the room tended to be of higher frequency amplitude modulations. Only two patients have a minimum roughness less than 0.10 aspers. The just noticeable difference is 0.004 aspers, which is much lower than the standard deviation of 0.39 for all of the roughness data. Because of this, a patient would likely be able to perceive these changes in the roughness over time.

3.4 Relating acoustic metrics to patient physiology

This section reports the statistical link between the acoustic characteristics previously analyzed and the physiological responses of subjects. One of the hypotheses of this dissertation is that patient physiology is related to the acoustics of the hospital. This section uses various statistical models to determine the significance of relationships that may or may not exist.

3.4.1 Background Physiological Data

The physiological data was taken for each of the 19 subjects. As stated above in the methodology, the physiological measurements were taken at 1-minute intervals, time-synced with the sound level meter logging functions and the digital audio files. Recall that the audio files were recorded during three or four hours of this period. In this research, for consistency of the data set, only the hours that the digital audio files recorded were used for all statistical analysis. Thus, for each patient, the same three or four hours of physiological, sound level meter, and digital audio files were used. This allowed for consistent data sets between analyses without compromising the sample size.

3.4.2 Correlations

The cluster plot method provides insight that some significant relationships may or may not exist; however, rigorous statistical analysis is needed to show if statistically significant relationships are actually present. One common tool that can be utilized is statistical correlation. This data set of physiological data and acoustic data is well-suited for such analysis. As a reminder, the data set consists of the time-synced 1-minute logs of the sound level meter and audio recordings along with 1-minute measurements of physiological measurements. Both Pearson and Spearman correlations are calculated with statistical significance set for $p<0.01$.

Table 16 shows that the physiological data is statistically correlated with the sound level metrics. The Pearson method is used for this analysis. In this table, the r is given with $p<0.01$ significance. A blank shows that there is no statistically significant correlation between the two variables. The actual Pearson Product Moment correlations are reported.

It is shown in Table 16 that blood pressure and respiratory rate are positively correlated to all four sound level meter metrics (N=2817). Oxygen saturation is negatively correlated to all sound level metrics except for L_{Amax}. Again, oxygen saturation shows a decreasing trend with an increase in sound level metric, as described above in the cluster plots. Heart rate is only positively correlated to L_{Amin} and not statistically correlated to any other sound level metric. Note that the Spearman correlation method reveals the same statistically significant correlations and directions as the Pearson method, further confirming the correlation between the physiological measurements and the sound level metrics.

Table 16. Pearson correlations between physiological measurements and sound level meter metrics

	Heart Rate (beats per minute)	Oxygen Saturation (S_{O2})	Resp. Rate (breaths per minute)	Blood Pressure (Sys.) (mmHG)	Blood Pressure (Dias.) (mmHG)	Blood Pressure (Mean) (mmHG)
L_{Aeq}	--	-0.156	0.223	0.228	0.201	0.219
L_{Amax}	--	-0.124	0.171	0.122	0.128	0.126
L_{Cpk}	--	-0.137	0.160	0.107	0.130	0.119
L_{Amin}	0.122	-0.262	0.297	0.325	0.293	0.305

It may be hypothesized that a physiological reaction will not necessarily occur within the same minute as a change in sound level. For example, after a loud event there may be a delayed physiological reaction of several minutes before heart rate increases. The delayed correlation results did not reveal generally better or worse statistical correlation values. The results can be seen in Appendix C.

The psychoacoustic metrics were calculated using the digital audio files. They were then re-organized into 1-minute intervals to correspond and time sync with the physiological measurements used above. Similar correlation analyses were performed (p<0.01) and results are shown in Table 17. Recall that previously, for traditional sound level metrics, heart rate was not significantly correlated to anything except L_{Amin}.

Interestingly, in this psychoacoustic analysis, heart rate is positively correlated to all the psychoacoustic metrics except fluctuation strength. Blood pressure is also positively correlated to all the metrics except fluctuation strength and respiratory rate is positively correlated to all metrics. Oxygen saturation correlations have conflicting results—with no correlation to SIL and Loudness, and with conflicting correlation directions with regard to sharpness, fluctuation strength and roughness. These results show that there are correlations present, but the cause for the conflicting results is left for future research. For example, a more targeted study focused on oxygen saturation may provide clarity on these correlations. Similarly, a more targeted study for roughness should occur in future research. This is the only psychoacoustic metric that showed significant correlations for all the physiological metrics; thus, roughness could potentially be an acoustic metric that can be used to predict physiological response.

One additional item to note, there exists a slight “circular” issue between alarms and physiological response. A scenario may exist where an alarm may go off due to heighted blood pressure, and subsequently the heart rate may rise, which then causes the heart rate alarm to go off, which causes more physiological reactions and alarms. The question arises: does the alarm cause the physiological reaction, or do the physiological changes cause the alarm? Correlations do not report causation, only correlation. One way to delve into this problem is to eliminate alarms from the data set. To address this issue, a subsequent analysis was run where if any alarm took place in an hour’s measurement, the entire hour’s data was eliminated from the calculation. Ultimately, roughly 1/2 of the hours used in the total data set were eliminated and the correlation was determined in this “no-alarm” calculation (N=1548) as seen in Table 18.

Table 17. Correlation results relating physiological measurements and psychoacoustic metrics ($p<0.01$)

	Heart Rate (beats per minute)	Oxygen Saturation (S_{O2})	Resp. Rate (breaths per minute)	Blood Pressure (Sys.) (mmHG)	Blood Pressure (Dias.) (mmHG)	Blood Pressure (Mean) (mmHG)
SIL (dB)	0.108	--	0.292	0.201	0.283	0.242
Loudness (sones)	0.125	--	0.308	0.207	0.294	0.243
Sharpness (acums)	0.264	0.090	0.367	0.242	0.159	0.214
Fluctuation Strength (vacils)	--	0.050	0.178	--	--	--
Roughness (aspers)	0.042	-0.033	0.300	0.161	0.152	0.154

Table 19 shows the "no-alarm" correlations for psychoacoustic metrics and the results show that most relationships are statistically significant. This alarm-free scenario offers a calculation that eliminates this circular problem, since there are no alarms that can cause a physiological reaction in this case. Correlations remained similar to the previous calculation (Table 17), which signify that even without alarms, the relationships between noise and physiological response are still valid. Roughness again is the only metric that is correlated to all the physiological metrics. However, unlike the previous psychoacoustic correlations made in Table 17, all the significant correlations for oxygen saturation are in the expected negative direction.

Table 18. Correlations between physiological measurements and sound level meter metrics with alarm data removed ($p<0.01$).

	Heart Rate (beats per minute)	Oxygen Saturation (S_{O2})	Resp. Rate (breaths per minute)	Blood Pressure (Sys.) (mmHG)	Blood Pressure (Dias.) (mmHG)	Blood Pressure (Mean) (mmHG)
L_{Aeq}	--	-0.118	0.251	0.286	0.233	0.267
L_{Amax}	--	-0.059	0.261	0.119	0.118	0.120
L_{Cpk}	--	-0.112	0.251	0.105	0.134	0.118
L_{Amin}	--	-0.317	0.099	0.438	0.394	0.421

Table 19. Correlations between physiological measurements and sound level meter metrics with alarm data removed ($p<0.01$).

	Heart Rate (beats per minute)	Oxygen Saturation (S_{O2})	Resp. Rate (breaths per minute)	Blood Pressure (Sys.) (mmHG)	Blood Pressure (Dias.) (mmHG)	Blood Pressure (Mean) (mmHG)
SIL (dB)	0.140	-0.051	0.323	0.084	0.207	0.143
Loudness (sones)	0.172	-0.050	0.298	0.103	0.230	0.155
Sharpness (acums)	0.348	--	0.452	0.209	0.074	0.154
Fluctuation Strength (vacils)	0.056	--	0.316	0.079	0.049	0.094
Roughness (aspers)	0.219	-0.181	0.277	0.147	0.335	0.226

3.4.4 Linear Regression and Curve Estimation

Linear correlations and curve estimations were used to further develop the relationship between acoustics and physiology. Simple correlation may not provide enough insight, thus linear regression and curve estimation was completed. Results are shown in Appendix D and E.

3.4.5 Risk Ratio

One motivation behind this project was to determine whether a threshold of response existed—in other words, to see if patients respond physiologically as noise surpasses a certain level threshold. In other words, is there a certain noise level where heart rate begins to increase? Statistical risk ratio allows for this type of analysis.

Risk ratio, as stated above, provides the increase or decrease in the risk of an outcome due to exposure of a certain stimulus. An example of this would be, "there is a 25% increased risk of napping due to reading this dissertation" where the stimulus would be this reading dissertation. For this research, the aim is to determine if there is an increased risk of heightened physiological response due to elevated noise level. As a reference, the MATLAB code for risk ratio analyses can be found in Appendix F.

Risk ratio is generally calculated using data that exposes one population with a stimulus and has a second population that is the control group. However, the data in this research is purely observational and does not cleanly fit the general model for risk ratio, where the input is either a yes or no response. For this data, interpretation and modification was needed to answer the question, "Did physiological data heighten with increasing noise levels?" This requires a yes/no response to determine probabilities, whereas the data in its original format was on a continuous scale.

In order to do this analysis, the data was therefore split into two groups, with demarcation occurring at a specified sound level. In both of the two groups, averages were computed and compared with one another. For example, when analyzing heart rate and L_{Aeq} data, all the data that was less than 50 dB L_{Aeq} was in one group, and all the data greater than 50 dB L_{Aeq} was put into another group. The average for the lower group was calculated, and the probability of heart rate being greater than the average in that group was determined by counting the number of events greater than the average and dividing that by the total number of events in the lower group. In the upper group, the probability was determined again by counting the number of occurrences greater than the lower group's average and dividing by the total number of events in the upper group. If the upper group's probability was higher than the lower group's, then it was determined that it may be more likely to have a higher heart rate if sound level is greater than 50 dB $L_{Aeq.}$ These calculated probabilities were then placed in the risk ratio calculations and the risk for a higher probability of elevated heart rate due to exposure to noise greater than 50 dB L_{Aeq} was determined. For these calculations, many different thresholds were used to determine if one threshold triggered more statistically significant risk ratios.

Table 20 summarizes the risk ratio method for statistically significant ($p<0.05$) results. Oxygen saturation in this table gives the risk of a decrease in oxygen saturation where all others provide the risk of an increase of physiological activity. At the 50 dB L_{Aeq} threshold, there are statistically significant risk ratios for all the physiological parameters. For example, there is a 22% increased risk of elevated heart rate as L_{Aeq} surpasses 50 dB. This table shows some of the statistically significant results at these particular thresholds with the 95% confidence intervals below in the parenthesis. The 50 dB L_{Aeq} threshold seems to be a turning point for physiological function, as other thresholds attempted in this analysis did not provide as many significant results or as strong of results. However, additional analyses should be run with larger, more controlled patient populations to determine the actual risks associated with various noise thresholds. Further, some of the confidence intervals were relatively wide, indicating more uncertainty about the effect. Regardless, the statistically significant risk ratios demonstrated in this study suggest that in order to prevent the risk of higher physiological response to occur, that average hospital noise should definitely be less than 50 dB L_{Aeq}.

Similar risk ratio analyses are performed for the psychoacoustic metrics. The results are seen in Table 21. The thresholds selected were the measured averages of each psychoacoustic metric (shown in Table 11-Table 15 and repeated in Table 21). Oxygen saturation has a negative risk, which means that there is risk in oxygen saturation decreasing. This is consistent with all the other analyses presented here—oxygen saturation decreases with a rise in sound level. Heart rate, respiratory rate, and blood pressure metrics also show generally consistent directions that there exists an increased risk of a higher probability of elevated physiological response when the psychoacoustic averages are exceeded. The results also show that changes in roughness, in general, create the highest risk, thus possibly implying that roughness is the most sensitive metric. This reinforces the results from the psychoacoustic correlations, where roughness was the only metric to be significantly correlated to all the physiological metrics. However, some of the roughness confidence intervals are relatively wide, pointing to limited knowledge of the effect and the need for future research. Overall, psychoacoustic metrics have more frequent significant risks; concluding that physiological response is possibly linked more strongly to psychoacoustic metrics than sound level metrics.

As with the correlations above, risk ratio was evaluated for the data set with the alarm data removed from the set. This is to address the question of whether the physiological measurement triggered the alarm, or if the alarm excited a physiological response. Table 22 shows the risk ratio for sound level metrics and physiological measurements with this alarm data removed. The 50 dB L_{Aeq} threshold again holds for a cut-off value for statistically significant risks. Additionally, 105 dB L_{Cpk} is a similar threshold for significant risk for both heart rate and oxygen saturation. This is generally consistent in nature to the risk ratios that include the alarms (Table 20).

Similarly, the same trends hold for comparing the risk ratios of psychoacoustic metrics with and without alarms. These risk ratios, without alarms, for psychoacoustic metrics are presented in Table 23. As before, the roughness metric is consistently showing clear risks for every physiological metric. Once again, roughness has regularly shown to be the metric that relates to physiological changes. The same general trends hold for both alarm and non-alarm results, which show that even without alarms, these thresholds of noise or psychoacoustic metric cause increased risk for physiological change.

Table 20. Risk Ratio results relating physiological measurements with sound level meter metrics

	L_{Aeq}	L_{Amin}	L_{Amax}	L_{Amax}	L_{Cpk}	L_{Cpk}
Threshold	50 dB	45 dB	50 dB	60 dB	90 dB	105 dB
Heart Rate (beats per minute)	22% (6%, 40%)	49% (27%, 75%)				135% (126%, 175%
Oxygen Saturation (S_{O2})		-45% (-29%,-57%)	-27% (-15%,-37%)			98% (87%, 109%)
Resp. Rate (breaths per min)	47% (31%, 65%)	37% (17%, 60%)	57% (35%, 82%)			
Systolic BP (mmHg)	63% (45%, 82%)	79% (61%, 98%)		36% (20%, 55%)	26% (7%, 48%)	
Diastolic BP (mmHg)	44% (30%, 59%)	25% (11%, 39%)		27% (13%, 42%)	29% (5%, 58%)	
Median BP (mmHg)	37% (23%, 53%)	37% (22%, 53%)		17% (3%, 32%)	29% (2%, 62%)	22%

Table 21. Risk Ratio results relating physiological measurements to psychoacoustic metrics

	SIL	Loudness	Sharpness	Fluctuation Strength	Roughness
Threshold	41	6	2	0.03	0.94
Heart Rate (beats per minute)	50% (35%, 65%)	48% (33%, 63%)	18% (5%, 32%)	19% (6%, 34%)	-14% (-3%, -24%)
Oxygen Saturation (S_{O2})	-14% (-6%, -22%)	-12% (-3%. -20%)	-13% (-4%, 21%)	-17% (-9%, -25%)	-30% (-22%, -38%)
Respiratory Rate (breaths per minute)			28% (11%, 47%)		36% (20%, 54%)
Systolic BP (mmHg)	39% (23%, 57%)	32% (17%, 50%)	74% (58%, 93%)	31% (16%, 49%)	63% (47%, 81)
Diastolic BP (mmHg)	45% (32%, 59%)	45% (32%, 59%)	15% (3%, 29%)	14% (2%, 28%)	90% (75%, 106%)
Median BP (mmHg)	30% (16%, 45%)	25% (12%, 41%)	45% (30%, 61%)	20% (6%, 36%)	57% (43%, 73%)

Table 22. Risk Ratio results relating physiological measurements with sound level meter metrics without alarms

	L_{Aeq}	L_{Amin}	L_{Amax}	L_{Amax}	L_{Cpk}	L_{Cpk}
Threshold	50 dB	45 dB	50 dB	60 dB	90 dB	105 dB
Heart Rate (beats per minute)		-44% (-16%, -62%)	-27% (-12%, -40%)			220% (206%, 234%)
Oxygen Saturation (S_{O2})		-52% (-34%,-65%)	-34% (-20%, -46%)			
Resp. Rate (breaths per min)	39% (16%, 67%)	-53% (-26%, 69%)	55% (33%, 81%)			258% (243%, 273%)
Systolic BP (mmHg)	40% (20%, 64%)	84% (58%, 114%)		19% (1%, 40%)		
Diastolic BP (mmHg)	31% (15%, 50%)	29% (10%, 51%)		25% (10%, 43%)		
Median BP (mmHg)	26% (8%, 47%)	55% (31%, 82%)				

Table 23. Risk Ratio results relating physiological measurements to psychoacoustic metrics with alarms removed

	SIL	Loudness	Sharpness	Fluctuation Strength	Roughness
Threshold	41	6	2	0.03	0.94
Heart Rate (beats per minute)	63% (39%, 91%)	85% (61%,114%)	33% (15%, 54%)	41% (17%, 70%)	54% (34%, 77%)
Oxygen Saturation (S_{O2})			-18% (-3%, -30%)		-56% (-48%, -64%)
Respiratory Rate (breaths per minute)	42% (20%, 69%)	32% (10%, 58%)	90% (64%, 110%)	70% (44%, 102%)	-27% (-13%, -39%)
Systolic BP (mmHg)			69% (48%, 93%)		25% (8%, 45%)
Diastolic BP (mmHg)	41% (14%, 45%)	32% (17%, 49%)			45% (30%, 63%)
Median BP (mmHg)			28% (12%, 47%)		19% (5%, 35%)

3.4.6 Alarms

Six different alarms were analyzed from the digital audio recordings of the Sweden study. The six different alarms were the taky alarm, hopade ves, HF 48<50, dsat 78<80, and kammar taky. The English versions of these alarms are tachycardia alarm (Tachy), couplet ventricular contractions alarm (VC), heart rate alarm triggered at 50 bpm (HR 48<50), oxygen desaturation alarm triggered when oxygen saturation dropped below 80% (dsat 78<80), and the chamber tachycardia alarm (CTachy).

With the digital audio recordings, the alarms were isolated and the L_{Aeq} for each alarm was calculated in ArtemiS. Furthermore, these L_{Aeq} averages were compared to the average sound level for each patient whose alarm was going off. This is shown below in Table 24.

Table 24. Table of Average Alarm L_{Aeq}

Alarm	**Alarm L_{Aeq} (dB)**	**Patient Number**	**Room L_{Aeq} (dB)**
Tachy	55.4	5	55.6
VC	55.8	6	51.6
HR 48<50	61.2	20	53.9
Dsat 78<80	50.6	12	53.1
Dsat 48<80	60.8	13	49.5
CTachy	44.6	15	51.1

The average L_{Aeq} of the room is shown for a representative patient who had the alarm sounding. The room average was calculated by taking the hour that contained the alarm and averaging that hour's L_{Aeq}. The reason for analyzing this is to compare the alarm to the baseline value of that hour's sound level. Since the alarm could be at night comparing it to the L_{Aeq} for the entire day rather than an average L_{Aeq} at night does not make sense because the baseline to compare it to would not make any sense and no conclusions could be drawn from that. The reason for comparing the alarm to this particular hour's sound level average is so that a difference can be found. Using this difference and the previously discussed statistical results, a physiological change in a patient is possible due to the alarm noise. It was conjectured that the average L_{Aeq} values for the alarms would be higher than the average L_{Aeq} for the surrounding hour for each patient. However, this is only true for half of the alarms, since L_{Aeq} itself is time and energy sensitive. At any given time, the instantaneous sound level may be different than the hour's equivalent sound level. Alarms may not have much sound power, but they are still audible.

The nontraditional metrics, such as psychoacoustic values, were also calculated for these alarms. The psychoacoustic metrics calculated for each alarm were; Articulation Index, Fluctuation Strength, Loudness, Roughness, Sharpness, Spectral Fluctuation Strength, Spectral Loudness Spectral Roughness, Speech Intelligibility Index, Speech Intelligibility Level and Tonality. The average psychoacoustic values for each alarm are given in the Table 25.

There are multiple potential applications for calculating all of the psychoacoustic values in Table 25. The first is so that they can be compared to the average psychoacoustic measurements that have been calculated for these patients previously. When doing this comparison, a difference can be found and inserted into a previously found statistically significant equation (i.e., linear, compound, or logistical) to calculate potential change in physiological response. The reason for determining the change in physiological measurements is to see if the alarms themselves can cause stress on the human body. One concern of this study was the circular question, “Did the alarm go off and thus cause a physiological change, or was there a change due to noise in the room and then the alarm went off?” This type of analysis can help predict what type of physiological response to expect due to different types of alarms.

Another application for these metrics is to characterize the soundscape of the alarms. For example, the loudness for the majority of the alarms was from five to ten sones, which is roughly equivalent to automobile noise, and louder than a person talking. Figure 17, Figure 18 and Figure 19 are representative samples of how the psychoacoustic metrics change through time as the alarm is sounding. The spectral loudness in Figure 19 represents a spectrogram of loudness over time. This provides spectral information across time for loudness.

Table 25. Average Alarm Psychoacoustic Values

Alarm	**Tachy**	**VC**	**HR 48<50**	**desat 78<80**	**TachyC**
Subject #	5	6	10	12	15
AI	90.2%	86.7%	81.6%	94.9%	98.8%
Fluctuation Strength vs. Time	0.036 vacil	0.046 vacil	0.051 vacil	0.026 vacil	0.007 vacil
Loudness vs. Time	6.1 sones	7.7 sones	9.5 sones	5.7 sones	4.5 sones
Roughness vs. Time	1.1 asper	1.3 asper	1.1 asper	0.8 asper	0.8 asper
Sharpness vs. Time	2.5 acum	2.0 acum	2.9 acum	1.8 acum	1.7 acum
Spec. fluctuation Strength	0.039 vacil	0.048 vacil	0.093 vacil	0.044 vacil	---
Spec. Loudness	8.8 sones	10.0 sones	13.1 sones	7.0 sones	4.9 sones
Spec. Roughness	1.1 asper	1.3 asper	1.2 asper	0.9 asper	0.9 asper
SII vs. Time	0.75	.69	.65	.82	.92
SIL-4	45.6 dB	45.5 dB	44.6 dB	41.3 dB	36.4 dB
Tonality vs. Time	0.23 tu	0.21 tu	0.31 tu	0.33 tu	0.24 tu

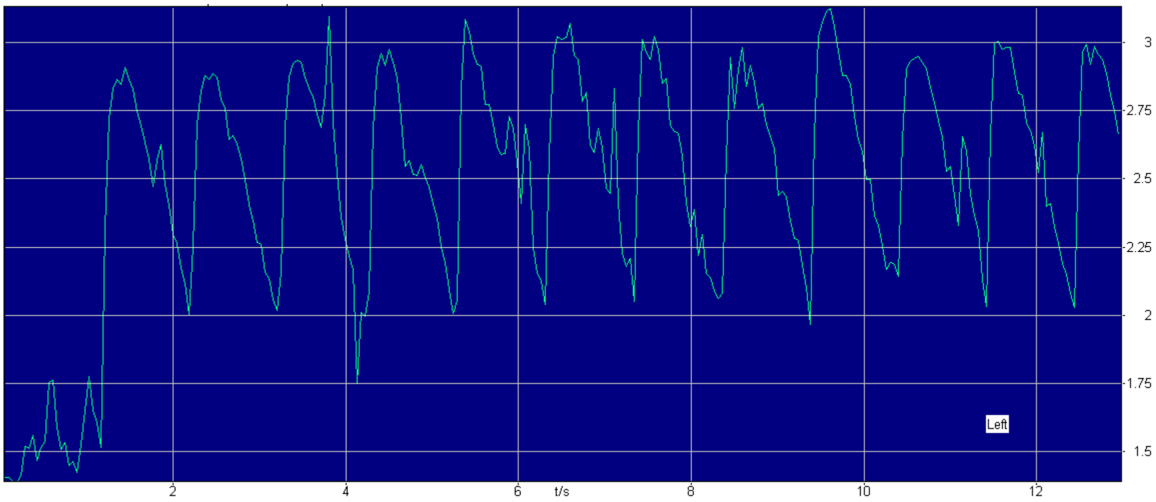

Figure 17. Desat78<80 Sharpness vs. Time Graph.

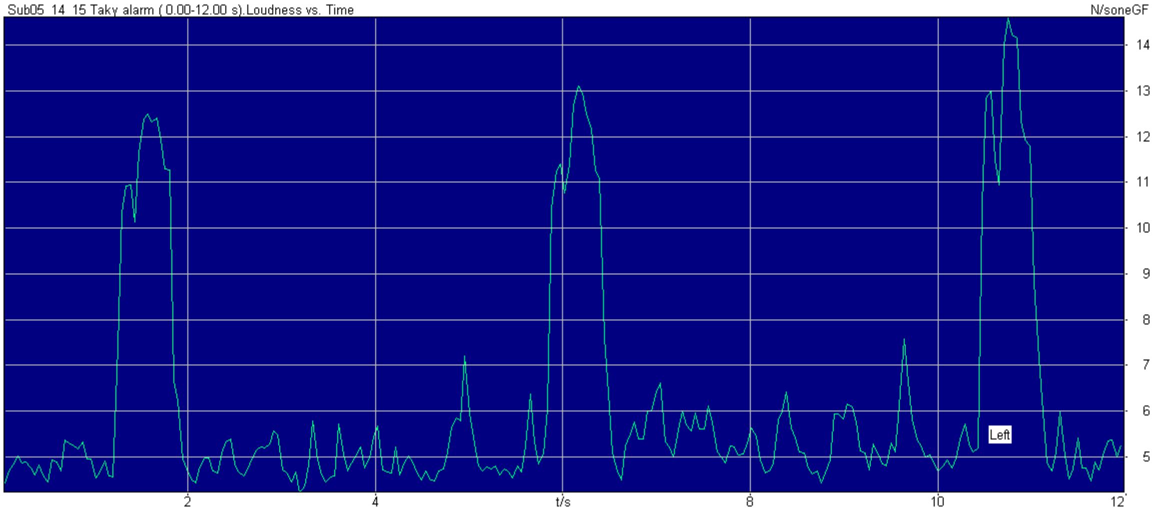

Figure 18. Tachy Alarm Loudness vs. Time Graph

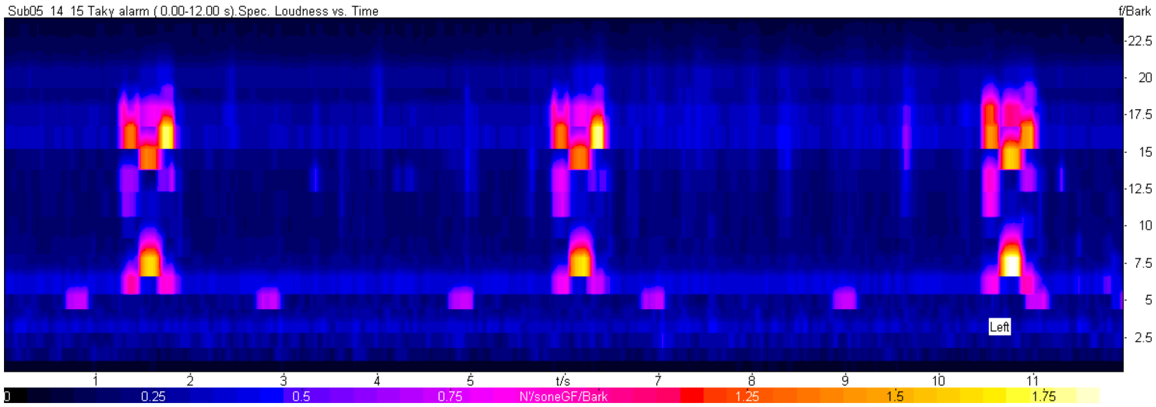

Figure 19. Tachy alarm and spectral loudness

3.4.7 Speech Intelligibility

In order to study speech intelligibility, the digital audio files were analyzed. Occurrence rate, as described above, is used in this application to understand the temporal patterns of speech intelligibility. With this method, the amount of time the ward spends in poor intelligibility regions can be determined.

The Sweden hospital ICU recordings show high overall speech intelligibility in all of its rooms as seen in Figure 20. Approximately 75% of the time, SII is greater than 0.75 (“good” region) and speech intelligibility is above 0.4 (“marginal” region) nearly 100% of the time. Based on the traditional qualitative labels, the majority of the time, SII is in the “good” region. For only less than 3% of the time, SII is below 0.4, or “poor”. After a simple aural inspection of the files, the audio recordings seem generally quiet, with primarily impulsive alarm noise and other short sounds occurring intermittently. These short impulsive alarms and other short noise sources likely contribute to the 3% of time that SII is less than 0.4.

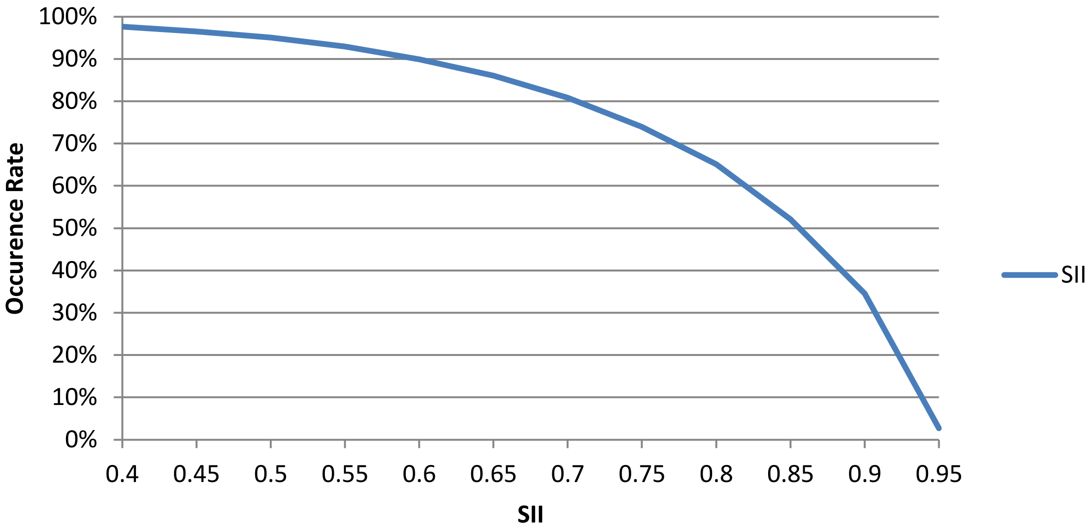

Figure 20. Occurence rate for speech intelligibility index in all rooms

3.5 Conclusions and Interpretation

One of the hypotheses of this research is that increasing sound levels may potentially elicit heightened physiological responses. In order to test this hypothesis, an acoustic characterization of the ICU soundscape was necessary. This was accomplished through sound level meter and digital audio recording measurements. Results reveal that the average level was approximately 52 dB L_{Aeq}. This is much higher than the WHO recommendations of unoccupied rooms [2]. As a point of comparison, the unoccupied level was 43 dB L_{Aeq} which also exceeds WHO recommendations. When comparing only sound levels during nurse work shifts, only the overnight work shift (from 9pm-7am) had unoccupied levels that did not surpass the 35 dB L_{Aeq} WHO nighttime recommendations. The average sound level results for the occupied rooms show that the nighttime levels are the quietest times in the ICU. This is consistent with the typical witnessed activity that can occur in an ICU. During the day, there are generally more doctor and nurse rounds, more visitors, more patient care activities, and generally more movement of equipment and people in the halls.

Unoccupied room measurements show the baseline noise of the room. The noise sources present in an unoccupied room are relatively few. The few sources may include the building HVAC noise and any noise being transmitted through the door, walls, and window—such as staff conversation, alarms in the halls or neighboring rooms, telephones, or traffic noise. When comparing the spectrum of occupied and occupied rooms, the differences are solely due to the occupied in-room sources—patient noise, alarm noise, staff and visitor conversation, medical equipment noise, and other noise sources such as televisions. In the 250 Hz octave band, there is a difference of approximately 10 dB and in the 4000 Hz octave band, the difference is nearly 15 dB greater. It is seen that these occupied noise sources contribute greatly to the baseline noise of the room.

The occurrence rate graphs reiterate the notion that levels are quieter overnight. The two daytime shifts consistently show higher rates of occurrence of higher average sound levels, maximum levels, and peak levels. This is particularly noticeable in the maximum value analysis where the daytime levels show a convex shaped S-curve that emphasize higher values, whereas the overnight levels show a concave shaped S-curve that show smaller values. Of particular note, the overall L_{Aeq} of the unoccupied room shows quiet levels; however, the peak levels are still present in this unoccupied room. The unoccupied room noise sources are generally building HVAC noise, which are not peaky. This probably can be interpreted that the more impulsive noise sources from the hall, nurse stations, and potentially other occupied rooms, are leaking through the walls, windows and doors. Noise isolation concerns need to be addressed in future research.

One limitation of this study is that 1-minute increments were used for the sound level meter metrics and the physiological measurements. This sampling rate of measurement is not very frequent, and thus, short or instantaneous changes in blood pressure or heart rate will be missed. Additionally, impulsive sound sources can be missed when using 1-minute logging on the sound level meter. Using shorter time increments may be able to show more detail about physiological responses. Additionally, with shorter increments, analysis can be done to see if noise and acoustic events lead physiological events/changes. This is a way causation can be shown.

The non-traditional methods that were utilized applied key psychoacoustic metrics used in other fields of acoustics to hospitals. These acoustic results provide a baseline set of psychoacoustic metrics to acoustically characterize an ICU—no literature reviewed above considers most of these metrics, such as loudness, sharpness, fluctuation strength, and roughness. Basic averages were calculated for the measurements. It is shown that loudness is approximately 6 sones, which is louder than a typical television. Sharpness was 2 acums, which is considered to be less sharp than a flute or recorder. SIL was approximately 42 dB, which is below the 57 dB threshold for normal conversation. Fluctuation strength was 0.03 vacils and roughness was 0.94 aspers.

The statistical analyses provide clearer indications that noise and physiology are linked. All of the methods, correlations, regression, curve estimation and risk ratio statistical results show consistently that some relationship exists between noise and patient physiology. In general, blood pressure was the most consistent physiological measurement to have statistically significant results. Blood pressure was correlated with all of the sound level and psychoacoustic metrics tested. Additionally, linear regression showed that for 10 dB increase in L_{Aeq}, blood pressure rose by 12 mmHg systolic and 5 mmHg diastolic. For one jnd increase for the psychoacoustic metrics, the linear regression results showed that systolic blood pressure increased by 0.5 to 2.4 mmHg, and diastolic blood pressure increased by 0.25 to 1.1 mmHg. A jnd by definition is defined to be the just noticeable difference, or what is a barely perceptible difference. Most sonic activity in a room will cause more than a barely perceptible change in psychoacoustic metrics. This is shown in the alarm results. Future research should focus on these psychoacoustic changes that are greater than just one jnd.

The risk ratio analyses yielded that at 50 dB L_{Aeq}, systolic blood pressure had a 61% increased risk of elevation and diastolic blood pressure had a 52% increased risk of elevation. Similar results are found using the measured average psychoacoustic metrics as a threshold. Blood pressure appears in this data to provide clear results while the other physiological metrics are less consistent.

Furthermore, the alarm data suggests that alarm noise may have an undesirable effect on the acoustic soundscape and patient physiology. Alarms must be loud enough to be heard and yet alarms can cause a substantial background noise increase in a room. Additionally, the function of an alarm is to alert the staff when a physiological function has reached some threshold. However, the alarm sounding may be loud enough to potentially trigger other physiological responses, based on the linear regression and risk ratio results. In other words, a tachycardia alarm may sound and the noise of the alarm may cause a rise in blood pressure.

The use of the psychoacoustic metrics show a novel approach for charactering the hospital soundscape. The use of psychoacoustics can perhaps provide better links to patient outcomes because these metrics focus on how humans perceive noise. In particular, roughness is shown here to be consistently related to physiological response. It was the only metric that was statistically significant in relation to all the physiological metrics. It also showed the highest risks in the risk ratio methods when compared to other psychoacoustic metrics. Roughness is a metric that focuses on temporal amplitude changes. This implies that steady state noises may not affect physiology as much as those sources that are time-varying in nature. Future research can determine if particular noise sources have high roughness values and test the effect of these sources on physiological responses.

These analyses show that statistically significant relationships between sound and physiology do exist in this general ICU patient population. These results must be interpreted through the lens that the patient population tested in this study is heterogeneous. The design of the study focused on a general patient population to attempt to provide general results, but in doing so, this heterogeneous population is attained. Physiologic interpretation of these changes is difficult, in part because this is a heterogeneous patient population. Taken as a whole this data best suggests increased psychological distress as psychoacoustic or traditional sound level measures change, but this interpretation may not hold universally for all patient populations. Depending on the patient's underlying condition, these changes could be interpreted as being either positive or negative. Changes in heart rate, respiratory rate, and blood pressure of the magnitudes could potentially be considered significant and could potentially lead to changes in their management. For example, elevations in blood pressure might lead to decreasing doses of vassopressors and the addition of anti-hypertensive medications. Significant changes in respiratory rate can be interpreted in a variety of ways depending on the patient's condition – it could be interpreted negatively as worsening acidosis, pain, psychological distress, under-sedation or infection. Increases of respiratory rate could positively be interpreted as improving alertness or neurologic status.

However, given the concerns stated immediately above about placing clinical significance to the results stated in this chapter, some general claims can be made. This dissertation does not aim to make medical judgments; however, the physiological metrics chosen for this study have been proven to be critical clinical measures of health. Furthermore, when a doctor sees patient data, one of three actions usually occurs: 1) the status quo is kept; 2) judgments are made based on specific patient data and broad general rules of thumb do not apply; or 3) the patient is deemed to be in emergency "code blue" status. After consulting medical professionals about results presented in this chapter, it is believed that in most cases, their advice would be to make a specific judgment based on that particular patient's history and medical condition. Certainly, there would be situations, based on the individual patient, where small changes in physiology could create emergency situations, and there would also be situations in other patients where small changes in physiology would warrant no change in treatment.

This chapter uncovers significant relationships between patient physiological response and hospital noise levels. Acoustic characterization of the ICU was performed with traditional sound level metrics and nontraditional psychoacoustic metrics taken from digital audio recordings. Statistically significant results show relationships through correlations, linear regression, curve estimation and risk ratios. Both traditional and non-traditional metrics have statistically significant relationships with patient physiology and thus, acousticians and administrators should utilize these metrics when characterizing hospital noise and designing new hospitals.

CHAPTER 4 - METRICS AFFECTING STAFF OUTCOMES (JOHNS HOPKINS HOSPITAL STUDY)

4.1 Introduction

Acoustical metrics in the previous chapter focused on patient outcomes, but another major group of occupants in hospitals is the staff. Staff members work every day in these hospital wards and the effect of noise can create physiological problems in addition to entirely different sets of issues related to task performance. The papers reviewed in Chapters 1 focuses on average sound level, L_{Aeq}, but this research attempts to determine which other metrics may be more appropriate in understanding staff outcomes. The hypotheses, presented in Chapter 1, for how metrics affect staff outcomes are:

- Staff Outcomes (JHU) Hypotheses
    - Traditional sound level metrics and room acoustic metrics (DL_2 (a spatial sound decay metric), reverberation time, clarity, and speech intelligibility) improve with added absorption.
    - Nurse outcomes of perceived annoyance, stress symptoms, specific noise sources, etc. improve with added absorption.

This chapter of this dissertation studies hematological cancer wards in the Weinberg Building of the Johns Hopkins University Hospital in Baltimore Maryland. Four identical wards on the fifth floor were chosen. For this project, the wards went through series of acoustical changes. At each step, acoustic measurements were taken to quantify the changes and questionnaire surveys were also administered to measure staff response.

The aims of this project were: (a) the continuing development of a novel sound absorbing panel suitable for unique hospital requirements, (b) conduct detailed acoustic measurements of the sound environment including background noise, energy decay, and speech intelligibility, (c) to determine the staff's perception of the sound environment using questionnaires, and (d) statistically relate the objective (b) and subjective (c) parameters. The results of this study are used to evaluate the impact of acoustic absorption on subjective and objective parameters as well as to identify areas for future research.

4.1.1 Ward Background

This research was performed at Weinberg Building at the Johns Hopkins University Hospital in Baltimore, MD, USA. The wards selected were four hematological cancer units that housed approximately 20 patients each. Each of the wards had the same general types of patients, staff activities, and architectural floor plan. The layout of the wards is a rectangular racetrack design with a primary support services core in the middle of the ward surrounded by a rectangular corridor and patient rooms at the periphery as seen in Figure 21 and Figure 22. The support core contained two central nurse stations in opposite corners. Additionally, four small satellite nurse work areas were located along the corridors.

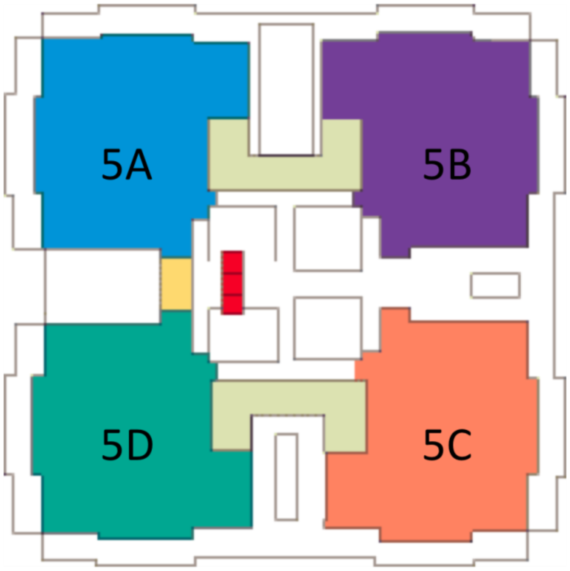

Figure 1. Floor plan for Weinberg fifth floor.

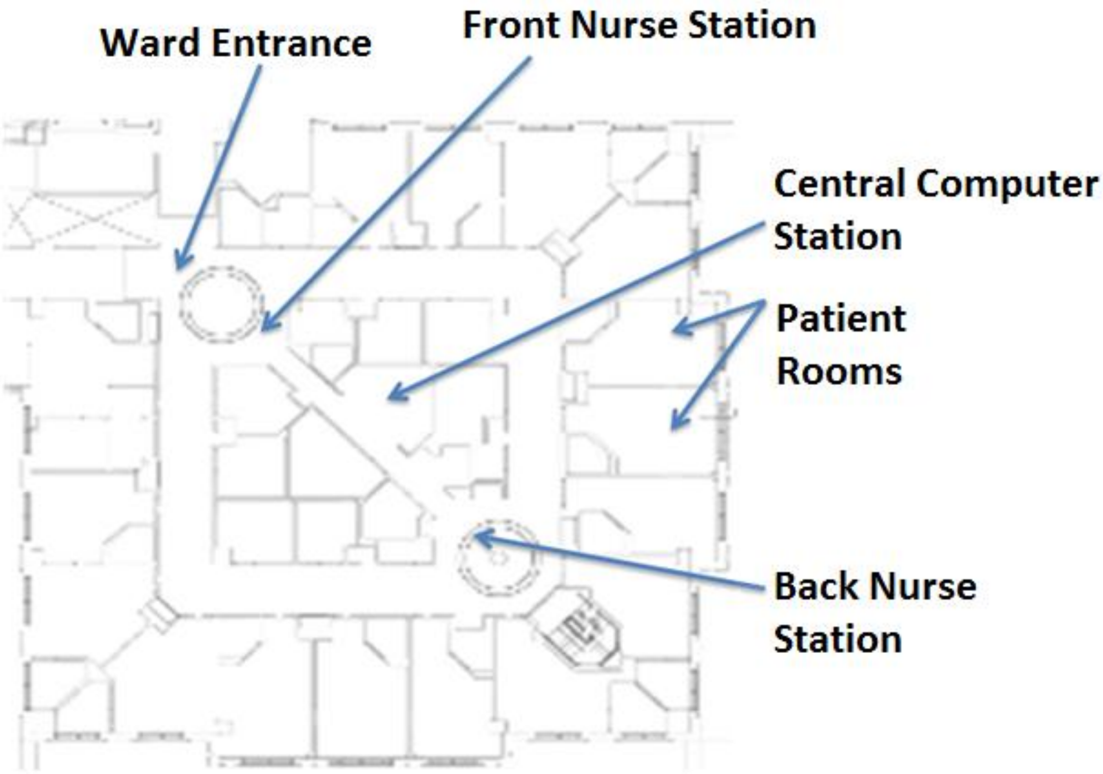

Figure 22. Detailed Floor plan of Weinberg 5C.

These wards house immuno-suppressed patients and require surfaces that cannot harbor bacteria—thus traditional acoustical ceiling tiles or carpet cannot be used in these wards. Before any acoustical modification occurred for this study, all the surfaces were essentially acoustically “hard”, or predominantly reflective. These surfaces included linoleum tile floors and gypsum board walls and ceilings. The surfaces were likely selected due to ease of cleanability and the anti-bacterial and anti-porous properties of the surfaces. At both the central computer station, there are computers and telephones present. Along the halls, there are paging systems and telephones, as well. In the corners of the halls, there are 45-degree walls that may contribute to strong specular sound reflections around corners. Additionally, there is a circular dome-like architectural design feature directly over each of the two nurse stations, which potentially led to sound focusing effects.

4.1.2 Panels as developed by DuPont and JHU

Increasing hospital noise levels and strict requirements on building materials have resulted in hospitals having noise levels without adequate solutions for the problem. One of the easiest solutions to control noise, especially cart noise, is to carpet the ward (commercial grade carpet adds limited sound absorption but greatly reduces wheel noise). Because of the general inability to adequately clean the carpet, tile floors were present in the wards; thus, noise control solutions could only be applied to the walls or ceilings.

A few companies (Armstrong, USG, Ecophon and others) offer cleanable, or hygienic, acoustic panels that are, generally, constructed from mineral fiber-board sealed with vinyl facing; however, they may provide less sound absorption than is desired for these types of spaces. Several solutions that are commercially available, such as a perforated vinyl film or latex coated fiberglass board, offer options that potentially may not adhere to both the hospital's cleanability requirements and the ideal absorption desired in these spaces. The sound absorbing surface area is limited, thus the efficiency of each panel must be maximized.

4.1.3 Previous Xorel® Noise Control Solution

One way to construct a better sound absorbing panel is to use a standard material with superior sound absorption properties and modify it so that it will be acceptable within hospital material guidelines. The MacLeod et al. [154] solution was an example of this type of acoustic panel. Two-inch thick fiberglass with a density of 3.0 pounds per cubic foot (pcf) was used as the sound absorbing material and it was covered with Xorel® fabric. Xorel® was chosen because it had already been approved by the hospital for use in the hematological wards. Figure 23 shows the absorption coefficients for the uncovered fiberglass batts (Johns Manville, "Insul-Shield Data Sheet," Building Insulation Division, JM.com, 2006) and of the fiberglass wrapped in Xorel® measured at the Johns Hopkins University's Acoustics Lab. Figure 23 illustrates clearly that the Xorel® wrapping effectively reduces the sound absorption, mainly in the higher frequency region above 1 kHz. When these panels were implemented in Weinberg 5C by MacLeod et al., the subjective response was generally positive while the quantitative acoustic background noise data showed approximately a 6 dB reduction in background noise and a reverberation time reduction of around 50% [154]. To summarize, the MacLeod et al. study reported improvements in background noise level, reverberation time, and general staff perception when absorption was added via the Xorel® panels [154]. This dissertation study will present a much more detailed assessment of the impact of new "optimized" panels, including acoustic measurements of not only background noise level and reverberation time, but also sound propagation (as measured by DL_2) and speech intelligibility. Additionally, the current study includes a more detailed analysis of staff response, including an expanded questionnaire and statistical analysis between objective and subjective measures.

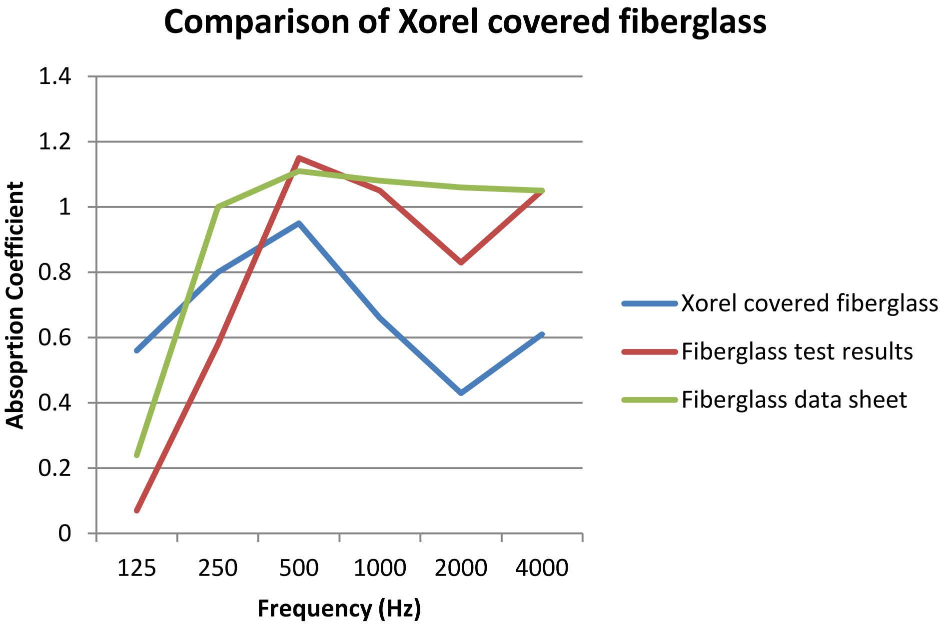

Figure 23. Absorption Coefficient for Xorel Solution

The Johns Hopkins University collaborators were responsible for the further development of these sound panels [155]. The impetus for a better noise control solution, beyond the preliminary solution achieved in MacLeod et al. [154], came from three major drawbacks of Xorel®. First, Xorel® is not a cost effective solution. The cost of approximately over $2 USD per square foot of Xorel® makes this preliminary solution financially challenging for hospitals on a large scale. Second, Xorel®'s woven structure has an irregular surface that, when glued with wallpaper paste, has problems adhering to itself and to the pressure sensitive adhesive on the Velcro strips used to attach the panels to the walls and ceiling. The outer fabric must securely seal the fiberglass inside the panel or the panel will not meet the requirements of a hematological ward. For Velcro to work as a ceiling mount the Velcro must adhere tightly to the panel surface, the ceiling, and the Velcro itself. The mount on the panels failed due to: 1) the Velcro adhesive inability to adhere adequately to the Xorel® surface and 2) the shearing of the Velcro under the strain of the panel's weight over time. As mentioned in MacLeod's study, the Velcro mounting was the preferred mounting method because drilling holes in the units is not possible [154]. Finally, to be cleanable and water-resistant, Xorel®'s woven structure is thick and heavy weight; therefore, it was difficult to achieve a clean presentable face on the panel. The result was sagging panels, air pockets, rounded corners, and a baggy, unprofessional look. Aesthetic improvement was a major consideration of the staff and research team when implementing the next stage of panels described in this dissertation.

4.1.4 Optimized Tyvek Noise Control Solutions

As a cost effective substitute for Xorel®, DuPont™ Tyvek® was used to wrap the fiberglass panels. Tyvek® is a thin, light, and durable flash spun nonwoven material made of high-density polyethylene, which is widely used in construction, envelopes, medical packaging, clean room apparel, and more. Due to the unique porous structure, it has high resistance to water penetration and small particles (including bacteria) and it is still acoustically translucent. Polyethylene is well known for natural resistance to bacterial and fungal growth without adding antimicrobials. Tyvek® is a certified class A material per ASTM E84 flammability standard [156].

The final, optimized panels tested in this dissertation were the result of two iterations of design, Tyvek® I and Tyvek® II. Tyvek® I, installed in Weinberg 5B, consisted of 2-inch thick, 3 pcf density fiberglass panels (same fiberglass material as the MacLeod's panels) wrapped in Tyvek® with use of an adhesive to secure the material to the front, back, and sides of the fiberglass. The sides of the fiberglass panel were additionally hardened with a special glue to create a visually pleasing look and the panels were mounted using Velcro tape. For Tyvek® II, in Weinberg 5A, no adhesive was used on the panel face and VOC-free (volatile organic compound) mounting adhesive was used for panel mounting. Figure 24 shows the sound absorption coefficients measured in a reverberant room per ASTM C423 mounting A for a) the fiberglass panel without facing, b) the panel with Tyvek® I, and c) with Tyvek® II. It is clear that the Tyvek® decreases the sound absorption but an important result of these tests is the acoustical difference between Tyvek® I and Tyvek® II. They both wrap identical fiberglass batts with the same material with the only difference being the amount of glue used to secure the Tyvek® to panel. With less glue (Tyvek® II), the absorption increases. All absorption tests reported in this dissertation were made in the same reverberation room at the Johns Hopkins University; thus, there should be no inter-lab variability between results.

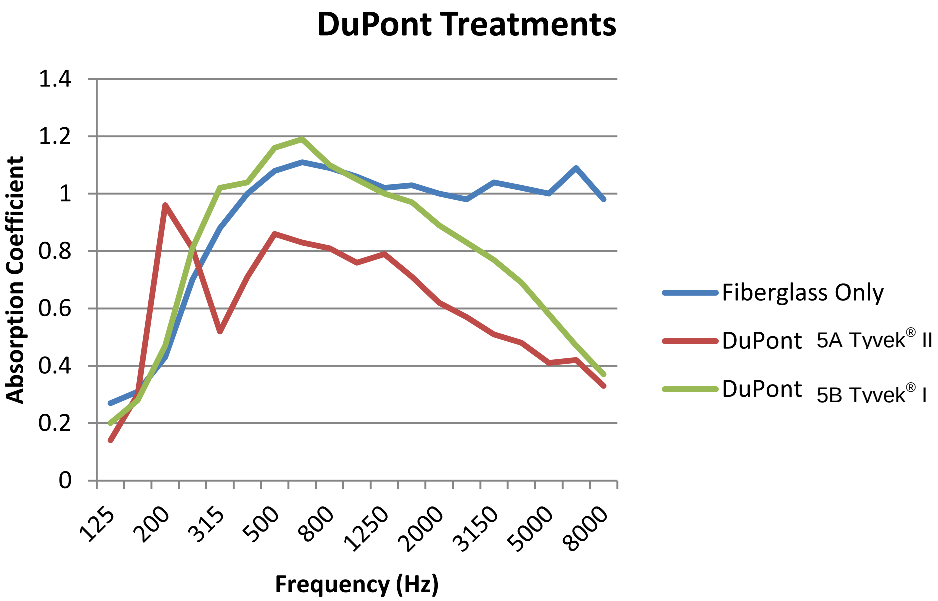

Figure 24. Absorption Coefficients for Fiberglass only, Tyvek® I, and Tyvek® II solutions

4.2 Methodology

4.2.1 Installation of Tyvek® Panels in Weinberg

The project was split into two phases as the development of the Tyvek® panels progressed. In the first phase, four different acoustic treatments were installed in the four Weinberg wards and basic acoustic measurements were conducted. The second phase focused on quantifying detailed aspects of the acoustic environment and subjective response for an untreated ward and a ward treated with the final, optimized Tyvek® II panels. The third and final phase was similar to the second, but was conducted in the ORs.

For the first phase of this study, the acoustic treatments (i.e., panel size and layout) slightly differed in each ward due to the differences in available space and mirror-like symmetry, but care was taken to ensure that the same surface area of approximately 700 square feet was covered in each ward. Ward 5A contained the latest implementation of DuPont™ Tyvek® Panels (Tyvek® II) having NRC (noise reduction coefficient) 1; Ward 5B contained the first implementation of DuPont™ Tyvek® (Tyvek® I) panels having NRC 0.75; Ward 5C contained the original MacLeod (Xorel®) solution; and 5D was untreated at the time of measurement in November 2009.

The second phase of this project only focused on the acoustically treated 5A ward and the untreated 5D ward. The sole acoustic difference between 5A and 5D was the acoustical treatment installed. Ward 5A was treated with DuPont™ Tyvek® Panels (Tyvek® II) over approximately 700 square feet. The panels were installed on the upper walls and ceilings of the corridors and in the domes above the front and back nurse stations. Contrarily, 5D was left in an untreated fashion, with no acoustical absorption added.

4.2.2 Acoustic Methodology

Several types of detailed acoustical measurements were taken for this study at similar locations in each of the wards. Background noise level measurements were taken using a Larson Davis 824 sound level meter over two time scales: 24-hours and 30-minutes. One-minute averaging intervals, a range of 40 – 110 dB, and fast response time (0.125 sec; [131]) were used for all background noise measurements. In many previous studies, the response time was set to slow (1 sec; [131]), which may have resulted in decreased ability to capture the impulse sounds that can occur in a hospital environment [39]. A-weighted equivalent, maximum, minimum (L_{Aeq}, L_{Amax}, L_{Amin}) and C-weighted peak (L_{Cpk}) were recorded. One-third octave band unweighted frequency levels were also taken.

The 24-hour measurements were taken at the front and back nurse stations located closest to the entrance of the ward (labeled as the “front nurse station” in this dissertation). The microphone was mounted at standing ear height at approximately 60 inches. The 30-minute measurements were made: 1) in the hallway, 2) in the central computer station/staff work area, and 3) in the back/main nurse’s station furthest from the entrance (labeled as “back nurse station” in this paper). These locations are shown in Figure 25. These three locations were measured in all four wards, consisting of 12 total 30-minute measurements. Additionally, other spaces were selected for 30-minute measurements including a consultation room, a break room, an occupied patient room, and an unoccupied patient room. Note that there was no modified acoustical treatment in these other spaces. The length and locations of all measurements were dictated by access to the facility and research logistics.

Reverberation times (RT) were measured using two methods. For the initial measurements in the first phase and for the operating room measurements, a Brüel and Kjær Pulse system was used to make one-third octave band interrupted noise reverberation measurements in all four wards. A high-level white noise signal was activated for five seconds at which point it was abruptly stopped and the first twenty decibels of decay were measured; from this data, the reverberation time (T60) was extrapolated. In the second phase of measurements, the reverberation time was extracted from the room impulse response. The room impulse response measurement system consisted of a GSR omni-directional dodecahedral loudspeaker, EASERA software v1.1, and Larson Davis 824 sound level meter microphones. A maximum length sequence (MLS) excitation signal was used. This signal was preferred over the sine-sweep method because it was thought to be less intrusive to occupants. Several measurements were made per ward and then averaged together across locations for an overall reverberation time. Microphones were placed on stands at a height of approximately 60 inches and placed near the middle of the corridor. Four locations near the front nurse's station were selected. Sixty decibels of reverberation decay is difficult to measure in a noisy environment such as a hospital; thus, a 20 dB decay was extrapolated to determine the RT time.

Speech Intelligibility Index (SII) and Articulation Index (AI) were evaluated in order to assess the overall speech intelligibility in the two wards. Both metrics were calculated from the sound level meter noise data. Specifically, SII was calculated from the one-third octave band noise data and processed using the ANSI S3.5-1997 standard [20]. AI was calculated using values from ANSI S3.5-1969 R 1989 Standard [146].

DL_2 was measured along the corridor in 5A and 5D. The DL_2 measurement setup included the same GSR omni-directional dodecahedral loudspeaker and a Larson Davis 824 sound level meter set up on a tripod at a height of approximately 60 inches. The speaker was placed on the floor at one end of the hallway and white noise was emitted. Five-second A-weighted sound level measurements were taken at one-meter increments down the length of the hallway. The distances ranged from one-meter to 12 meters as seen in Figure 25. These 5-second measurements were made during quiet periods, where there were minimal additional transient noises in the wards. The standard recommends a minimum of 24 measurement points; however, the maximum length of the hallways was only ~12 meters. One additional requirement of microphone locations is that “the last measurement point on the path shall be located at a minimum distance of 1.5 m from any wall or large reflecting object.” In most hallways, this criterion cannot be met; a hallway would have to have a width greater than 3m. The standard also indicates that “if possible, measurements shall be carried out with all machines, ventilation system, high-pressure pipework leading through the room, etc. being inoperative except for the sound source used for the test [132].” In a hospital ward that operates 24-hours a day, this suggestion cannot be accommodated. The inability to meet with these criterions does not invalidate the measurement. In fact, as will be shown below, this measurement helps to not only quantify the waveguide phenomena noted in MacLeod’s study [154], but it may better characterize the acoustic soundscape of the actual, realistic hospital working environment.

Additionally, two binaural HEADs were used in what was termed as “dueling HEAD” measurements. These measurements were simultaneous and attempted to record the same audio events at two discrete locations. These digital audio files were made with 16 bit quantization and 44.1 kHz sampling rate. Locations for these dueling HEADs measurements were at the central computer stations, the nurse stations, and near the doctor’s rounds that occur sporadically throughout the day. These recordings allow direct comparison between different parts of the ward. Speech intelligibility comparisons can be ascertained from these measurements as well.

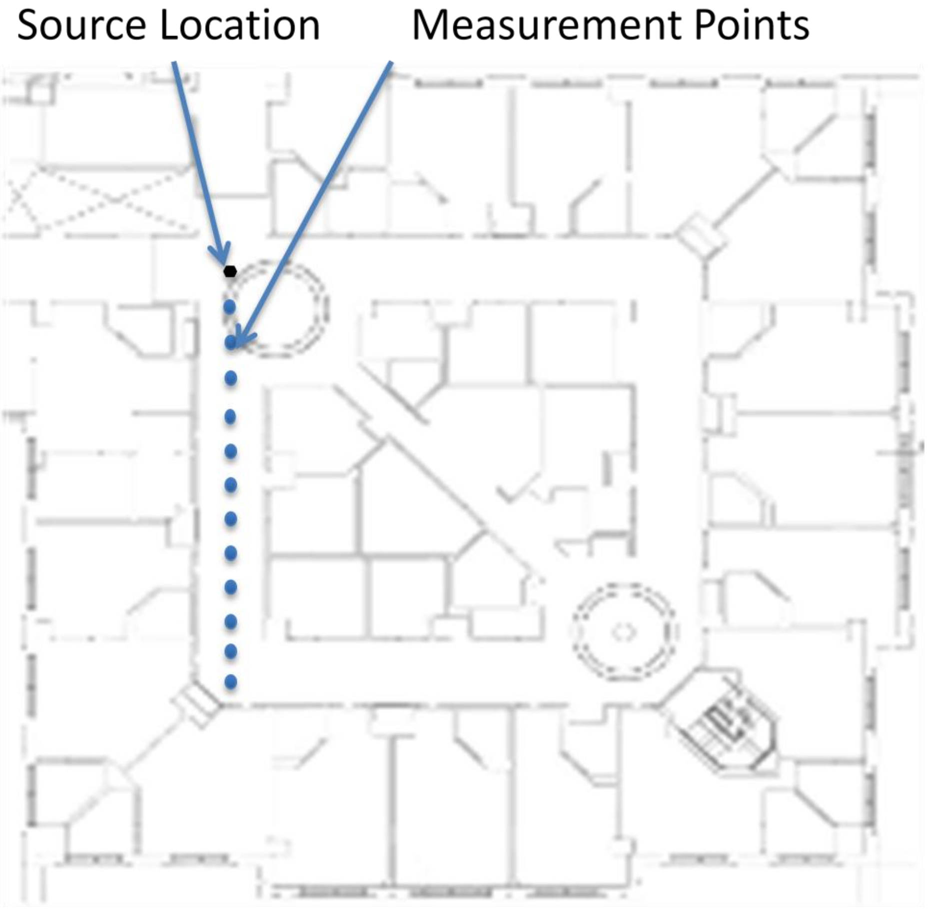

Figure 25. DL_2 Measurement Locations

4.2.3 Staff questionnaire

A twenty-question paper questionnaire was developed for the nurses to determine their perception of the sound environment. Registered nurses were selected for this study since they spent the most time on the wards and did not rotate wards.

The questions can be broken down into different categories. Demographic data was collected on job titles, gender, work shift/hour information, and work history. The second type of question asked about noise sources—if they heard particular noises, if the noise affected them, and if they experienced a particular type of reaction due to a particular noise. The last type of question targeted the subject's hearing—asking if they had hearing impairments or noise sensitivity. Of the twenty questions, 17 were closed-ended, and 3 were open-ended. In the closed-ended response section, a 5-point scale was used. For example, they were asked to what degree (from "Not at all" to "A great deal") noise contributed to some physiological symptom such as headache or tiredness. The questionnaire can be found in Appendix G.

The results from each ward were analyzed separately and then compared against each other to see how the difference in acoustical environment affected the staff's perception. Software used for the questionnaire analysis was SPSS v. 17 and Microsoft Excel.

4.2.4 Limitations in methodology

The Johns Hopkins Hospital is a 365-day a year, 24-hour a day facility where scheduling installation of panels or conducting surveys entirely revolves around the convenience of the hospital and the hospital staff. For example, to install the panels, no screws could be put in the walls without vacating the entire ward of all patients. Thus, sometimes the direct comparisons that were initially planned were impossible to conduct.

A treated versus untreated analysis was desired for this study. This had to be done in two different manners. In phase II, for the acoustic measurements, Ward 5A was treated with the DuPont™ Tyvek® Panels (Tyvek® II) panels. Contrarily, Ward 5D was left untreated for these acoustic measurements. However, it was not possible to collect staff survey in both 5A and 5D to correspond with the acoustic measurements; thus, survey data was collected in 5A before and after panel installation. This before/after survey collection still compares a treated and untreated scenario. This methodology is not ideal, but given the hospital requirements and circumstances, it was the best possible option to gather acoustic and survey data in both treated and untreated scenarios.

4.3 RESULTS AND DISCUSSION

4.3.1 Phase One: Development of "Optimized" Panels

Phase One of this study compares the performance between the various panel iterations, including the previously installed Xorel® panels and the current Tyvek® treatments. One way to quantify the performance of these panels is to analyze the changes in background noise level and reverberation times measured in the wards due to the different panels.

Reverberation time, RT, measurements results are shown in Figure 26. As can be seen, all acoustic treatments made significant improvement to the wards' acoustic environment by lowering the reverberation time by more than 0.6 seconds below 1000 Hz. Overall, the Xorel® solution delivered the best performance. Tyvek® II performs similarly to the Xorel® solution at low frequencies, but was less effective at mid and high frequencies. Tyvek® I fell generally short of both the Xorel® and Tyvek® Treatment II solutions.

The reasons for the difference in RT between Xorel® and other solutions are still somewhat unclear. Comparison of sound absorption coefficients of Xorel® panels measured in the Johns Hopkins University lab and Tyvek® panels measured in an independent laboratory suggest that Xorel® and Tyvek® Treatment II panels would perform similarly. The obvious difference between the two solutions is the use of glue to secure Tyvek® to the sides of the fiberglass panel in Tyvek® II, effectively negating the sound absorption of the panel edges. Therefore, the panel-face area was equal in all cases but the "active" area was actually different with the Xorel® solution having 29% (197 ft^2) more absorbing area in the ward. However, the glued edges achieved the staff-requested "professional" look.

Despite the better RT performance of the previous Xorel® solution, the Tyvek® II panels did prove to be an overall cost effective solution that was more aesthetically pleasing and therefore achieved the primary goals of the "optimized" panel redesign. This solution and other similar types of solutions can be used to mitigate large-scale noise problems in many areas of a hospital, especially when the area cannot be closed or shut down for full renovation and/or the construction of a drop ceiling is not an option.

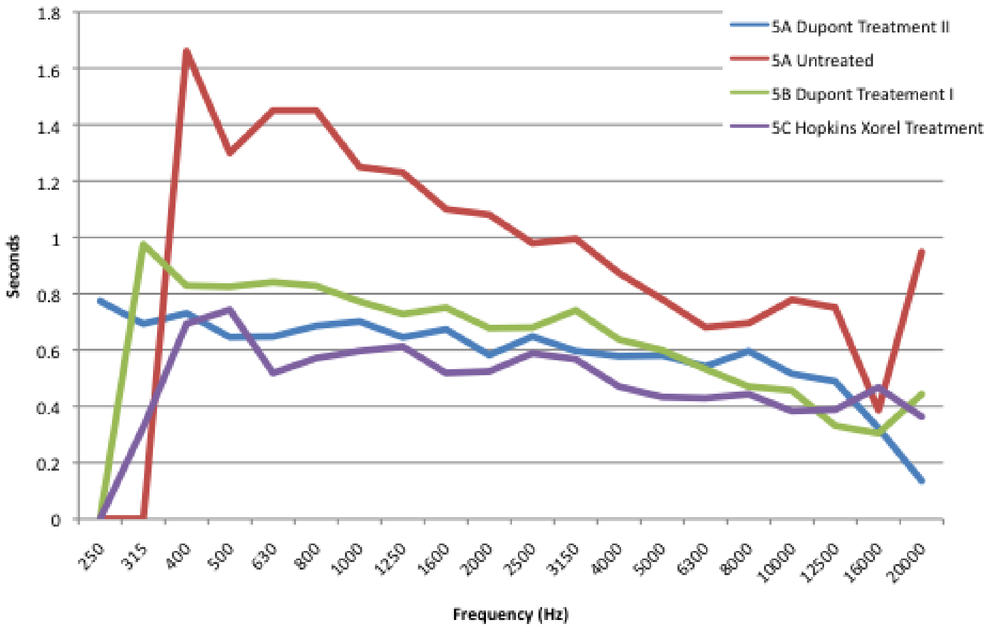

Figure 2. Comparison of Reverberation times for the Untreated, Xorel®, Tyvek® I, and Tyvek® II solutions.

Additionally, the present Tyvek® solution offers more absorption at low frequencies then typical cleanable drop ceiling panels. Future work may investigate the possibility of other materials that combine low cost, high sound absorption, and are also able to meet the hospitals requirements on cleanability and flammability.

Gluing the panels to the walls and ceiling can work as a semi-permanent retrofit mounting technique but absorption is less effective. The Johns Hopkins University team is currently exploring new easily removable mounting methods necessary for cleaning. Additionally, further research is being performed to look at the possibility of acoustically tuned mounts that can increase absorption at particular frequencies. By adjusting the distance of the panel from the ceiling or wall, it is possible to increase or decrease the absorption in certain frequency bands. These new mounting methods may be applicable to a variety of panels and do not use glue, thus, retaining the acoustical properties of the panels. Figure 27 shows a typical final mount for the Tyvek® II panels.

Figure 27. Installed Panels in Weinberg 5A

4.3.2 Phase Two: Acoustic results of treated and untreated wards

4.3.2.1 Background noise results

Phase two of this study made direct comparisons between the optimized Tyvek® II treated ward (5A) and an untreated ward (5D). Results from the background noise measurements taken in both 5A and 5D are presented in Table 26. As previously stated, ward 5A was treated with added absorption whereas 5D was untreated with primarily hard surfaces. Table 26 compares the L_{Aeq} at multiple locations in each ward. These results show elevated noise levels in both wards that exceed the WHO standards that state that L_{eq} in a patient room should not exceed 35dBA during the day, 30 dBA at night, and that L_{Amax} should not exceed 40 dBA at night. Moreover, direct comparisons can be made between the untreated ward and the treated ward. For example, in the treated 5A ward, a 4 dB reduction in L_{Aeq} and drop of 7 dB in L_{Amin} was measured at the front nurse station. The other locations in the treated 5A ward were also generally quieter than the untreated 5D locations, with roughly a 3 dB difference in L_{Aeq} in all of the locations.

Table 26. A-weighted equivalent, maximum, minimum (L_{Aeq}, L_{Amax}, L_{Amin}) and C-weighted peak (L_{Cpk}) sound pressure level measured at various locations in wards 5A and 5D.

Noise Measure (dB)				
	L_{Aeq}	L_{Amax}	L_{Cpk}	L_{Amin}
5A-Back Nurse Station	57	84	107	43
5A-Hallway	59	81	103	47
5A-Central Computer Station	60	85	104	44

5A-Front Nurse Station	60	103	117	60
5D-Back Nurse Station	62	80	98	61
5D-Hallway	62	82	106	54
5D-Central Computer Station	65	81	98	51
5D-Front Nurse Station	64	105	130	67

The difference in sound pressure level may be due to changes in sound power in the wards. To investigate this issue, sound power was calculated, given a known surface area, volume and a measured reverberation time. Based on the geometry of these identical wards, the surface area was ~650 m^2 and the volume was ~600 m^3. The distance the microphone from the source, r, is 5 meters. Additionally, the directivity coefficient, D, is assumed to be 1. The reverberation time results are shown in Table 27. Reverberation time results will be discussed in greater detail below. The average absorption coefficient, $\bar{\propto}$, can be found through Equation 11 and once the $\bar{\propto}$ value is found it is then substituted into Equation 12 to find the room constant, R. Subsequently, R can be substituted into the sound pressure level equation, Equation 13, along with the variables D, r, and L_p. The equation can be manipulated to solve for L_w shown in Equation 14. Octave band sound power level values are shown in Table 28.

Table 27. Reverberation Times for wards 5A (Treated) and 5D (Untreated)

Octave Band Center Frequency (Hz)	*250*	*500*	*1000*	*2000*
5A	0.59	0.59	0.58	0.56
5D	0.84	0.83	0.78	0.71

$$RT = \frac{.1611V}{S\,\overline{\propto}} \tag{11}$$

$$R = \frac{S\,\overline{\propto}}{1-\overline{\propto}} \tag{12}$$

$$L_p = L_w + 10\log(\frac{D}{4\pi r^2} + \frac{4}{R}) \tag{13}$$

$$L_w = L_p - 10\log(\frac{D}{4\pi r^2} + \frac{4}{R}) \tag{14}$$

The objective in calculating these sound power values is to verify that the changes in sound pressure was not entirely due to differences in sound power level. For example if the difference in L_p between 5D Central and 5A Central is the same as the difference in L_w between 5D Central and 5A Central, then the panels may not have any acoustic effect on the measurements. Contrarily, if the sound pressure changes, and yet sound power remains similar between measurements, then the acoustic panels will prove to be effective. In all average (L_{eq}) sound pressure level measurements, the untreated 5D showed louder values than the treated 5A. The amount of sound pressure increase in 5D is shown in Table 29. Similarly, Table 30 illustrates the sound power level differences between 5A and 5D, with the untreated 5D always exhibiting higher power levels as well.

As shown above, the differences in L_p and L_w are different. The sound power differences are always less than the sound pressure level differences. This result shows that the sound panels are effective; however, the change in sound pressure level cannot be entirely attributed to the absorption of the panels. All the measurements, even preliminary unreported results, show that the treated ward had lower sound pressure levels than the untreated wards. Other environmental factors may play roles in the decrease of sound pressure level. For example, the lowering of reverberation time may make it easier to communicate so people may not have to speak quite as loudly or repeat themselves as much. This behavioral change may contribute to the lowering of background noise levels. Additionally, if background noise level is lowered, pager systems, alarm noise, and other volume controlled sources may be reduced as well. These acoustic panels, ultimately, are making the sound power levels drop consistently. Thus, the panels have the direct acoustic function of reducing reverberation time; but, they also have an additional further reaching property of creating a quieter soundscape.

Table 28. Sound power levels for different locations within wards 5A (Treated) and 5D (Untreated)

Frequency	5ACentral	5AHall	5ANurse	5DCentral	5DHall	5DNurse	5AOverall	5DOverall
250	75	72	69	76	74	73	73	80
500	76	72	71	79	75	75	72	77
1000	75	71	70	75	72	73	70	74
2000	70	69	67	72	70	70	70	72

Table 29. Sound pressure level (L_{eq}) differences between 5A and 5D

Difference=L_{eq}(5D) – L_{eq}(5A)

Frequency	Central	Hall	Nurse	Overall
250	3.6	3.7	5.6	7.6
500	4.6	4.2	5.9	6.4
1000	3.2	3.2	5.1	5.6
2000	2.8	2.0	4.2	2.7

Table 30. Sound power level (L_w) differences between 5A and 5D

Difference=L_w(5D) – L_w(5A)

Frequency	Central	Hall	Nurse	Overall
250	1.9	2.0	3.9	5.9
500	3.0	2.5	4.2	4.8
1000	0.7	0.7	2.6	3.8
2000	1.7	0.8	3.1	1.6

4.3.2.2 Spectral results

Figure 28 reveals the spectrum for the L_{eq} measurements at the various locations. It shows that for all locations, untreated 5D has generally greater L_{eq} levels at frequencies below 4000 Hz, with the greatest differences generally occurring in the mid-range of 200-2000 Hz. The panels in treated 5A have the highest absorption coefficients in this frequency range; thus, the reduction in noise is most likely attributed to the addition of these panels.

4.3.2.3 Indoor Noise Criteria

Several different indoor noise criteria were calculated for the four cancer wards using the spectral results. Specifically, Noise Criteria (NC), Balanced Noise Criteria (NCB), Room Criteria (RC), and Room Criteria Mark II (RC Mark II) were evaluated. Overall results are shown in Table 31. In comparing similar locations between 5A and 5D, results show that the treated 5A was generally rated quieter, by approximately 4 rating points on average, with a range of 3-6 rating points difference. The spectral quality descriptors do not show much difference in NCB; however, with RC, several of the 5D locations are “Neutral” instead of “Hissy” indicating that there is relatively less high frequency energy in the “Neutral” cases than in the “Hissy” cases. Even though the threshold between “Hissy” and “Neutral” is 3 dB from the rating line by definition, since the overall rating score increases, the absolute threshold in terms of decibel also increases. The 3dB difference shifts downward with the decrease of RC rating. Thus, this may account for why the untreated 5D ward is considered “Neutral” while the treated 5A ward is “Hissy.” The panels are most effective in the mid-frequencies, thus causing the RC rating in the treated 5A to be lower than the untreated 5D. However, these panels are not as effective in the higher frequencies, thus making less of an impact. Looking at the spectral results in Figure 28, the high frequencies levels between the two wards are very similar—so when the overall RC rating is lowered, with the same high frequency energy, the treated 5A ward now appears to be “Hissy” even though it does not contain more high frequency energy. Regardless, in nearly all scenarios, the treated ward yielded a quieter noise metric than the untreated ward—thereby showing that the addition of these sound absorbing panels likely had a positive impact on the noise soundscape. However, the potential impact of the panel installation on spectral quality (e.g., switching from neutral to hissy after installing panels) should be investigated further.

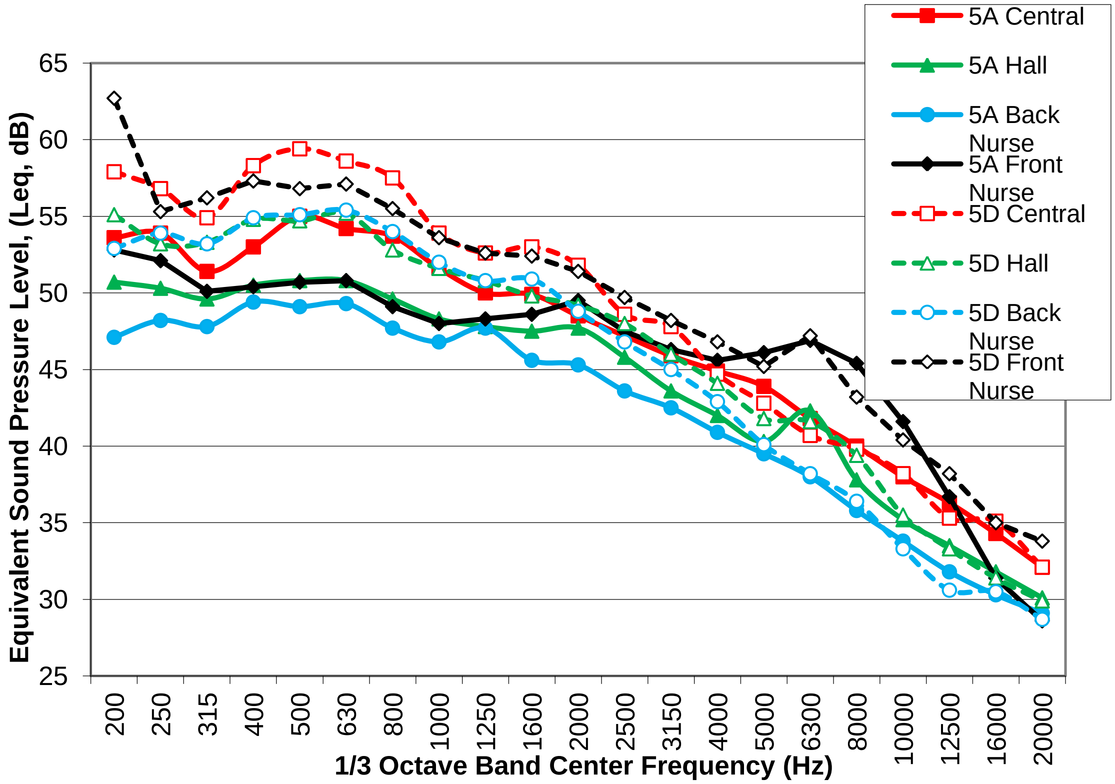

Figure 28. Results from unweighted (L_{eq}) sound pressure level measurements at various locations in wards 5A and 5D.

Table 31. Indoor noise criteria ratings calculated from noise measurements at various locations in wards 5A and 5D. N denotes neutral, R denotes rumbly, HF denotes hissy, and V denotes vibrational ratings.

Indoor Noise Criteria Rating				
	NC	*NCB*	*RC*	*RC Mark II*
5A-Back Nurse Station	51	50 HF, V	52 HF, V	52 HF, V
5A-Hallway	53	52 HF, V	54 HF, V	54 HF, V
5A-Central Computer Station	56	55 HF, V	56 HF, V	56 HF, V
5A-Front Nurse Station	55	53 HF, V	54 HF, V	54 HF, V
5D-Back Nurse Station	57	55 HF, V	57 N, V	57 HF, V
5D-Hallway	57	55 HF, V	57 N, V	57 HF, V
5D-Central Computer Station	60	58 HF, V	60 N, V	60 HF, V
5D-Front Nurse Station	59	57 R, HF, V	59 HF, V	59 HF, V

4.3.2.4 DL_2 results

DL_2 measurements were conducted in both wards and analyzed in an A-weighted one-third octave band method. Results are shown in Figure 29. DL_2 is the measure of decay in decibels per doubling of distance. For all frequencies above 200 Hz, 5A exhibited a higher DL_2 value. These results can be interpreted to show that sounds will propagate with less sound decay in the untreated 5D ward when compared to the treated 5A ward. For example, a telephone ring tone will decay less quickly as it propogates down the hall in the untreated 5D than in the treated 5A. Sound will build up more readily with a lower DL_2. Although the numbers may only be around 1 dB difference in DL_2, these numbers may accumulate noticeably over several distance doublings.

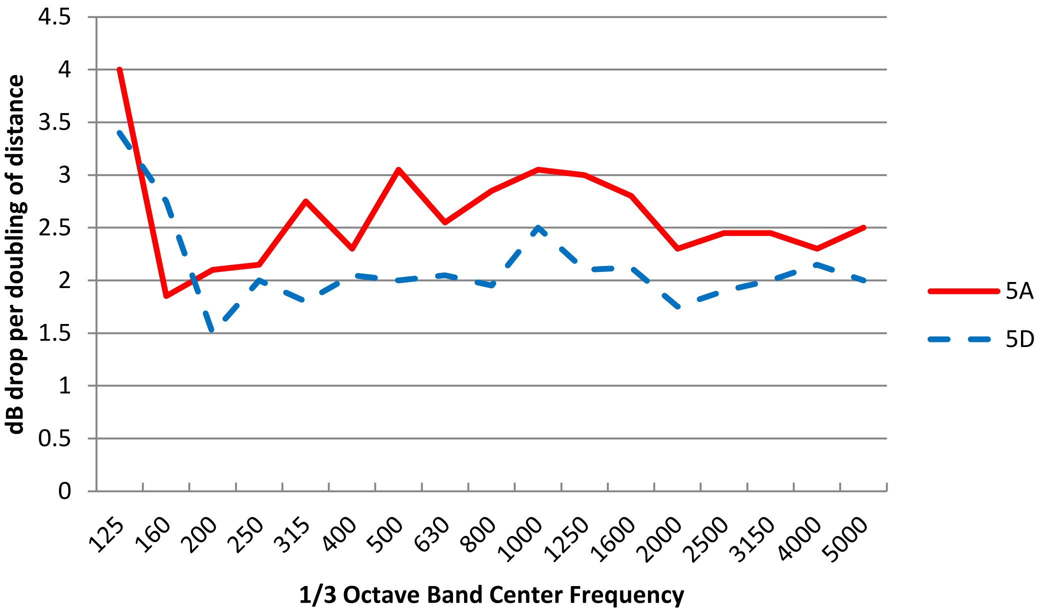

Figure 29. Results from DL_2 measurements (dB drop per doubling of distance) across frequency in wards 5A and 5D.

4.3.2.4 Modified DL_2 and Spatial Sound Distribution Curve

Figure 30 and Figure 31 show the SSDC for wards 5A (treated) and 5D (untreated) compared to the free field at 500 hertz and 2000 hertz. All the curves lie well above the free field line as this expected in a reverberant enclosed space like a hallway. The 500 Hz SSDC provides a large amount of acoustical information. First, treated 5A's SSDC results line is closer to the free field line, especially at large distances, meaning that 5A is more open (absorptive) than 5D is. Second, the treated 5A SSDC results shows significant decibel decay up to 8 meters and then levels off, while the untreated 5D shows significant decibel decay only to 5 meters. The region until the 8m mark for 5A and the 5m mark for 5D can be considered the “near” region. The extended near region in treated 5A can be interpreted as increased attenuation of first and early reflections by the panels. Any curves beyond this “near” region can be viewed to be in the “far” region since neither curve exhibits a significant “middle” region. Most hallways should exhibit similar behavior since the confining ceiling and walls will quickly induce a large amount of reflections blurring the division between middle and far regions. In the “far” regions, both graphs level out at the level of the background noise. The most revealing difference in data comes from this difference in SSDC region length and not from the DL_2, since the DL_2 would be approximately equal past 8 m.

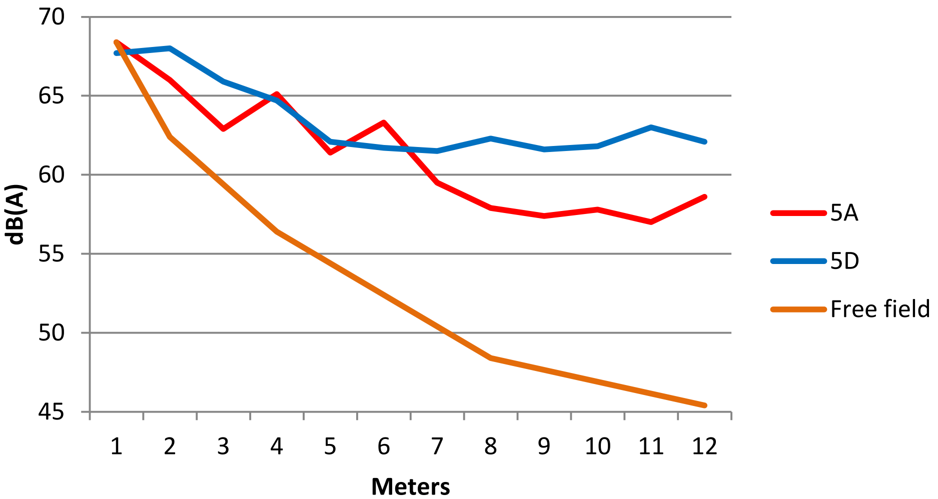

Figure 30. SSDC for 500 Hz comparing the treated 5A to the untreated 5D to the theoretical Free Field

The 2000 Hz graph, in Figure 31, reveals a different characteristic about these wards. Here the shapes of the SSDC for 5A and 5D are very similar. Besides a larger initial drop in the treated 5A SSDC, the slope of both SSDCs is nearly identical and, hence, their respective DL_2's. The larger early drop of treated 5A (between 0-3 meters) can once again be seen as the panels subduing the influence of the strong early reflections. Additionally, 3m is approximately where the measurements are no longer in the open front nurse station area but enter fully into the hallway. Beyond 3m, both curves slowly approach the background noise level with the treated 5A SSDC having a slightly larger slope or DL_2. The difference between the 500 and 2000 Hz graphs are consistent with the absorption coefficients of the panels; as absorption coefficients decrease above 500 Hz.

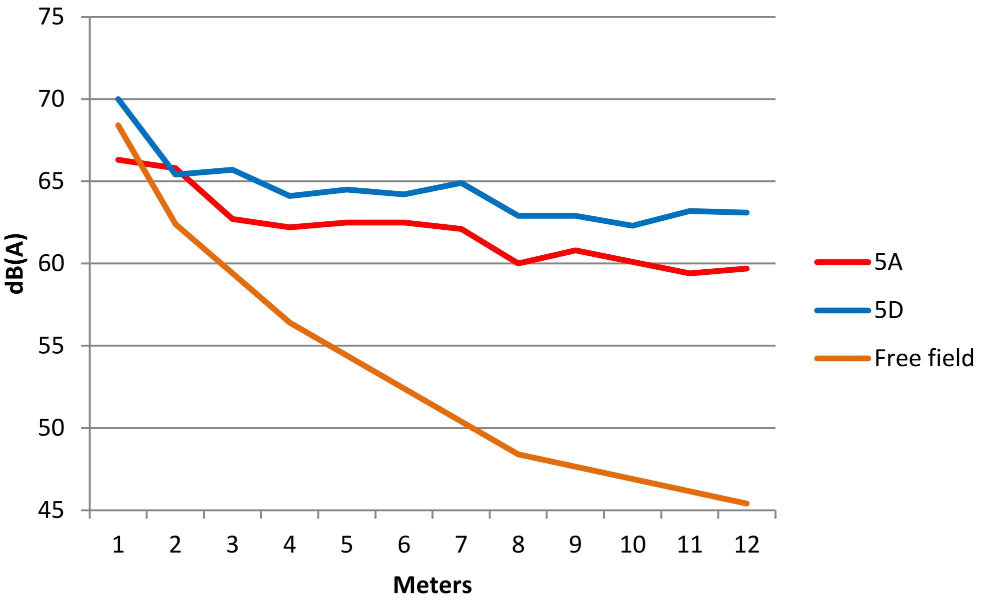

Figure 31. SSDC for 2000 Hz comparing the treated 5A to the untreated 5D to the theoretical Free Field

Figure 30 and Figure 31 also show the panel’s effectiveness at lower speech frequencies and their ability to potentially mitigate strong early reflections. Alternately, another way to interpret the data is that the panels mitigate the corridor effects, extending the feeling of openness in the treated ward. At higher frequencies, above 2000 Hz for example, the panels still impact the early reflections but to a lesser degree. The slow approach toward the background noise level in the 2000 Hz graph indicates the waveguide effect of the corridor. As with reverberation measurements, the SSDC provides more information when the source level is high. Being in a hospital with resting patients, the level used for these tests was not optimal but adequate to demonstrate the effectiveness of the panels and validity of these measurements.

4.3.2.5 Reverberation time results

Table 32 shows the octave band reverberation times averaged across multiple trials in both wards. As expected, the untreated 5D ward has a higher RT in almost all frequency ranges. For example, at 500 Hz RT was reduced by 0.24 seconds, or 29%. This is a higher percentage than the jnd for reverberation time [150]. Thus, this change will be noticeable by the staff members and other occupants of the ward hallways.

Table 32. Results from reverberation time (RT) measurements across frequency in wards 5A and 5D

Reverberation Time (RT, sec)						
Octave Band Center Frequency (Hz)	*250*	*500*	*1000*	*2000*	*4000*	*8000*
5A	0.59	0.59	0.58	0.56	0.50	0.48
5D	0.84	0.83	0.78	0.71	0.71	0.68

4.3.2.6 Speech intelligibility results

Speech Intelligibility Index (SII) and Articulation Index (AI) results are presented in Figure 32. The results show that the treated ward 5A has higher SII in every scenario measured. For example, at the front nurse station, 5A had a 52% improvement in SII score from 0.25 in 5D to 0.38 in 5A. Similarly, the AI scores are better in each scenario in the treated 5A ward. Figure 32 also shows qualitative ratings of “good,” “marginal,” and “poor” for various AI and SII scores. As indicated, scores above 0.75 correspond to “good” speech intelligibility, scores in the 0.4-0.75 range are “marginal,” and any scores below 0.4 are considered “poor” [20]. Based on these ratings, 5A generally has a “poor” to “marginal” rating and 5D is “poor” for speech intelligibility. No measurement yielded a “good” rating.

In both of these speech measures, it has been found that the treated 5A ward exhibited a better speech environment than the untreated 5D, but is likely still not adequate. It is believed that the small improvement in intelligibility is due to the addition of the sound absorbing acoustic panels as the sound absorbing panels have the highest absorption coefficients in the speaking range. However, as no locations showed "good" intelligibility and very few showed "marginal" intelligibility, even after adding absorption, it may be that additional noise control measures such as more absorption are necessary in these units.

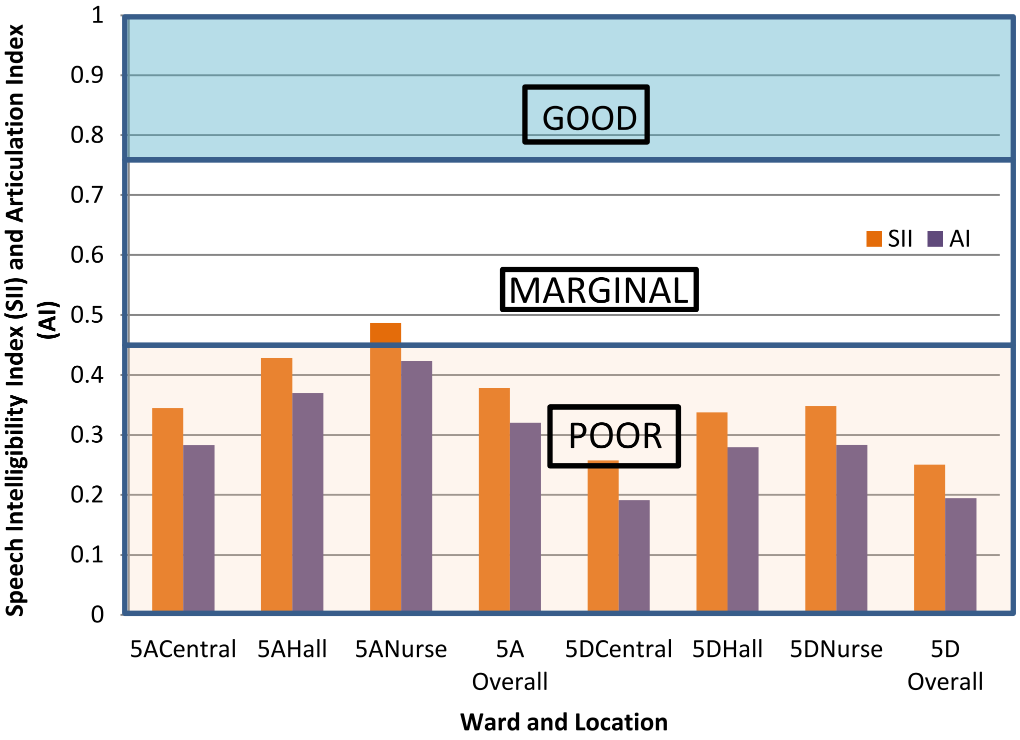

Figure 32. Speech intelligibility index (SII) and Articulation Index (AI) results at various locations in wards 5A and 5D. Qualitative descriptors of "good," "marginal," and "poor" ranges of intelligibility are shown as shaded regions.

4.3.2.7 SII Occurrence Rates

In the previous chapter, occurrence rates were used to describe the temporal distribution of sound levels. Here, the same concept is used, but now, occurrence rates will be used to describe the temporal distribution of speech intelligibility. For example, applying occurrence rate to SII, the amount of time that SII is considered “poor” can now be determined. This type of analysis was performed using audio recordings taken in both 5A and 5D.

Using the dueling HEADs as mentioned before, SII measurements were made and the results are shown in Table 33. To recall, two different HEAD recordings were made in each ward at the same time, resulting in simultaneous measurements. The locations included the back nurse station, the central computer station and doctor’s rounds locations. For these simultaneous recordings, for example, one HEAD would record the rounds, while at the same time the other HEAD records the nurse’s station.

Table 33 provides the results of these SII measurement comparisons. Each row consists of one simultaneous measurement, with each HEAD giving an SII result for each ear. For example, in the first row, one HEAD records at the central computer station in 5A, and the other HEAD records at the back nurse station in 5A. This data tends to show trends that in general, 5D has lower SII although differences are often small. These trends seem to further corroborate other data previously presented.

Comparing data within a given row in Table 33 can lead to observations of how one location’s noise may affect another location’s speech intelligibility. For example, the SII ratings derived from background noise measurements, shown in Figure 32, show the back nurse station to have a rating of SII=0.42. In the first row of Table 33, HEAD 2 measured SII without the presence of the rounds, and SII matches the results in Figure 32 almost exactly (SII = 0.43). The second row shows SII during rounds, with HEAD 2 measuring SII as 0.23 at a location very close to the doctor's rounds. However, less than 20 feet down the hall, HEAD 1 measures the SII at the back nurse station as only slightly better at 0.29. Therefore, the SII at the back nurse station decreased during rounds. Essentially, the speech that occurs in the rounds is causing the background noise in the ward to be so high that the speech intelligibility in the nurse station suffers.

Figure 33 and Figure 34 show SII occurrence rate graphs at the central computer station and the back nurse station for the treated 5A and untreated 5D, respectively. These graphs show that the treated 5A seemingly has a more even temporal SII distribution at different locations as compared to the untreated 5D. In other words, the central computer area and nurses station have about the same SII occurrence rate slope in treated 5A, but the nurse station has a markedly worse SII occurrence rate slope (more percent of time with lower SII) than the central computer area in the untreated 5D. These graphs are relatively consistent with the SII occurrence rate graphs calculated for other locations.

Table 33. SII data for different locations of the dueling HEADS in both ward 5A and 5D

	HEAD 1			**HEAD 2**	
	Left	Right		Left	Right
5A Central	0.44	0.45	5A Back Nurse	0.43	0.43
5A Back Nurse	0.29	0.28	5A Rounds	0.23	0.23
5A Back Nurse B	0.43	0.41	5A Rounds B	0.39	0.40
5D Central	0.42	0.42	5D Back Nurse	0.25	0.26
5D Back Nurse	0.28	0.29	5D Rounds	0.23	0.23
5D Back Nurse B	0.26	0.27	5D Rounds B	0.20	0.19

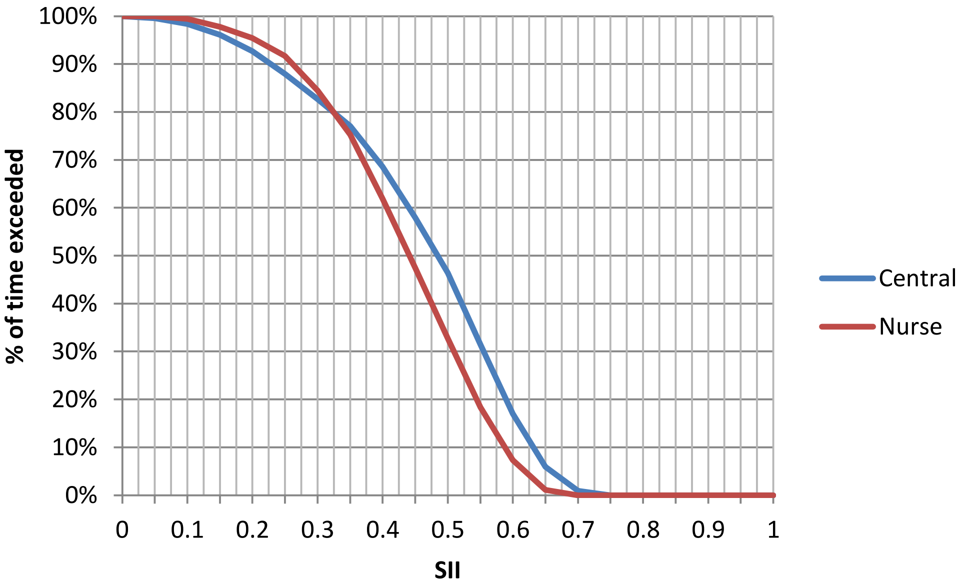

Figure 33. SII Occurrence Rate for Treated 5A between the Central Computer and Back nurse stations

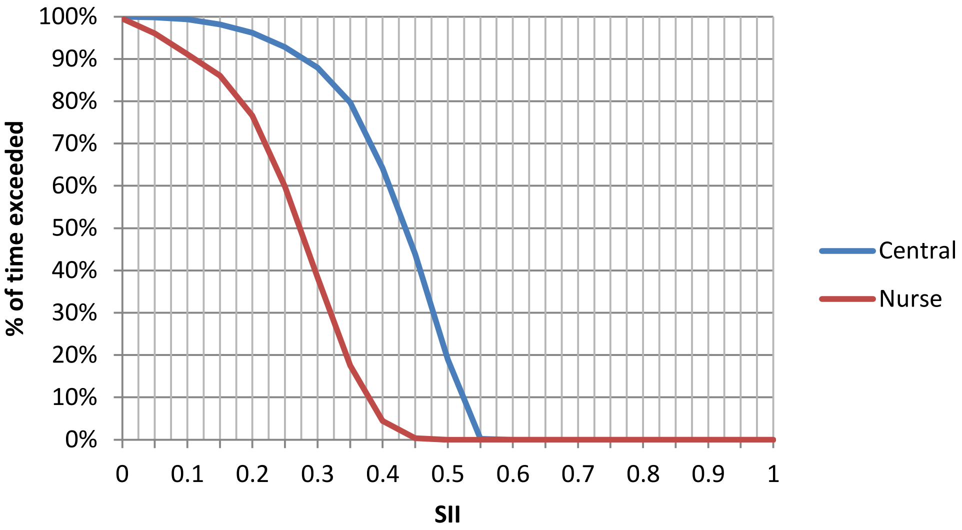

Figure 34. SII Occurrence Rate for Untreated 5D between the Central Computer and Back nurse stations

Another way to analyze these SIIs is to compare the SII results from the treated 5A to the same location in the untreated 5D. This can provide a direct comparison between the treated and untreated scenario. Figure 35 shows the SII occurrence rate for the treated 5A and untreated 5D at the central computer station. Of particular note, SII in treated 5A exceeded 0.45 only about 55% of the time at the central computer station. Recall that SII=0.45 is the cutoff between "poor" and "marginal" intelligibility. Similarly, ward 5A was essentially never in the "good" range (> 0.75). Comparing that to the 5D results, the 5D slope is much steeper, indicating more time with lower SII. As a point of comparison, SII exceeded 0.45 about 45% of the time, less than that of the treated 5A. A more dramatic comparison can be seen at the back nurse stations in Figure 36. This comparison begins to show that these acoustic panels are helping with speech intelligibility. As above, these graphs are representative of the entire data set, and the data as a whole shows that the treated 5A have a better SII rating for a higher percentage of time.

Further development of these dueling HEAD measurements will be discussed as a part of future research. Longer sample times and more measurements will provide a more comprehensive understanding and detailed temporal distribution of the soundscape. However, these preliminary findings show consistently that these acoustic panels are effective and can help speech intelligibility. Ultimately, these dueling HEAD measurements show the potential need for improved SII in hospital wards.

The SII results presented above provide a major contribution to the understanding of speech intelligibility and to the characterization of hospital noise. The occurrence rates in particular provide a temporal understanding to speech intelligibility that can be used to determine the bounds of acceptability. Single-number values and qualitative descriptors such as “poor” or “marginal” do not provide information on the time-varying nature of speech intelligibility. The unique aspect of occurrence rate graphs is that it provides readily accessible information on how often SII is better than specified threshold values. In mission critical environments like hospitals, the difference between potential miscommunication and mistakes can be the matter of just few syllables or a few seconds of disturbing background noise. The SII occurrence rate metric precisely highlights this temporal distribution of speech intelligibility.

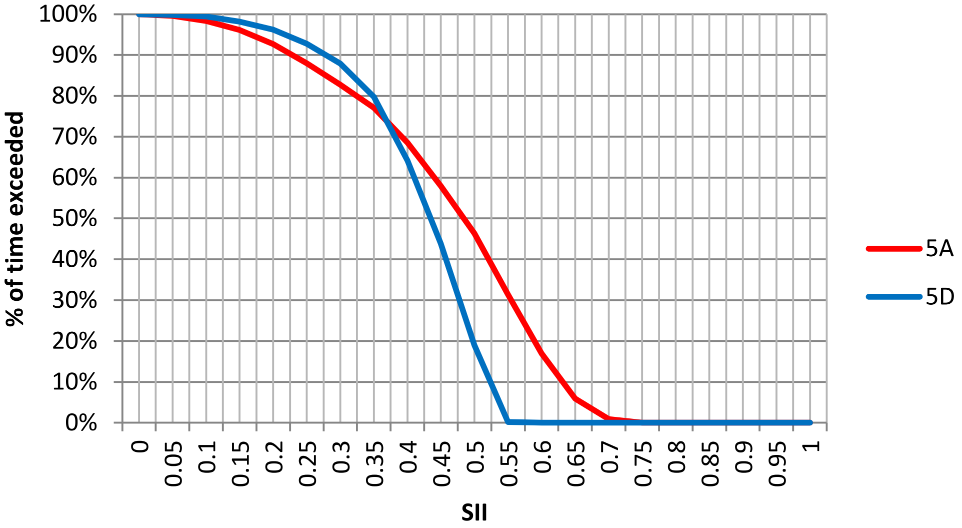

Figure 35. Central Computer Station SII comparison between treated 5A and untreated 5D

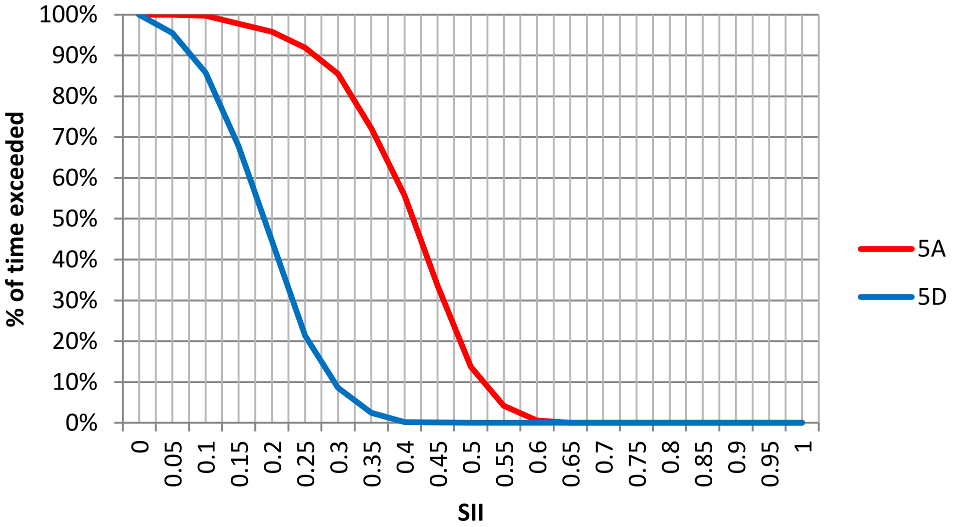

Figure 36. Back Nurse Station SII comparison between treated 5A and untreated 5D

4.3 Staff questionnaire results

Surveys were administered to the nursing staff in phase two of this project. Due to logistics and scheduling in the hospitals, a direct comparison between the treated 5A and untreated 5D could not be made with regards to the survey. However, it was possible to administer a before and after treatment survey in ward 5A, which provides some insight into the impacts of adding absorption on occupants. Mean comparing t-tests were utilized to determine if there were statistically significant differences in staff perception between the treated and untreated condition.

The before survey consisted of 31 nurses with approximately a 30% response rate. All respondents were female and had an average age of 31.3. 30 of the nurses were full-time and one was part-time. One respondent claimed to have a hearing impairment (ringing). On a scale from 1-5, with 1 corresponding to not sensitive and 5 corresponding to very sensitive, the nurses in the before study had an average of 3.1 for noise sensitivity. The after survey, with a slightly higher response rate of 35%, consisted of 35 nurses with all female respondents and average age of 29.8. 31 of the nurses were full-time and four were part-time and no respondents claimed to have any known hearing impairments. Using the same scale for sensitivity, the nurses for the after study had an average of 2.7 for noise sensitivity. Due to the relatively small sample size, differences in survey responses across demographic variables were not analyzed.

The first part of the questionnaire asked about annoyance due to noise sources. Figure 37 shows the results of a treated/untreated comparison of perceived noise sources and all items in Figure 37 are statistically significant ($p<0.05$). The scores range from 1-5, with a higher number corresponding to more annoyance. The results show that paging systems, phones, carts, footfall, visitors talking, and staff talking were all less annoying in the treated condition. Interestingly, subjects were also asked about noise sources typically located in patient rooms and not in corridors, such as patient bodily sounds, alarms, and medical equipment operational noise. These patient room sources were not perceived as significantly different in the treated versus untreated conditions, which is expected considering that the panels were only installed in the corridors.

Another part of the questionnaire asked how the noise affected the nurses and if the noise caused difficulties in their work. The statistically significant results ($p<0.05$) are shown in Figure 38. Results show that the addition of the panels had a significant impact on concentration and communication; specifically, that nurses in the treated condition perceived less concentration problems and less trouble communicating with staff or holding telephone conversations. This again is consistent with the location of the panels and the typical locations of these staff activities. For example, nurses perceived no significant difference in their ability to communicate with patients and this is expected since panels were not installed in patient rooms.

Other items on the questionnaires did not appear as statistically significant; however, looking at the data as a whole, the trend was that every single noise source was less annoying in the treated space rather than the untreated space. Similarly, every question about difficulties and the work environment showed a trend of improvement in the treated space. It is clear from these results that the addition of these acoustic panels were perceived as an improvement by the nursing staff.

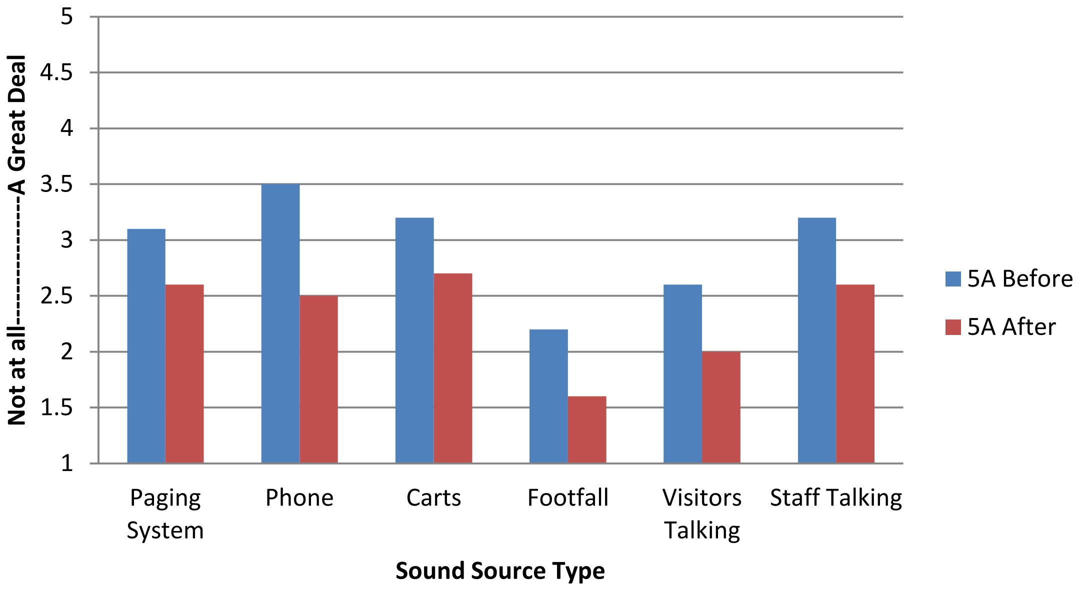

Figure 37. Statistically significant questionnaire differences in annoyance between sources in 5A versus 5D

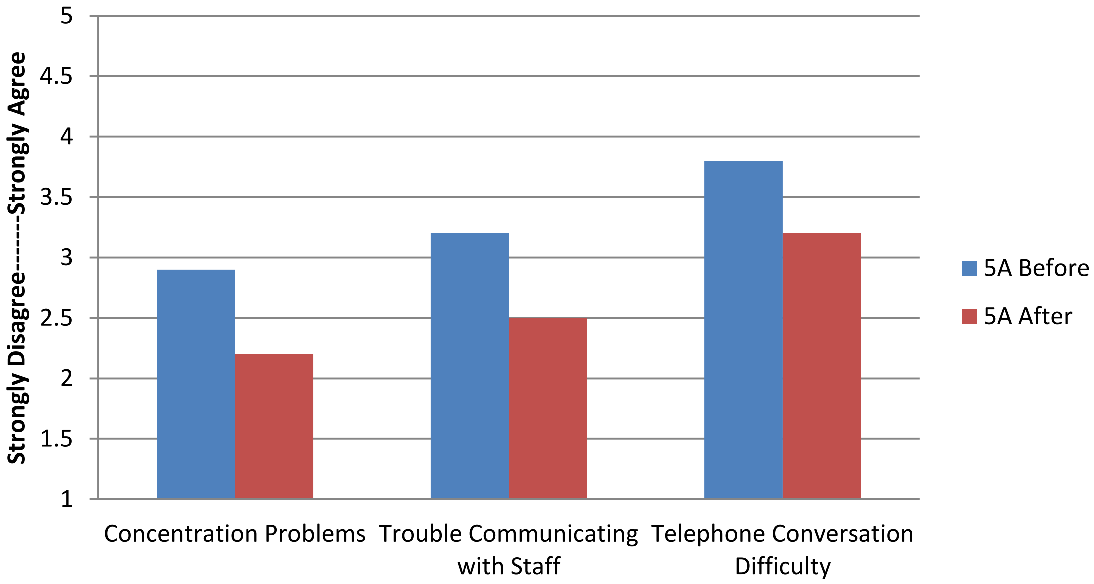

Figure 38. Statistically Significant questionnaire difference in difficulties in sound environment between 5A and 5D

4.4 DISCUSSION AND CONCLUSIONS

Hospitals are continually expanding but construction is expensive and owners rarely consider noise control as a necessary expense. Recently published papers highlighting negative impacts of sound on patients, alongside the trend towards digital hospitals are beginning to bring more attention to the acoustical problems; but, as is the case in most construction, acoustics are often not considered or budgeted before construction commences. Therefore, retrofit solutions may remain the primary method for hospital noise control.

The retrofit solution discussed in this dissertation was built on previous work from the Johns Hopkins University (Phase 1) that developed an “optimized” cost feasible and aesthetically pleasing solution for retrofit hospital noise control that meets the strictest of hospital requirements. By wrapping a fiberglass panel in a thin, light, and durable flash spun nonwoven material the Johns Hopkins team was able to retain much of the fiberglass sound absorption characteristics while meeting the hospital’s strict building material requirements. The Hopkins team is currently pursuing additional work on new materials and mounting methods that may be able to achieve better results than those presented in this paper but require further investigation.

The optimized panels in this study do likely result in a noticeable improvement in reverberation time. Meng et al. 2006 show that a 5-10% change in reverberation time is the just noticeable difference (jnd) in change of RT in non-music settings [150]. In this study, all the recorded differences in RT from untreated to treated condition exceed the 5-10% jnd change. Perceptually, the installed sound panels likely created a noticeable change in RT in the treated condition.

Phase two of this study evaluated the impact of adding acoustical absorption to a hospital ward. A specific comparison between an untreated ward and a ward treated with absorbing panels was made. The spatial sound distribution curve (SSDC) was used to characterize corridor sound propagation in addition to reverberation time, and background noise measurements were complemented with noise criteria and speech intelligibility findings in order to provide a more thorough description of the acoustical environment in hospitals. Using these new measurement techniques and new materials, we are better able to describe hospital noise problems and how to treat them. The data presented in this paper shows improvements in background noise, reverberation time, DL2, and speech intelligibility, with a consistent trend of improvement from the untreated to the treated ward. Additionally, the sound power present in the treated 5A was lower than the sound power present in the untreated 5D. Even though it is shown that the absorbing panels reduced the overall noise levels in the treated 5A when compared to the untreated 5D, the sound power differences also show that the panels have an additional effect in the treated 5A. The reduction of sound power implies that the panels may be changing the acoustic patterns as well in the wards, e.g., the staff may not talk as loudly or repeat themselves as often after the panels are installed. It is concluded that the addition of these sound absorbing panels improved the soundscape of these wards.

Among the noise measurements, the 24-hour measurements at the front nurse station were found to be more sensitive than the 30-minute measurements in comparing the two wards. As these measurements were taken in a live, working hospital, the researchers had little to no control over the activities in the ward. For the 30-minute measurements, the activity levels may be different in each measurement. For example, even though the hallway was measured in both 5A and 5D in the same location, one measurement may have included more people traffic than the other measurement. Thus, the 30-minute measurements may be more insightful and helpful for direct results instead of comparative results. For the 24-hour data, the activity levels average out over the measurement period, thus possibly revealing a more holistic picture of the soundscape. Furthermore, the comparisons between the two wards can be made in a more realistic way. Even longer background noise measurements at each location may be desirable, but the length is often dictated by access to the site and other research logistics. The multiple measurements of impulse response and DL_2 were designed to minimize any effects of unusual transient conditions.

The DL_2 data is a newer metric investigated in this study that highlights the differences between wards. The free field value for DL_2 is 6 dB—corresponding to the inverse-square law decay. However, due to multiple sources of reflection in the indoor environment the indoor maximum of DL_2 is expected to be lower. With the treated 5A showing improved DL_2 numbers across the most of the frequency spectrum, it is believed the sound absorbing panels help with the sound decay in the hallway. Additionally, the difference in DL_2 values appears to be the greatest in the areas where the absorption coefficient is the highest for the panels. The higher DL_2 in the treated 5A means that sounds do not propagate down the corridors as much as sounds in the untreated 5D. As discussed previously, the corridors can act as a waveguide due to the geometry and surface properties of the ward. Differences of 1 dB increments in DL_2 can accumulate to a noticeable amount over the span of long corridors, especially when this racetrack ward design promotes propagation around the corners. In previous studies, [158-161] the investigators have focused on open office conditions. DL_2 measurements in open offices in the literature yield high DL_2 results. An open-office study [161] has measured DL_2 ranging from 2.0 to 11.7; whereas other studies [158] report DL_2 values from 3.3 dB to 6.6 dB. Additionally, DL_2 was measured before and after the installation of absorptive material in the open office [159]. The DL_2 differences varied from no change to a 1.4 dBA improvement in DL_2.

The reduction in reverberation time in the treated ward 5A is a noticeable improvement. Meng et al. show that a 5-10% change in reverberation time is the just noticeable difference (jnd) in change of RT in non-music settings. In this study, all the recorded differences in RT from 5D to 5A exceed the 5-10% jnd change. Perceptually, the installed sound panels have created a noticeable change in RT in the treated ward [150]. The effects of this reverberation time reduction can help speech communication as speech intelligibility is generally governed by two factors: background noise and by reverberation time.

In analyzing the speech intelligibility results, one can see that intelligibility is generally considered “poor” in the untreated ward. Poor speech intelligibility can potentially be a factor in miscommunication between nurses, doctors, and patients. This may be one source of medical error that could be improved with the installation of absorbing panels. This improvement is due to the reduction of noise levels and reverberation time in the ward. However, even in the treated ward, the speech intelligibility rating is “Poor” to “Marginal.” This shows that speech intelligibility continues to be an area that needs further research and improvements. The occurrence rate analysis further show the temporal distribution of SII. Although 5A SII occurrence rates were better than the untreated 5D, speech was almost never considered “good.” The hospital ward should be an area where clear speech is a priority—a mistake in medical communication can result in misdiagnoses, incorrect dosages of medicine, among other potentially harmful effects.

Some of the indirect impacts of the acoustical treatment were on the staff’s perceived work environment. As described earlier, previous studies suggest that elevated noise levels can cause increased stress, a reduction in productivity, and changes in the psychosocial environment, among others. The survey results from this study show that the addition of panels helped significantly reduce annoyance due to corridor sounds and improve perceived communication and concentration. In fact, every item on the questionnaire showed a trend towards improvement in the treated ward rather than the untreated ward. The changes in the acoustics due to the addition of these optimized panels are making a generally positive impact on the nursing staff’s perception of the working environment.

Future research in this area is necessary in order to make better improvements to the hospital environment, as described in Chapter 5. The acoustic measurements and surveys in this dissertation were limited by logistics, including the fact that the ward is a 24-hour occupied environment. Additional, detailed measurement of the acoustic environment away from the activity would be ideal; however, it is unrealistic to shut down a hospital ward for the purpose of research. One alternative is to develop computer models of the wards in order to optimize the panel locations and geometry in order to provide the best soundscape.

In summary, the solutions presented in this study are applicable to even the most restrictive areas of hospitals, and can help hospitals approach the WHO and more recently developed guidelines. The data presented in this dissertation shows improvements in background noise, reverberation time, DL_2, and speech intelligibility, with a consistent trend of improvement from the untreated to the treated ward. Most importantly, these solutions may contribute to greater staff well-being.

CHAPTER 5- CONCLUSION

Hospital noise research will continue to be an important topic as researchers are learning more about how to better quantify hospital noise and its relationship to patient physiology and staff responses. Previous research has been limited by sample size, limited patient population types, potentially incomplete acoustic analysis, for example.

This dissertation attempts to reconcile some of these potential holes in the previous research. In Chapter 3, patients in a Swedish hospital ICU were the focus of a study where acoustic and physiological measurements were taken. The original hypothesis for the patient outcomes was presented in Chapter 1:

- Traditional and non-traditional sound level metrics are statistically related to patient physiological outcomes of heart rate, respiratory rate, oxygen saturation, and blood pressure.

This study comprehensively analyzed the acoustical environment of the ICU. Average, minimum, maximum, and peak sound levels were reported by 24-hour periods, by work shifts and by patients' rooms. Additionally, occurrence rates, audio recordings, standard psychoacoustic metrics of SIL, loudness, sharpness, fluctuation strength, and roughness were determined, as well. By analyzing these comprehensive acoustic measurements and utilizing a host of statistical models, links between noise and patient physiological responses were made. Statistically significant relationships, via correlations, linear regressions, curve estimations, and risk ratios, were all present in this study. Specifically the risk ratios clearly demonstrate the risk of heightened physiological response based on increased noise level. The result of these risk ratios is that there is now a defined threshold where noise levels were found to cause increased risk in this patient population. This threshold concept is important to define as future building codes and guidelines need metrics and thrsholds that relate to more accurate acoustic expectations of modern occupants. Additionally, the psychoacoustic metrics presented here represent a new facet of research in the field of hospital acoustics. The baseline psychoacoustic measurements and their evident relationship to physiological metrics will lead to a new area of research that will be stated below. Roughness in particular is a metric that was consistently related to patient physiology and may be one of the best metrics to define these relationships. With each additional facet of this study, the link between hospital sound and patient physiology were present; thus, this dissertation concludes that these links do exist and that noise does cause physiological responses in the general ICU patient population.

Thus, the patient outcomes hypothesis was confirmed in this dissertation: links do exist and noise does cause potentially negative physiological responses in the general ICU patient population. This dissertation extends on previous studies by using general patient populations, more detailed traditional measurements, by developing psychoacoustic relationship, and incorporating new statistical models like risk ratios. The major contributions are that this dissertation:

- Characterized hospital noise and created baseline data for occurrence rate and psychoacoustic metrics in intensive care unit patient rooms.
- Used a novel approach by using psychoacoustic metrics known to relate to human perception (but have not been previously studied in hospitals) to characterize the hospital soundscape. Additionally, these psychoacoustic

metrics were used to reveal the relationships between noise and patient physiological response.

  - Showed statistically significant relationships between traditional and nontraditional acoustic metrics with patient physiology in a general patient population. These relationships include unique applications of psychoacoustic metrics and statistical models such as the risk ratio.
    - Correlations and risk ratio clearly show these relationships. The statistically signficant correlations (p<0.01) between physiological measurements and both sound level metrics and psychoacoustic metrics showed that this relationship is not due to chance. Additionally, risk ratio results showed statistically significant (p<0.05) increases of risk (between 15-60%) at various metric thresholds. For example, 50 dB L_{Aeq} was a threshold that was found to bring increased risk to the subjects for this patient population.
    - Roughness is a pyschoacoustic metric that was consistently, statistically significantly related to the physiological measurements. It also was the most sensitive psychoacoustic metric when comparing risk ratio results.

Using these new measurement techniques, there are now better methods to describe hospital noise and better explain hospital patient responses to noise. This dissertation clearly shows that the noise in hospitals is related to patient physiology.

In Chapter 4, staff responses were examined at a hematological ward in a major hospital in Baltimore, Maryland. The original hypotheses presented in Chapter 1 for the staff outcomes were:

- Traditional sound level metrics and room acoustic metrics (DL_2 (a spatial sound decay metric), reverberation time, clarity, and speech intelligibility) improve with added absorption.
- Nurse outcomes of perceived annoyance, stress symptoms, specific noise sources, etc. improve with added absorption.

Recently published papers highlighting the negative impacts of sound on patients, alongside the trend towards digital hospitals are beginning to bring more attention to the acoustical problems; but, as is the case in most construction, acoustics are rarely considered or budgeted before construction begins. Therefore, retrofit solutions may remain the primary method for hospital noise control. Collaborators have previously developed a novel acoustic panel that met the hospital requirements for cleanability. This study incorporates a treated/untreated test scenario where both the acoustics of the ward and the staff responses are compared from an untreated ward scenario to a treated ward scenario. The developed optimized panels in this study did result in a noticeable improvement in reverberation time, with changes ranging from 0.2-0.3 seconds, which exceed the 5-10% change necessary for a just noticeable difference. The spatial sound distribution curve (SSDC) was used to characterize corridor sound propagation in addition to reverberation time, and background noise measurements were complemented with noise criteria and speech intelligibility findings in order to provide a more thorough description of the acoustical environment in hospitals. The treated 5A was generally rated quieter, by approximately 4 RC Mark II points on average, with a range of 3-6 rating points difference. Speech intelligibility was also calculated as part of the treated/untreated study and it was shown to be "poor" for both wards; however, in general, intelligibility was improved in the treated wards by approximately 0.1 points on the SII scale. Occurrence rates for speech intelligibility also provide a temporal view of the variations in speech intelligibility. Lastly, a questionnaire was completed by the nurses in the wards and in general, these panels showed improvement in staff perception. Specifically, noise sources in areas where the acoustic panels were installed, such as telephones and staff conversation, and the ability to communicate were statistically significant improvements in the treated scenario.

The staff outcome hypotheses were confirmed in Chapter 4 of this dissertation. Speech intelligibility was calculated as part of the treated/untreated study and it was shown to be "poor," but intelligibility did improve with the added absorption. Occurrence rates for speech intelligibility, reverberation time, and DL_2 also all improved with added absorption. The major contributions are that this dissertation:

- Showed the effectiveness of sound absorbing panels on staff response in a live working hospital.
- Showed that in the treated ward, the measured equivalent sound levels were reduced by approximately 3 dB; reverberation time was shortened by 0.2-0.3 seconds, and DL_2 showed nearly 1 dB faster rate of spatial decay.
- Determined detailed speech intelligibility ratings in an ICU ward
    - Created a baseline for speech intelligibility data for an ICU ward. Nearly all measurements showed a "poor" rating.

- Showed the improvement of intelligibility in a treated ward when compared to an untreated ward.
- Determined the temporal distribution of speech intelligibility in both the treated and untreated scenarios. These SII occurrence rates showed clear improvements in intelligibility in the treated wards. The development of SII occurrence rates can be used widely to show the time-varying nature of speech intelligibility.
- Compared the speech intelligibility between two points in the same ward—showing how one area's intelligibility could be affected by another area's noise.

This study showed that acoustic absorption will positively affect staff responses, will lover noise and power levels in a ward, will reduce reverberation time, and provide better speech intelligibility.

Future research will continue to make the case that hospital noise can significantly impact both the patients and the staff. This future research should include similar types of studies but with more controlled patient populations without compromising the sample size. Working with medical professionals and other collaborators will be essential to move forward and determine which physiological metrics will be the most important. Ultimately, the patient research should show which noise sources cause what kind of response and what the effect of these responses will be. Future research should also investigate computer modeling of the wards and potentially develop general design criteria for the most effective absorbing panel coverage areas and placements. To further the knowledge with speech intelligibility, specific intelligibility studies should be done.

Medical students regularly participate in simulations that can be used to study how speech intelligibility can create or propagate medical errors. These simulations can intentionally insert speech communication errors and then determine if or how the noise in the rest of the simulation masks this intentional error. This will allow a definitive link between noise, speech intelligibility, and medical errors.

One particular challenge in this field of research is developing methods that allow for the study of causation, i.e., researchers need to show that a certain acoustic event causes a certain physiological response. Statistical models in this dissertation show correlations or relationships, but not causation. Future research will need to study causation. Causation could potentially by revealed through more controlled studies (e.g. lab studies, strict patient populations) where the researchers systematically alter only one variable at at time. Other studies to show causation could look at the temporal sequence of events, where researchers may be able to demonstrate that a certain acoustic event leads a certain physiological response. The goal of this future research is to use these various studies to show that acoustics can cause physiological responses through converging validity.

Additionally this research can be transferred directly to other areas of the hospital. Since the panels have shown promise and effectiveness in the Weinberg cancer wards, similar installations can be made in spaces such as operating rooms, which have problematic noise levels and similar cleanability requirements. The panels presented in Chapter 4 have been used in a pilot study in operating rooms [152]. Preliminary measurement results have recorded unacceptable background noise levels in the operation room; additionally, post-installation measurements have shown reductions in reverberation time. Similar questionnaire studies, as used in the ICUs studies, could be administered to the staff of the operating rooms. Future research will include operating rooms as well as other types of wards within the hospital.

Furthermore, there are fundamental tradeoffs between noise and occupant response. If background noise is low, the speech intelligibility increases, but speech privacy can potentially be compromised. Also, there may be a scenario where reverberation time is too low and the anechoic effect of the ward is distracting and unnatural for the occupants, but too much reverberation can compromise speech intelligibility. Future research should aim at finding this optimized “sweet spot” of acoustic metrics, such as background noise levels or reverberation time guidelines, where the noise levels are conducive to intelligibility, privacy and positive occupant outcomes.

This dissertation shows that noise in hospitals is a continual problem. With the rising levels in hospitals, this problem will continue to worsen. The patients will have adverse physiological effects and the staff will face potential annoyance and communication problems. This document shows these effects for a general patient population and on ICU nurses. It is the hope that this research will lead to healthier and safer environments for the patients to recover more fully and for the staff to work in a less adverse environment.

APPENDIX A – CLUSTER PLOT METHODS

Initial scatter plots of the data used background sound lever meter metrics as the independent (x-axis) variable and the physiological measurements as the dependent (y-axis) variable. Scatter plots were inconclusive due to the overwhelming number of data points, oftentimes 2000-3000 data points per graph, for the combined data set of all the patients.

In order to parse through the data, a series of “cluster plots” were developed. For this method, the data was “clustered” to try to reduce the plotted data points. For a given x-axis interval, the y-axis data was averaged to attempt to approximately represent all the values of that interval into one point—thereby clustering all the data in that interval to one point. For this data, the x-axis interval was set to be 5 dB. As an example, to calculate a representative interval for this method, one could focus on the 50 to 55 dB interval, and then average all the heart rate values to determine the clustered, averaged heart rate value for the 50 to 55 dB interval. This process was repeated for all the desired intervals and physiological parameters in the data set. The MATLAB code is in Appendix B.

In general, this visual method showed some trends relating increasing noise and a change in physiological response. The plots in general that showed the clearest trends related increasing noise to increasing respiratory rate. For example, Figure 39 shows a slope of approximately of an increase of 3 breaths per minute for an increase of 10 db L_{Cpk}. This relationship shown in Figure 39 is visually clear and is representative of several other graphs. However, other relationships are not as clear.

With regards to heart rate, the cluster plots seem to show little trend. No easy relationship can be seen in the cluster plots between heart rate and L_{Aeq} and L_{Amin}. However, Figure 40 shows that in the plot between heart rate and L_{Amax}, if the first data point from the left and the point to the furthest right are considered outliers, then the ten points between 40 dB L_{Amax} and 90 dB L_{Amax} show a slight trend of increasing heart rate with increasing maximum noise. Similarly, focusing on heart rate and L_{Cpk} as seen in Figure 41, if the two clustered points less than 60 dB L_{Cpk} and the one clustered point greater than 100 dB L_{Cpk} are considered outliers, a clear trend can be seen for the seven remaining points. Similar trends are shown in systolic, diastolic, and median blood pressure.

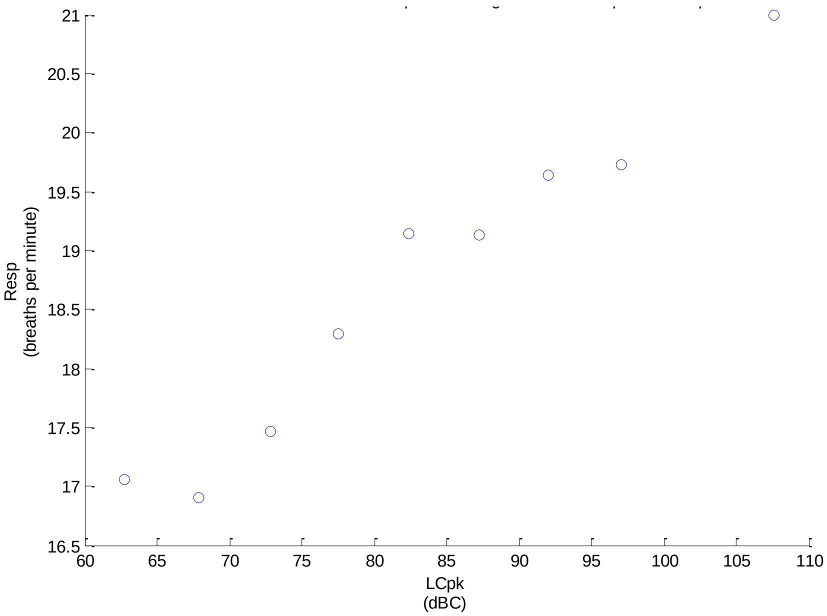

Figure 39. Cluster Plot for L_{Cpk} and Respiratory Rate

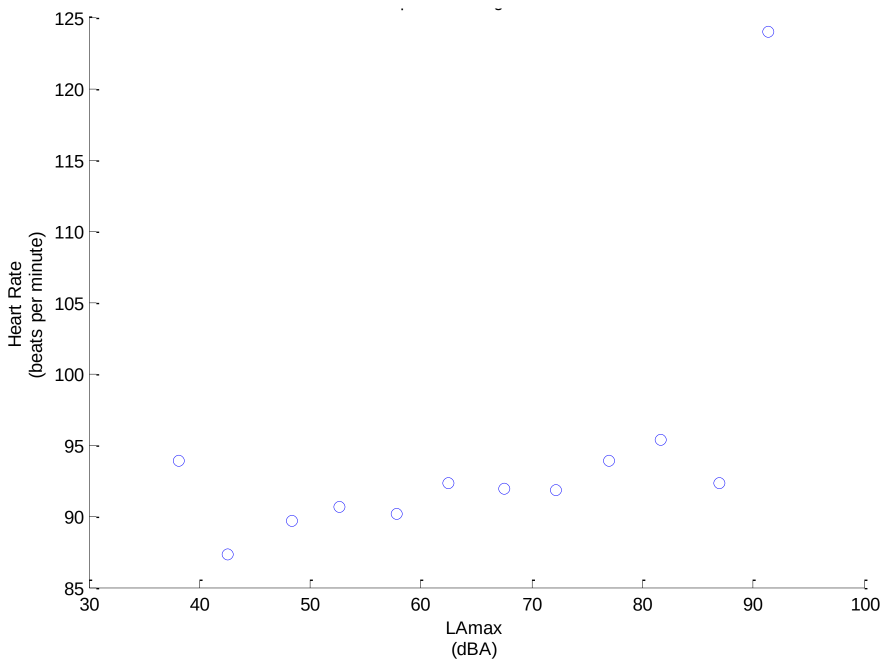

Figure 40. Cluster Plot for L_{Amax} and Heart Rate

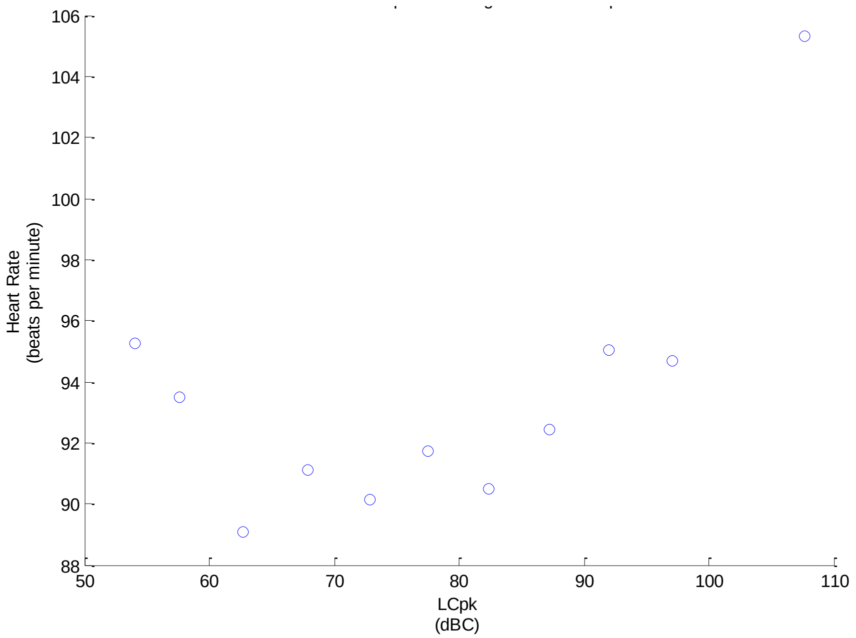

Figure 41. Cluster Plot for L_{Cpk} and Heart Rate

Similar analysis can be done for oxygen saturation. Just as with heart rate, not all figures show trends, and with some graphs, extreme left or right points may have to be considered outliers to see if there are trends or not. Note that it appears that when noise increases, oxygen saturation may decrease. This is consistent with some of the intuition gained from the literature review; e.g., that a healthier patient will have higher oxygen saturation.

One of the weaknesses of this method is that this only gives a visual clustering representation of the data. Each data point is given the same weight in this method, where in actuality; one point may cluster many more points than another point. This is most evident in the extreme left and right points of the graphs. There may only be a handful of data points averaged together to form these outlier cluster points, whereas a cluster point towards the middle of the graph may average together hundreds of points. However, this weakness in this method can also partially be used to justify ignoring these extreme left and right points when visually determining if a trend exists. Because these extreme points only represent a small percentage of the data, they could be ignored with care. Another weakness of this method is that there is no calculation of statistical significance. Regardless, the main advantage of this cluster plot method is that from a large data set, trends can now be seen in a coarse way and it can help determine if further analysis is warranted.

APPENDIX B – CLUSTER PLOT MATLAB CODE

```
clear all
close all
clc

[data,names]=xlsread('HospDataWithNoIDNoAlarm.xls');
names=names(1,:);
Time=data(:,1);
HF=data(:,2);
SPO2=data(:,3);
Resp=data(:,4);
ArtSys=data(:,5);
ArtDias=data(:,6);
ArtMedel=data(:,7);
LAeq=data(:,8);
LAFmax=data(:,9);
LCpk=data(:,10);
LAmin=data(:,11);

%LAeq vs HF
LAeq3035=LAeq(find(LAeq>30 & LAeq<35));
HFLAeq3035=HF(find(LAeq>30 & LAeq<35));

LAeq3540=LAeq(find(LAeq>35 & LAeq<40));
HFLAeq3540=HF(find(LAeq>35 & LAeq<40));

LAeq4045=LAeq(find(LAeq>40 & LAeq<45));
HFLAeq4045=HF(find(LAeq>40 & LAeq<45));

LAeq4550=LAeq(find(LAeq>45 & LAeq<50));
HFLAeq4550=HF(find(LAeq>45 & LAeq<50));

LAeq5055=LAeq(find(LAeq>50 & LAeq<55));
HFLAeq5055=HF(find(LAeq>50 & LAeq<55));

LAeq5560=LAeq(find(LAeq>55 & LAeq<60));
HFLAeq5560=HF(find(LAeq>55 & LAeq<60));

LAeq6065=LAeq(find(LAeq>60 & LAeq<65));
HFLAeq6065=HF(find(LAeq>60 & LAeq<65));

LAeq6570=LAeq(find(LAeq>65 & LAeq<70));
HFLAeq6570=HF(find(LAeq>65 & LAeq<70));

LAeq7075=LAeq(find(LAeq>70 & LAeq<75));
HFLAeq7075=HF(find(LAeq>70 & LAeq<75));

LAeq7580=LAeq(find(LAeq>75 & LAeq<80));
HFLAeq7580=HF(find(LAeq>75 & LAeq<80));

LAeq8085=LAeq(find(LAeq>80 & LAeq<85));
HFLAeq8085=HF(find(LAeq>80 & LAeq<85));
```

```
LAeq8590=LAeq(find(LAeq>85 & LAeq<90));
HFLAeq8590=HF(find(LAeq>85 & LAeq<90));

LAeq9095=LAeq(find(LAeq>90 & LAeq<95));
HFLAeq9095=HF(find(LAeq>90 & LAeq<95));

LAeq95100=LAeq(find(LAeq>95 & LAeq<100));
HFLAeq95100=HF(find(LAeq>95 & LAeq<100));

LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
HFLAeq100105=HF(find(LAeq>100105 & LAeq<100105));

LAeq105=LAeq(find(LAeq>105));
HFLAeq105=HF(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
LAeq4550Mean=nanmean(LAeq4550);
LAeq5055Mean=nanmean(LAeq5055);
LAeq5560Mean=nanmean(LAeq5560);
LAeq6065Mean=nanmean(LAeq6065);
LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);

HFLAeq3035Mean=nanmean(HFLAeq3035);
HFLAeq3540Mean=nanmean(HFLAeq3540);
HFLAeq4045Mean=nanmean(HFLAeq4045);
HFLAeq4550Mean=nanmean(HFLAeq4550);
HFLAeq5055Mean=nanmean(HFLAeq5055);
HFLAeq5560Mean=nanmean(HFLAeq5560);
HFLAeq6065Mean=nanmean(HFLAeq6065);
HFLAeq6570Mean=nanmean(HFLAeq6570);
HFLAeq7075Mean=nanmean(HFLAeq7075);
HFLAeq7580Mean=nanmean(HFLAeq7580);
HFLAeq8085Mean=nanmean(HFLAeq8085);
HFLAeq8590Mean=nanmean(HFLAeq8590);
HFLAeq9095Mean=nanmean(HFLAeq9095);
HFLAeq95100Mean=nanmean(HFLAeq95100);
HFLAeq100105Mean=nanmean(HFLAeq100105);
HFLAeq105Mean=nanmean(HFLAeq105);

LAeqHFWeight=[length(LAeq3035) length(LAeq3540) length(LAeq4045)
length(LAeq4550) length(LAeq5055) length(LAeq5560) length(LAeq6065)
length(LAeq6570) length(LAeq7075) length(LAeq7580) length(LAeq8085)
length(LAeq8590) length(LAeq9095) length(LAeq95100) length(LAeq100105)
length(LAeq105)]
```

```
LAeqCluster=[LAeq3035Mean LAeq3540Mean LAeq4045Mean LAeq4550Mean
LAeq5055Mean LAeq5560Mean LAeq6065Mean LAeq6570Mean LAeq7075Mean
LAeq7580Mean LAeq8085Mean LAeq8590Mean LAeq9095Mean LAeq95100Mean
LAeq100105Mean LAeq105Mean];
HFLAeqCluster=[HFLAeq3035Mean HFLAeq3540Mean HFLAeq4045Mean
HFLAeq4550Mean HFLAeq5055Mean HFLAeq5560Mean HFLAeq6065Mean
HFLAeq6570Mean HFLAeq7075Mean HFLAeq7580Mean HFLAeq8085Mean
HFLAeq8590Mean HFLAeq9095Mean HFLAeq95100Mean HFLAeq100105Mean
HFLAeq105Mean];

figure(1)
scatter(LAeqCluster, HFLAeqCluster)
xlabel('LAeq')
ylabel('HF')
title('Cluster scatter of means at specified ranges between LAeq and
HF')

%LAeq vs SP02
LAeq3035=LAeq(find(LAeq>30 & LAeq<35));
SPO2LAeq3035=SPO2(find(LAeq>30 & LAeq<35));

LAeq3540=LAeq(find(LAeq>35 & LAeq<40));
SPO2LAeq3540=SPO2(find(LAeq>35 & LAeq<40));

LAeq4045=LAeq(find(LAeq>40 & LAeq<45));
SPO2LAeq4045=SPO2(find(LAeq>40 & LAeq<45));

LAeq4550=LAeq(find(LAeq>45 & LAeq<50));
SPO2LAeq4550=SPO2(find(LAeq>45 & LAeq<50));

LAeq5055=LAeq(find(LAeq>50 & LAeq<55));
SPO2LAeq5055=SPO2(find(LAeq>50 & LAeq<55));

LAeq5560=LAeq(find(LAeq>55 & LAeq<60));
SPO2LAeq5560=SPO2(find(LAeq>55 & LAeq<60));

LAeq6065=LAeq(find(LAeq>60 & LAeq<65));
SPO2LAeq6065=SPO2(find(LAeq>60 & LAeq<65));

LAeq6570=LAeq(find(LAeq>65 & LAeq<70));
SPO2LAeq6570=SPO2(find(LAeq>65 & LAeq<70));

LAeq7075=LAeq(find(LAeq>70 & LAeq<75));
SPO2LAeq7075=SPO2(find(LAeq>70 & LAeq<75));

LAeq7580=LAeq(find(LAeq>75 & LAeq<80));
SPO2LAeq7580=SPO2(find(LAeq>75 & LAeq<80));

LAeq8085=LAeq(find(LAeq>80 & LAeq<85));
SPO2LAeq8085=SPO2(find(LAeq>80 & LAeq<85));

LAeq8590=LAeq(find(LAeq>85 & LAeq<90));
SPO2LAeq8590=SPO2(find(LAeq>85 & LAeq<90));
```

```
LAeq9095=LAeq(find(LAeq>90 & LAeq<95));
SPO2LAeq9095=SPO2(find(LAeq>90 & LAeq<95));

LAeq95100=LAeq(find(LAeq>95 & LAeq<100));
SPO2LAeq95100=SPO2(find(LAeq>95 & LAeq<100));

LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
SPO2LAeq100105=SPO2(find(LAeq>100105 & LAeq<100105));

LAeq105=LAeq(find(LAeq>105));
SPO2LAeq105=SPO2(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
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LAeq5055Mean=nanmean(LAeq5055);
LAeq5560Mean=nanmean(LAeq5560);
LAeq6065Mean=nanmean(LAeq6065);
LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);

SPO2LAeq3035Mean=nanmean(SPO2LAeq3035);
SPO2LAeq3540Mean=nanmean(SPO2LAeq3540);
SPO2LAeq4045Mean=nanmean(SPO2LAeq4045);
SPO2LAeq4550Mean=nanmean(SPO2LAeq4550);
SPO2LAeq5055Mean=nanmean(SPO2LAeq5055);
SPO2LAeq5560Mean=nanmean(SPO2LAeq5560);
SPO2LAeq6065Mean=nanmean(SPO2LAeq6065);
SPO2LAeq6570Mean=nanmean(SPO2LAeq6570);
SPO2LAeq7075Mean=nanmean(SPO2LAeq7075);
SPO2LAeq7580Mean=nanmean(SPO2LAeq7580);
SPO2LAeq8085Mean=nanmean(SPO2LAeq8085);
SPO2LAeq8590Mean=nanmean(SPO2LAeq8590);
SPO2LAeq9095Mean=nanmean(SPO2LAeq9095);
SPO2LAeq95100Mean=nanmean(SPO2LAeq95100);
SPO2LAeq100105Mean=nanmean(SPO2LAeq100105);
SPO2LAeq105Mean=nanmean(SPO2LAeq105);

LAeqSPO2Weight=[length(LAeq3035) length(LAeq3540) length(LAeq4045)
length(LAeq4550) length(LAeq5055) length(LAeq5560) length(LAeq6065)
length(LAeq6570) length(LAeq7075) length(LAeq7580) length(LAeq8085)
length(LAeq8590) length(LAeq9095) length(LAeq95100) length(LAeq100105)
length(LAeq105)]

LAeqCluster=[LAeq3035Mean LAeq3540Mean LAeq4045Mean LAeq4550Mean
LAeq5055Mean LAeq5560Mean LAeq6065Mean LAeq6570Mean LAeq7075Mean
```

```
LAeq7580Mean LAeq8085Mean LAeq8590Mean LAeq9095Mean LAeq95100Mean
LAeq100105Mean LAeq105Mean];
SPO2LAeqCluster=[SPO2LAeq3035Mean SPO2LAeq3540Mean SPO2LAeq4045Mean
SPO2LAeq4550Mean SPO2LAeq5055Mean SPO2LAeq5560Mean SPO2LAeq6065Mean
SPO2LAeq6570Mean SPO2LAeq7075Mean SPO2LAeq7580Mean SPO2LAeq8085Mean
SPO2LAeq8590Mean SPO2LAeq9095Mean SPO2LAeq95100Mean SPO2LAeq100105Mean
SPO2LAeq105Mean];

figure(2)
scatter(LAeqCluster, SPO2LAeqCluster)
xlabel('LAeq')
ylabel('SP02')
title('Cluster scatter of means at specified ranges between LAeq and
SP02')

%LAeq vs ArtSys
LAeq3035=LAeq(find(LAeq>30 & LAeq<35));
ArtSysLAeq3035=ArtSys(find(LAeq>30 & LAeq<35));

LAeq3540=LAeq(find(LAeq>35 & LAeq<40));
ArtSysLAeq3540=ArtSys(find(LAeq>35 & LAeq<40));

LAeq4045=LAeq(find(LAeq>40 & LAeq<45));
ArtSysLAeq4045=ArtSys(find(LAeq>40 & LAeq<45));

LAeq4550=LAeq(find(LAeq>45 & LAeq<50));
ArtSysLAeq4550=ArtSys(find(LAeq>45 & LAeq<50));

LAeq5055=LAeq(find(LAeq>50 & LAeq<55));
ArtSysLAeq5055=ArtSys(find(LAeq>50 & LAeq<55));

LAeq5560=LAeq(find(LAeq>55 & LAeq<60));
ArtSysLAeq5560=ArtSys(find(LAeq>55 & LAeq<60));

LAeq6065=LAeq(find(LAeq>60 & LAeq<65));
ArtSysLAeq6065=ArtSys(find(LAeq>60 & LAeq<65));

LAeq6570=LAeq(find(LAeq>65 & LAeq<70));
ArtSysLAeq6570=ArtSys(find(LAeq>65 & LAeq<70));

LAeq7075=LAeq(find(LAeq>70 & LAeq<75));
ArtSysLAeq7075=ArtSys(find(LAeq>70 & LAeq<75));

LAeq7580=LAeq(find(LAeq>75 & LAeq<80));
ArtSysLAeq7580=ArtSys(find(LAeq>75 & LAeq<80));

LAeq8085=LAeq(find(LAeq>80 & LAeq<85));
ArtSysLAeq8085=ArtSys(find(LAeq>80 & LAeq<85));

LAeq8590=LAeq(find(LAeq>85 & LAeq<90));
ArtSysLAeq8590=ArtSys(find(LAeq>85 & LAeq<90));

LAeq9095=LAeq(find(LAeq>90 & LAeq<95));
ArtSysLAeq9095=ArtSys(find(LAeq>90 & LAeq<95));
```

```
LAeq95100=LAeq(find(LAeq>95 & LAeq<100));
ArtSysLAeq95100=ArtSys(find(LAeq>95 & LAeq<100));

LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
ArtSysLAeq100105=ArtSys(find(LAeq>100105 & LAeq<100105));

LAeq105=LAeq(find(LAeq>105));
ArtSysLAeq105=ArtSys(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
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LAeq6065Mean=nanmean(LAeq6065);
LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);

ArtSysLAeq3035Mean=nanmean(ArtSysLAeq3035);
ArtSysLAeq3540Mean=nanmean(ArtSysLAeq3540);
ArtSysLAeq4045Mean=nanmean(ArtSysLAeq4045);
ArtSysLAeq4550Mean=nanmean(ArtSysLAeq4550);
ArtSysLAeq5055Mean=nanmean(ArtSysLAeq5055);
ArtSysLAeq5560Mean=nanmean(ArtSysLAeq5560);
ArtSysLAeq6065Mean=nanmean(ArtSysLAeq6065);
ArtSysLAeq6570Mean=nanmean(ArtSysLAeq6570);
ArtSysLAeq7075Mean=nanmean(ArtSysLAeq7075);
ArtSysLAeq7580Mean=nanmean(ArtSysLAeq7580);
ArtSysLAeq8085Mean=nanmean(ArtSysLAeq8085);
ArtSysLAeq8590Mean=nanmean(ArtSysLAeq8590);
ArtSysLAeq9095Mean=nanmean(ArtSysLAeq9095);
ArtSysLAeq95100Mean=nanmean(ArtSysLAeq95100);
ArtSysLAeq100105Mean=nanmean(ArtSysLAeq100105);
ArtSysLAeq105Mean=nanmean(ArtSysLAeq105);

LAeqArtSysWeight=[length(LAeq3035) length(LAeq3540) length(LAeq4045)
length(LAeq4550) length(LAeq5055) length(LAeq5560) length(LAeq6065)
length(LAeq6570) length(LAeq7075) length(LAeq7580) length(LAeq8085)
length(LAeq8590) length(LAeq9095) length(LAeq95100) length(LAeq100105)
length(LAeq105)]

LAeqCluster=[LAeq3035Mean LAeq3540Mean LAeq4045Mean LAeq4550Mean
LAeq5055Mean LAeq5560Mean LAeq6065Mean LAeq6570Mean LAeq7075Mean
LAeq7580Mean LAeq8085Mean LAeq8590Mean LAeq9095Mean LAeq95100Mean
LAeq100105Mean LAeq105Mean];
```

```
ArtSysLAeqCluster=[ArtSysLAeq3035Mean ArtSysLAeq3540Mean
ArtSysLAeq4045Mean ArtSysLAeq4550Mean ArtSysLAeq5055Mean
ArtSysLAeq5560Mean ArtSysLAeq6065Mean ArtSysLAeq6570Mean
ArtSysLAeq7075Mean ArtSysLAeq7580Mean ArtSysLAeq8085Mean
ArtSysLAeq8590Mean ArtSysLAeq9095Mean ArtSysLAeq95100Mean
ArtSysLAeq100105Mean ArtSysLAeq105Mean];

figure(3)
scatter(LAeqCluster, ArtSysLAeqCluster)
xlabel('LAeq')
ylabel('ArtSys')
title('Cluster scatter of means at specified ranges between LAeq and
ArtSys')

%LAeq vs ArtDias
LAeq3035=LAeq(find(LAeq>30 & LAeq<35));
ArtDiasLAeq3035=ArtDias(find(LAeq>30 & LAeq<35));

LAeq3540=LAeq(find(LAeq>35 & LAeq<40));
ArtDiasLAeq3540=ArtDias(find(LAeq>35 & LAeq<40));

LAeq4045=LAeq(find(LAeq>40 & LAeq<45));
ArtDiasLAeq4045=ArtDias(find(LAeq>40 & LAeq<45));

LAeq4550=LAeq(find(LAeq>45 & LAeq<50));
ArtDiasLAeq4550=ArtDias(find(LAeq>45 & LAeq<50));

LAeq5055=LAeq(find(LAeq>50 & LAeq<55));
ArtDiasLAeq5055=ArtDias(find(LAeq>50 & LAeq<55));

LAeq5560=LAeq(find(LAeq>55 & LAeq<60));
ArtDiasLAeq5560=ArtDias(find(LAeq>55 & LAeq<60));

LAeq6065=LAeq(find(LAeq>60 & LAeq<65));
ArtDiasLAeq6065=ArtDias(find(LAeq>60 & LAeq<65));

LAeq6570=LAeq(find(LAeq>65 & LAeq<70));
ArtDiasLAeq6570=ArtDias(find(LAeq>65 & LAeq<70));

LAeq7075=LAeq(find(LAeq>70 & LAeq<75));
ArtDiasLAeq7075=ArtDias(find(LAeq>70 & LAeq<75));

LAeq7580=LAeq(find(LAeq>75 & LAeq<80));
ArtDiasLAeq7580=ArtDias(find(LAeq>75 & LAeq<80));

LAeq8085=LAeq(find(LAeq>80 & LAeq<85));
ArtDiasLAeq8085=ArtDias(find(LAeq>80 & LAeq<85));

LAeq8590=LAeq(find(LAeq>85 & LAeq<90));
ArtDiasLAeq8590=ArtDias(find(LAeq>85 & LAeq<90));

LAeq9095=LAeq(find(LAeq>90 & LAeq<95));
ArtDiasLAeq9095=ArtDias(find(LAeq>90 & LAeq<95));
```

```
LAeq95100=LAeq(find(LAeq>95 & LAeq<100));
ArtDiasLAeq95100=ArtDias(find(LAeq>95 & LAeq<100));

LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
ArtDiasLAeq100105=ArtDias(find(LAeq>100105 & LAeq<100105));

LAeq105=LAeq(find(LAeq>105));
ArtDiasLAeq105=ArtDias(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
LAeq4550Mean=nanmean(LAeq4550);
LAeq5055Mean=nanmean(LAeq5055);
LAeq5560Mean=nanmean(LAeq5560);
LAeq6065Mean=nanmean(LAeq6065);
LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);

ArtDiasLAeq3035Mean=nanmean(ArtDiasLAeq3035);
ArtDiasLAeq3540Mean=nanmean(ArtDiasLAeq3540);
ArtDiasLAeq4045Mean=nanmean(ArtDiasLAeq4045);
ArtDiasLAeq4550Mean=nanmean(ArtDiasLAeq4550);
ArtDiasLAeq5055Mean=nanmean(ArtDiasLAeq5055);
ArtDiasLAeq5560Mean=nanmean(ArtDiasLAeq5560);
ArtDiasLAeq6065Mean=nanmean(ArtDiasLAeq6065);
ArtDiasLAeq6570Mean=nanmean(ArtDiasLAeq6570);
ArtDiasLAeq7075Mean=nanmean(ArtDiasLAeq7075);
ArtDiasLAeq7580Mean=nanmean(ArtDiasLAeq7580);
ArtDiasLAeq8085Mean=nanmean(ArtDiasLAeq8085);
ArtDiasLAeq8590Mean=nanmean(ArtDiasLAeq8590);
ArtDiasLAeq9095Mean=nanmean(ArtDiasLAeq9095);
ArtDiasLAeq95100Mean=nanmean(ArtDiasLAeq95100);
ArtDiasLAeq100105Mean=nanmean(ArtDiasLAeq100105);
ArtDiasLAeq105Mean=nanmean(ArtDiasLAeq105);

LAeqArtDiasWeight=[length(LAeq3035) length(LAeq3540) length(LAeq4045)
length(LAeq4550) length(LAeq5055) length(LAeq5560) length(LAeq6065)
length(LAeq6570) length(LAeq7075) length(LAeq7580) length(LAeq8085)
length(LAeq8590) length(LAeq9095) length(LAeq95100) length(LAeq100105)
length(LAeq105)]

LAeqCluster=[LAeq3035Mean LAeq3540Mean LAeq4045Mean LAeq4550Mean
LAeq5055Mean LAeq5560Mean LAeq6065Mean LAeq6570Mean LAeq7075Mean
LAeq7580Mean LAeq8085Mean LAeq8590Mean LAeq9095Mean LAeq95100Mean
LAeq100105Mean LAeq105Mean];
ArtDiasLAeqCluster=[ArtDiasLAeq3035Mean ArtDiasLAeq3540Mean
ArtDiasLAeq4045Mean ArtDiasLAeq4550Mean ArtDiasLAeq5055Mean
ArtDiasLAeq5560Mean ArtDiasLAeq6065Mean ArtDiasLAeq6570Mean
```

```
ArtDiasLAeq7075Mean ArtDiasLAeq7580Mean ArtDiasLAeq8085Mean
ArtDiasLAeq8590Mean ArtDiasLAeq9095Mean ArtDiasLAeq95100Mean
ArtDiasLAeq100105Mean ArtDiasLAeq105Mean];


figure(4)
scatter(LAeqCluster, ArtDiasLAeqCluster)
xlabel('LAeq')
ylabel('ArtDias')
title('Cluster scatter of means at specified ranges between LAeq and
ArtDias')

%LAeq vs ArtMedel
LAeq3035=LAeq(find(LAeq>30 & LAeq<35));
ArtMedelLAeq3035=ArtMedel(find(LAeq>30 & LAeq<35));

LAeq3540=LAeq(find(LAeq>35 & LAeq<40));
ArtMedelLAeq3540=ArtMedel(find(LAeq>35 & LAeq<40));

LAeq4045=LAeq(find(LAeq>40 & LAeq<45));
ArtMedelLAeq4045=ArtMedel(find(LAeq>40 & LAeq<45));

LAeq4550=LAeq(find(LAeq>45 & LAeq<50));
ArtMedelLAeq4550=ArtMedel(find(LAeq>45 & LAeq<50));

LAeq5055=LAeq(find(LAeq>50 & LAeq<55));
ArtMedelLAeq5055=ArtMedel(find(LAeq>50 & LAeq<55));

LAeq5560=LAeq(find(LAeq>55 & LAeq<60));
ArtMedelLAeq5560=ArtMedel(find(LAeq>55 & LAeq<60));

LAeq6065=LAeq(find(LAeq>60 & LAeq<65));
ArtMedelLAeq6065=ArtMedel(find(LAeq>60 & LAeq<65));

LAeq6570=LAeq(find(LAeq>65 & LAeq<70));
ArtMedelLAeq6570=ArtMedel(find(LAeq>65 & LAeq<70));

LAeq7075=LAeq(find(LAeq>70 & LAeq<75));
ArtMedelLAeq7075=ArtMedel(find(LAeq>70 & LAeq<75));

LAeq7580=LAeq(find(LAeq>75 & LAeq<80));
ArtMedelLAeq7580=ArtMedel(find(LAeq>75 & LAeq<80));

LAeq8085=LAeq(find(LAeq>80 & LAeq<85));
ArtMedelLAeq8085=ArtMedel(find(LAeq>80 & LAeq<85));

LAeq8590=LAeq(find(LAeq>85 & LAeq<90));
ArtMedelLAeq8590=ArtMedel(find(LAeq>85 & LAeq<90));

LAeq9095=LAeq(find(LAeq>90 & LAeq<95));
ArtMedelLAeq9095=ArtMedel(find(LAeq>90 & LAeq<95));

LAeq95100=LAeq(find(LAeq>95 & LAeq<100));
ArtMedelLAeq95100=ArtMedel(find(LAeq>95 & LAeq<100));
```

```
LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
ArtMedelLAeq100105=ArtMedel(find(LAeq>100105 & LAeq<100105));

LAeq105=LAeq(find(LAeq>105));
ArtMedelLAeq105=ArtMedel(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
LAeq4550Mean=nanmean(LAeq4550);
LAeq5055Mean=nanmean(LAeq5055);
LAeq5560Mean=nanmean(LAeq5560);
LAeq6065Mean=nanmean(LAeq6065);
LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);

ArtMedelLAeq3035Mean=nanmean(ArtMedelLAeq3035);
ArtMedelLAeq3540Mean=nanmean(ArtMedelLAeq3540);
ArtMedelLAeq4045Mean=nanmean(ArtMedelLAeq4045);
ArtMedelLAeq4550Mean=nanmean(ArtMedelLAeq4550);
ArtMedelLAeq5055Mean=nanmean(ArtMedelLAeq5055);
ArtMedelLAeq5560Mean=nanmean(ArtMedelLAeq5560);
ArtMedelLAeq6065Mean=nanmean(ArtMedelLAeq6065);
ArtMedelLAeq6570Mean=nanmean(ArtMedelLAeq6570);
ArtMedelLAeq7075Mean=nanmean(ArtMedelLAeq7075);
ArtMedelLAeq7580Mean=nanmean(ArtMedelLAeq7580);
ArtMedelLAeq8085Mean=nanmean(ArtMedelLAeq8085);
ArtMedelLAeq8590Mean=nanmean(ArtMedelLAeq8590);
ArtMedelLAeq9095Mean=nanmean(ArtMedelLAeq9095);
ArtMedelLAeq95100Mean=nanmean(ArtMedelLAeq95100);
ArtMedelLAeq100105Mean=nanmean(ArtMedelLAeq100105);
ArtMedelLAeq105Mean=nanmean(ArtMedelLAeq105);

LAeqArtMedelWeight=[length(LAeq3035) length(LAeq3540) length(LAeq4045)
length(LAeq4550) length(LAeq5055) length(LAeq5560) length(LAeq6065)
length(LAeq6570) length(LAeq7075) length(LAeq7580) length(LAeq8085)
length(LAeq8590) length(LAeq9095) length(LAeq95100) length(LAeq100105)
length(LAeq105)]

LAeqCluster=[LAeq3035Mean LAeq3540Mean LAeq4045Mean LAeq4550Mean
LAeq5055Mean LAeq5560Mean LAeq6065Mean LAeq6570Mean LAeq7075Mean
LAeq7580Mean LAeq8085Mean LAeq8590Mean LAeq9095Mean LAeq95100Mean
LAeq100105Mean LAeq105Mean];
ArtMedelLAeqCluster=[ArtMedelLAeq3035Mean ArtMedelLAeq3540Mean
ArtMedelLAeq4045Mean ArtMedelLAeq4550Mean ArtMedelLAeq5055Mean
ArtMedelLAeq5560Mean ArtMedelLAeq6065Mean ArtMedelLAeq6570Mean
ArtMedelLAeq7075Mean ArtMedelLAeq7580Mean ArtMedelLAeq8085Mean
```

```
ArtMedelLAeq8590Mean ArtMedelLAeq9095Mean ArtMedelLAeq95100Mean
ArtMedelLAeq100105Mean ArtMedelLAeq105Mean];

figure(5)
scatter(LAeqCluster, ArtMedelLAeqCluster)
xlabel('LAeq')
ylabel('ArtMedel')
title('Cluster scatter of means at specified ranges between LAeq and
ArtMedel')

%LAeq vs Resp
LAeq3035=LAeq(find(LAeq>30 & LAeq<35));
RespLAeq3035=Resp(find(LAeq>30 & LAeq<35));

LAeq3540=LAeq(find(LAeq>35 & LAeq<40));
RespLAeq3540=Resp(find(LAeq>35 & LAeq<40));

LAeq4045=LAeq(find(LAeq>40 & LAeq<45));
RespLAeq4045=Resp(find(LAeq>40 & LAeq<45));

LAeq4550=LAeq(find(LAeq>45 & LAeq<50));
RespLAeq4550=Resp(find(LAeq>45 & LAeq<50));

LAeq5055=LAeq(find(LAeq>50 & LAeq<55));
RespLAeq5055=Resp(find(LAeq>50 & LAeq<55));

LAeq5560=LAeq(find(LAeq>55 & LAeq<60));
RespLAeq5560=Resp(find(LAeq>55 & LAeq<60));

LAeq6065=LAeq(find(LAeq>60 & LAeq<65));
RespLAeq6065=Resp(find(LAeq>60 & LAeq<65));

LAeq6570=LAeq(find(LAeq>65 & LAeq<70));
RespLAeq6570=Resp(find(LAeq>65 & LAeq<70));

LAeq7075=LAeq(find(LAeq>70 & LAeq<75));
RespLAeq7075=Resp(find(LAeq>70 & LAeq<75));

LAeq7580=LAeq(find(LAeq>75 & LAeq<80));
RespLAeq7580=Resp(find(LAeq>75 & LAeq<80));

LAeq8085=LAeq(find(LAeq>80 & LAeq<85));
RespLAeq8085=Resp(find(LAeq>80 & LAeq<85));

LAeq8590=LAeq(find(LAeq>85 & LAeq<90));
RespLAeq8590=Resp(find(LAeq>85 & LAeq<90));

LAeq9095=LAeq(find(LAeq>90 & LAeq<95));
RespLAeq9095=Resp(find(LAeq>90 & LAeq<95));

LAeq95100=LAeq(find(LAeq>95 & LAeq<100));
RespLAeq95100=Resp(find(LAeq>95 & LAeq<100));

LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
```

```
RespLAeq100105=Resp(find(LAeq>100105 & LAeq<100105));

LAeq105=LAeq(find(LAeq>105));
RespLAeq105=Resp(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
LAeq4550Mean=nanmean(LAeq4550);
LAeq5055Mean=nanmean(LAeq5055);
LAeq5560Mean=nanmean(LAeq5560);
LAeq6065Mean=nanmean(LAeq6065);
LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);

RespLAeq3035Mean=nanmean(RespLAeq3035);
RespLAeq3540Mean=nanmean(RespLAeq3540);
RespLAeq4045Mean=nanmean(RespLAeq4045);
RespLAeq4550Mean=nanmean(RespLAeq4550);
RespLAeq5055Mean=nanmean(RespLAeq5055);
RespLAeq5560Mean=nanmean(RespLAeq5560);
RespLAeq6065Mean=nanmean(RespLAeq6065);
RespLAeq6570Mean=nanmean(RespLAeq6570);
RespLAeq7075Mean=nanmean(RespLAeq7075);
RespLAeq7580Mean=nanmean(RespLAeq7580);
RespLAeq8085Mean=nanmean(RespLAeq8085);
RespLAeq8590Mean=nanmean(RespLAeq8590);
RespLAeq9095Mean=nanmean(RespLAeq9095);
RespLAeq95100Mean=nanmean(RespLAeq95100);
RespLAeq100105Mean=nanmean(RespLAeq100105);
RespLAeq105Mean=nanmean(RespLAeq105);

LAeqRespWeight=[length(LAeq3035) length(LAeq3540) length(LAeq4045)
length(LAeq4550) length(LAeq5055) length(LAeq5560) length(LAeq6065)
length(LAeq6570) length(LAeq7075) length(LAeq7580) length(LAeq8085)
length(LAeq8590) length(LAeq9095) length(LAeq95100) length(LAeq100105)
length(LAeq105)]

LAeqCluster=[LAeq3035Mean LAeq3540Mean LAeq4045Mean LAeq4550Mean
LAeq5055Mean LAeq5560Mean LAeq6065Mean LAeq6570Mean LAeq7075Mean
LAeq7580Mean LAeq8085Mean LAeq8590Mean LAeq9095Mean LAeq95100Mean
LAeq100105Mean LAeq105Mean];
RespLAeqCluster=[RespLAeq3035Mean RespLAeq3540Mean RespLAeq4045Mean
RespLAeq4550Mean RespLAeq5055Mean RespLAeq5560Mean RespLAeq6065Mean
RespLAeq6570Mean RespLAeq7075Mean RespLAeq7580Mean RespLAeq8085Mean
RespLAeq8590Mean RespLAeq9095Mean RespLAeq95100Mean RespLAeq100105Mean
RespLAeq105Mean];

figure(6)
```

```
scatter(LAeqCluster, RespLAeqCluster)
xlabel('LAeq')
ylabel('Resp')
title('Cluster scatter of means at specified ranges between LAeq and
Resp')
```

APPENDIX C – DELAYED CORRELATIONS RESULTS

This section details the correlations between patient physiological response and sound level metric. The sound level metrics were delayed by 1, 2, 3, 4 and 5 minutes to see if there were changes in correlation due to a delayed physiological response. For this reason, an additional set of correlations are performed to account for a delayed physiological reaction. The same correlation analyses are performed for physiological delays of one, two, three, four and five minutes as shown in Tables 34-38. Interestingly, each table shows the same statistically significant relationships as the non-delayed result in Table 16. The delayed correlation results did not reveal generally better or worse statistical correlation values.

Table 34. Correlations with 1 minute physiological delay

	Heart Rate (beats per minute)	Oxygen Saturation (S_{O2})	Resp. Rate (breaths per minute)	Blood Pressure (Sys.) (mmHG)	Blood Pressure (Dias.) (mmHG)	Blood Pressure (Mean) (mmHG)
L_{Aeq}	--	-0.128	0.203	0.223	0.198	0.219
L_{Amax}	--	-0.104	0.139	0.117	0.125	0.129
L_{Cpk}	--	-0.119	0.122	0.100	0.126	0.124
L_{Amin}	0.120	-0.212	0.253	0.321	0.290	0.305

Table 35. Correlations with 2 minute physiological delay

	Heart Rate (beats per minute)	Oxygen Saturation (S_{O2})	Resp. Rate (breaths per minute)	Blood Pressure (Sys.) (mmHG)	Blood Pressure (Dias.) (mmHG)	Blood Pressure (Mean) (mmHG)
L_{Aeq}	--	-0.137	0.194	0.219	0.194	0.219
L_{Amax}	--	-0.108	0.138	0.113	0.121	0.132
L_{Cpk}	--	-0.113	0.128	0.094	0.119	0.122
L_{Amin}	0.121	-0.217	0.248	0.315	0.286	0.303

Table 36. Correlations with 3 minute physiological delay

	Heart Rate (beats per minute)	Oxygen Saturation (S_{O2})	Resp. Rate (breaths per minute)	Blood Pressure (Sys.) (mmHG)	Blood Pressure (Dias.) (mmHG)	Blood Pressure (Mean) (mmHG)
L_{Aeq}	--	-0.136	0.194	0.217	0.194	0.215
L_{Amax}	--	-0.110-	0.127	0.110	0.121	0.126
L_{Cpk}	--	-0.122	0.116	0.090	0.121	0.117
L_{Amin}	0.119	-0.215	0.247	0.317	0.287	0.304

Table 37. Correlations with 4 minute physiological delay

	Heart Rate (beats per minute)	Oxygen Saturation (S_{O2})	Resp. Rate (breaths per minute)	Blood Pressure (Sys.) (mmHG)	Blood Pressure (Dias.) (mmHG)	Blood Pressure (Mean) (mmHG)
L_{Aeq}	--	-0.137	0.184	0.214	0.191	0.213
L_{Amax}	--	-0.108	0.125	0.106	0.118	0.122
L_{Cpk}	--	-0.123	0.110	0.087	0.114	0.113
L_{Amin}	0.113	-0.211	0.243	0.319	0.289	0.303

Table 38. Correlations with 5 minute physiological delay

	Heart Rate (beats per minute)	Oxygen Saturation (S_{O2})	Resp. Rate (breaths per minute)	Blood Pressure (Sys.) (mmHG)	Blood Pressure (Dias.) (mmHG)	Blood Pressure (Mean) (mmHG)
L_{Aeq}	--	-0.125	0.184	0.215	0.192	0.210
L_{Amax}	--	-0.103	0.120	0.104	0.117	0.117
L_{Cpk}	--	-0.108	0.115	0.088	0.117	0.110
L_{Amin}	0.108	-0.214	0.21	0.318	0.287	0.302

APPENDIX D – LINEAR REGRESSION

The correlations above show that there are statistically significant relationships between acoustics and physiology; however, simple correlation may not provide enough insight. In order to determine more about the nature of the relationships, linear regression is used. This analysis can provide more detailed information—including the slope of the relationship, e.g., how much heart rate changes per increase of 10 dB. Ultimately, the linear regression determines the potentially statistically significant linear relationships between the independent and dependent variables.

For this data set, either the sound level meter metrics or the psychoacoustic values are used as the independent variables, and the physiological measurements are the dependent variable. Statistical significance is calculated for $p<0.05$.

Table 39 shows only the statistically significant relationships—i.e., blank cells indicate that any calculated result was not statistically significant. The outcome of a linear regression provides the linear slope of the relationship per unit increase. In this case, the results are linearly extrapolated for a 3 dB increase rather than 1 dB. 3dB is considered the jnd for sound level changes. As before, all relationship directions are consistent, with oxygen saturation showing a negative slope. Some results specifically show that as L_{Aeq} increases by 3 dB, oxygen saturation can drop 0.2%, respiratory rate increase by nearly 0.5 breaths per min, systolic blood pressure elevates by approximately 3.7 mmHg, diastolic blood pressure rises by 1.6 mmHg, and average blood pressure increases by 2.5 mmHg.

Table 39. Linear regression relationships between physiological measurements and sound level meter metrics

Variable Pair		**Slope for 3 dB**
Heart Rate (beats per minute)	L_{Aeq}	
	L_{Amin}	2.3
	L_{Amax}	
	L_{Cpk}	0.3
Oxygen Saturation (S_{O2})	L_{Aeq}	-0.2
	L_{Amin}	-0.6
	L_{Amax}	-0.1
	L_{Cpk}	-0.1
Respiratory Rate (breaths per minute)	L_{Aeq}	0.5
	L_{Amin}	
	L_{Amax}	0.3
	L_{Cpk}	3.0
Systolic Blood Pressure (mmHg)	L_{Aeq}	3.7
	L_{Amin}	
	L_{Amax}	1.3
	L_{Cpk}	1.2
Diastolic Blood Pressure (mmHg)	L_{Aeq}	1.6
	L_{Amin}	
	L_{Amax}	0.7
	L_{Cpk}	0.8

Average Blood Pressure (mmHg)	L_{Aeq}	2.5
	L_{Amin}	
	L_{Amax}	0.9
	L_{Cpk}	1.0

Table 40. Linear regression relationships between physiological measurements and psychoacoustic metrics

Variable Pair		**Slope for 1 jnd**
Heart Rate (beats per minute)	SIL (dB)	0.73
	Loudness (sones)	0.90
	Sharpness (acums)	1.11
	Fluctuation Strength (vacils)	0.49
	Roughness (aspers)	0.23
Oxygen Saturation (S_{O2})	SIL (dB)	
	Loudness (sones)	
	Sharpness (acums)	0.04
	Fluctuation Strength (vacils)	
	Roughness (aspers)	-0.05
Respiratory	SIL (dB)	0.41

Rate (breaths per minute)	Loudness (sones)	0.59
	Sharpness (acums)	0.51
	Fluctuation Strength (vacils)	0.55
	Roughness (aspers)	0.18
Systolic Blood Pressure (mmHg)	SIL (dB)	1.51
	Loudness (sones)	1.54
	Sharpness (acums)	1.58
	Fluctuation Strength (vacils)	2.37
	Roughness (aspers)	0.52
Diastolic Blood Pressure (mmHg)	SIL (dB)	0.96
	Loudness (sones)	0.98
	Sharpness (acums)	0.46
	Fluctuation Strength (vacils)	1.12
	Roughness (aspers)	0.25
Average Blood Pressure (mmHg)	SIL (dB)	1.19
	Loudness (sones)	1.16
	Sharpness (acums)	0.90
	Fluctuation Strength (vacils)	1.84
	Roughness (aspers)	0.34

Table 41. Just noticeable differences for psychoacoustic metrics

Psychoacoustic Metric	Just Noticeable Difference
SIL	1 dB
Loudness	0.5 sones
Sharpness	0.08 acums
Fluctuation Strength	0.012 vacils
Roughness	0.04 aspers

For the psychoacoustic linear regressions, seen in Table 40, only results that are statistically significant (*p*<0.05) are reported again. Cells left blank represent a result that is not significant. The slopes are normalized to one just noticeable difference (jnd) change in psychoacoustic metric. The jnds were determined from the refrigeration noise study (You and Jeon 2007) as described in Chapter 2. The jnds used are listed in Table 41 for reference.

The linear regression results show that for one jnd change in the psychoacoustic metrics, heart rate increased by 0.2 to 1.1 bpm; respiratory rate increased by 0.2 to 0.6 breaths/min, systolic blood pressure increased by 0.5 to 2.4 mmHg, diastolic blood pressure increased by 0.3 to 1.1 mmHg, and average blood pressure increased by 0.3 to 1.8 mmHg. Throughout the results, it appears that SIL and loudness provide similar results and track each other well. For respiratory rate, aside from roughness, the other four metrics consistently show approximately 0.4-0.6 breath/min change. Systolic blood pressure rises about 1.5-1.6 mmHg for one jnd increase for SIL, loudness and sharpness.

For the entire data set, it seems that physiological response is least sensitive to roughness, as it provides the smallest slope (or change in physiological response per psychoacoustic jnd). However, fluctuation strength provides the highest sensitivity for all three blood pressure parameters. This may be of particular interest because roughness and fluctuation strength are both temporal amplitude metrics, with roughness calibrated to a higher modulation frequency. This data suggests that blood pressure is affected more by low frequency modulation temporal changes rather than higher frequency modulation changes.

APPENDIX E – CURVE ESTIMATION

The linear regression, as its name indicates, attempts to fit a linear line to the data. However, relationships in the data may or may not be related in a linear fashion. Other relationship such as quadratic, logarithmic, or power relationships may better describe the trends in the data. For this reason, curve estimation is used to determine if these other types of relationships are more effective than simple linear regression.

These different curve estimation equations were calculated to see which held the highest statistical significance for each physiological measurement. These different estimation models gave a greater flexibility on ways to calculate predicted physiological values if only the acoustics of a room are known. The models used for comparison were logarithmic, inverse, quadratic, cubic, compound, power, s-curve, growth, exponential, and logistic. The equations for each of them are given in the table in Chapter 2 and copied again in Table 42 for quick reference.

Statistical significance was calculated for each of these models with each physiological metric. Table 43 below shows the percentage of the total number of analyses that are statistically significant, and specifically how many of the different models were significant for each different physiological measurement.

The models with the best statistical significance percentages were the compound and the logistical model, each with 100% of the results being significant across all physiological parameters. These models were also the only models statistically significant with more than 25% of the heart rate metrics. When plugging in values to test the coefficients, all of the models are consistently close.

Table 42. Equations for curve estimation models

Statistical Model	**Equation**
Logarithmic	$E(Y_t) = \beta_0 + \beta_1 \ln(t)$
Inverse	$E(Y_t) = \beta_0 + \dfrac{\beta_1}{t}$
Quadratic	$E(Y_t) = \beta_0 + \beta_1 t + \beta_2 t^2$
Cubic	$E(Y_t) = \beta_0 + \beta_1 t + \beta_2 t^2 + \beta_3 t^3$
Compound	$E(Y_t) = \beta_0 {\beta_1}^t$
Power	$E(Y_t) = \beta_0 t^{\beta_1}$
S	$E(Y_t) = \exp\left(\beta_0 + \dfrac{\beta_1}{t}\right)$
Growth	$E(Y_t) = \exp\,(\beta_0 + \beta_1 t)$
Exponential	$E(Y_t) = \beta_0 e^{\beta_1 t}$
Logistic	$E(Y_t) = \left(\dfrac{1}{u} + \beta_0 {\beta_1}^t\right)$

Table 43. Statistical significance percentages for curve estimation

	Log	Inverse	Quadratic	Cubic	Compound	Power	S-Curve	Growth	Exp	Logistic
Total %	66.7%	87.5%	66.7%	66.7%	100%	87.5%	87.5%	87.5%	87.5%	100%
Blood Pressure	58.3%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Heart Rate	25%	25%	25%	25%	100%	25%	25%	25%	25%	100%
Resp Rate	100%	100%	25%	25%	100%	100%	100%	100%	100%	100%
Oxygen Saturation	100%	100%	50%	50%	100%	100%	100%	100%	100%	100%

The coefficients of β included in Table 44 are for the logarithmic, inverse, and quadratic equations. The results for the other variables can be found in Appendix B. These coefficients can be plugged into the equations above and a physiological measurement can be predicted based on the given acoustical data. The only values of coefficients that are given are those that are statistically significant to less than $p<0.05$. This ensures that only the statistically significant equations will be calculated. The ** value in the table means that that coefficient is not statistically significant. Please note that DiasBP refers to diastolic blood pressure, AvgBP corresponds to average blood pressure, SysBP is systolic blood pressure, HR is abbreviated for heart rate, Resp is short for respiratory rate, and SPO2 refers to oxygen saturation.

Table 44. Coefficients for Curve Estimation

*Note: diasBP = diastolic blood pressure, sysBP = systolic blood pressure, avgBP = average blood pressure, HR = heart rate, Resp = respiratory rate, and SPO2 = oxygen saturation.

Relationship*	**Logarithmic**		**Inverse**		**Quadratic**		
Coefficient	β_1	β_0	β_1	β_0	β_1	β_2	β_0
DiasBP vs. LAeq	22.3	-24.3	-834.9	79.8	-3.6	0.0	133.0
DiasBP vs. LAmax		**	-576.4	72.2	-1.3	0.0	9.3
DiasBP vs. LAmin	58.9	-136.5	-2032.3	109.7	-7.1	0.1	183.1
DiasBP vs.		**	-1351.3	79.7	-1.6	0.0	113.4

LCpk							
AvgBP vs. LAeq	35.1	-53.4	-1358.1	111.1	-4.5	0.1	165.5
AvgBP vs. LAmax		**	-84.6	97.3	-1.4	0.0	115.3
AvgBP vs. LAmin	76.4	-204.3	-2879.0	150.2	-13.9	0.2	335.1
AvgBP vs. LCpk		**	-1777.9	105.7	-1.9	0.0	143.4
SysBP vs. LAeq	53.4	-85.5	-2122.8	166.2	-5.3	0.1	213.9
SysBP vs. LAmax		**	-1256.1	143.4	-1.4	0.0	149.0
SysBP vs. LAmin	116.6	-316.0	-4366.7	224.5	-23.4	0.3	553.6
SysBP vs. LCpk	31.6	-15.6	-2304.5	151.8	-2.4	0.0	199.5
HR vs. LAeq	**		**		**	**	
HR vs. LAmax	**		**		**	**	
HR vs. LAmin	33.3	-33.7	-1364.4	123.5	4.7	0.0	-24.9
HR vs. LCpk	**		**		**	**	
Resp. vs. LAeq	11.5	-25.7	-559.4	30.4	**	**	**
Resp. vs. LAmax	6.7	-8.8	-395.5	25.4	**	**	**
Resp. vs. LAmin	18.0	-48.5	-769.7	37.3	3.5	0.0	-63.0
Resp. vs. LCpk	8.5	-18.2	-669.9	27.5	**	**	**
SP02 vs. LAeq	-3.6	110.9	157.9	93.5		**	

SP02 vs. LAmax	-2.4	106.6	133.4	94.5	**	**	
SP02 vs. LAmin	-9.7	133.3	400.3	87.3	-1.2	0.0	126.8
SP02 vs. LCpk	-3.9	113.8	305.4	92.9	-0.3	0.0	109.3

Relationship	**Logarithmic**		**Inverse**		**Quadratic**		
Coefficient	β_1	β_0	β_1	β_0	β_1	β_2	β_0
diasBP vs. LAeq	22.307	-24.256	-834.85	79.774	-3.621	0.044	132.99
diasBP vs. LAFmax		**	-576.351	72.159	-1.332	0.013	9.273
diasBP vs. LAmin	58.858	-136.548	-2032.28	109.739	-7.055	0.098	183.126
diasBP vs. LCpk		**	-1351.31	79.716	-1.554	0.011	113.447
avgBP vs. LAeq	35.058	-53.378	-1358.15	111.077	-4.46	0.056	165.548
avgBP vs. LAmax		**	-84.63	97.251	-1.44	0.015	115.262
avgBP vs. LAmin	76.373	-204.324	-2879.03	150.2	-13.894	0.185	335.081
avgBP vs. LCpk		**	-1777.85	105.677	-1.868	0.014	143.441
sysBP vs. LAeq	53.446	-85.52	-2122.84	166.245	-5.309	0.069	213.877
sysBP vs. LAmax		**	-1256.09	143.41	-1.389	0.015	149.001
sysBP vs. LAmin	116.56	-315.974	-4366.69	224.46	-23.366	0.308	553.567
sysBP vs. LCpk	31.582	-15.577	-2304.54	151.787	-2.39	0.018	199.452
HR vs. LAeq	**		**		**	**	
HR vs.LAmax	**		**		**	**	
HR vs. LAmin	33.346	-33.725	-1364.44	123.535	4.709	-0.046	-24.853
HR vs. LCpk	**		**		**	**	
Resp. vs. LAeq	11.465	-25.72	-559.388	30.373	**	**	**
Resp. vs. LAmax	6.726	-8.754	-395.459	25.442	**	**	**
Resp. vs. LAmin	18.033	-48.504	-769.722	37.298	3.487	-0.036	-62.964
Resp. vs. LCpk	8.496	-18.194	-669.937	27.452	**	**	**
%SP02 vs. LAeq	-3.632	110.854	157.86	93.468		**	
%SP02 vs. LAmax	-2.393	106.564	133.383	94.511	**	**	
%SP02 vs. LAmin	-9.729	133.261	400.266	87.327	-1.187	0.011	126.781
%SP02 vs. LCpk	-3.915	113.849	305.406	92.854	-0.269	0.001	109.279

Relationship	**Cubic**			**Compound**		**Power**	
Coefficient	β_1	β_3	β_0	β_1	β_0	β_1	β_0
diasBP vs. LAeq	-1.468	0	98.574	1.008	41.437	0.309	18.223
diasBP vs. LAFmax	-0.503	6.56E-05	77.107	1.003	49.589	0.167	30.492
diasBP vs. LAmin	-2.549	0.001	115.129	1.02	26.037	0.773	3.29
diasBP vs. LCpk	-0.627	4.58E-05	88.543	1.004	45.463	0.268	18.822
avgBP vs. LAeq	-1.749	0	122.602	1.009	52.365	0.355	20.14
avgBP vs. LAmax	-0.526	7.56E-05	96.564	1.003	65.739	0.17	39.956
avgBP vs. LAmin	-5.425	0.001	208.049	1.021	35.591	0.809	3.816
avgBP vs. LCpk	-0.761	5.64E-05	114.138	1.003	61.75	0.245	27.564
sysBP vs. LAeq	-1.984	0	161.751	1.009	76.123	0.376	27.459
sysBP vs. LAmax	-0.471	8.19E-05	131.016	1.003	97.904	0.166	59.779
sysBP vs. LAmin	-9.207	0.002	339.981	1.022	46.713	0.83	5.215
sysBP vs. LCpk	-0.013	0.00E+00	137.875	1.003	94.249	0.213	46.741
HR vs. LAeq	**	**		1	88.816	**	
HR vs.LAmax	**	**		1	86.835	**	
HR vs. LAmin	3.016	0	-5.084	1.009	60.88	0.372	21.986
HR vs. LCpk	**	**		1.001	84.264	**	
Resp. vs. LAeq	**	**	**	1.014	9.314	0.674	1.316
Resp. vs. LAmax	**	**		1.006	12.353	0.375	3.875
Resp. vs. LAmin	3.847	-0.036	-62.946	1.027	5.903	1.159	0.238
Resp. vs. LCpk	**	**	**	1.006	11.057	0.5	2.041
%SP02 vs. LAeq		**		0.999	100.662	-0.038	112.092
%SP02 vs. LAmax		**		1	99.26	-0.025	17.243
%SP02 vs. LAmin	-0.752	9.50E-05	121.318	0.998	106.909	-0.1	140.92
%SP02 vs. LCpk	-0.162	5.89E-04	106.546	0.999	100.717	-0.041	115.712

Relationship	**S**		**Growth**		**Exponential**		**Logistic**	
Coefficient	β_1	β_0	β_1	β_0	β_1		β_1	β_0
diasBP vs. LAeq	-11.252	4.337	0.008	3.724	0.008	41.437	0.992	0.024
diasBP vs. LAmax	-7.782	4.235	0.003	3.904	0.003	49.589	0.997	0.02
diasBP vs. LAmin	-29.695	4.739	0.019	3.26	0.019	26.037	0.981	0.038
diasBP vs. LCpk	-19.132	4.348	0.004	3.817	0.004	45.463	0.996	0.022
avgBP vs. LAeq	-13.456	4.663	0.009	3.958	0.009	52.365	0.991	0.019
avgBP vs. LAmax	-8.195	4.522	0.003	4.186	0.003	65.739	0.997	0.015
avgBP vs. LAmin	-30.283	5.09	0.021	3.484	0.021	35.591	0.979	0.031
avgBP vs. LCpk	-17.568	4.609	0.003	4.123	0.003	61.75	0.997	0.016
sysBP vs. LAeq	-14.676	5.077	0.009	4.332	0.009	76.123	0.991	0.013
sysBP vs. LAmax	-8.398	4.914	0.003	4.584	0.003	79.904	0.997	0.01
sysBP vs. LAmin	-30.758	5.491	0.022	3.844	0.022	46.713	0.979	0.021
sysBP vs. LCpk	-15.323	4.969	0.003	4.546	0.003	94.249	0.997	0.011
HR vs. LAeq	**		**		**		1	0.011
HR vs.LAmax	**		**		**		1	0.012
HR vs. LAmin	-14.981	4.84	0.009	4.109	0.009	60.88	0.991	0.016
HR vs. LCpk	**		**		**		0.999	0.012
Resp. vs. LAeq	-33.026	3.574	0.014	2.232	0.014	9.314	0.987	0.107
Resp. vs. LAmax	-21.9	3.26	0.006	2.514	0.006	12.353	0.994	0.081
Resp. vs. LAmin	-49.643	4.083	0.027	1.175	0.027	5.903	0.947	0.169
Resp. vs. LCpk	-39.372	3.399	0.006	2.403	0.006	11.057	0.994	0.09
%SP02 vs. LAeq	1.654	4.537	0	4.612	0	100.662	1.001	0.01
%SP02 vs. LAmax	1.046	4.548	0	4.598	0	99.26	1	0.01
%SP02 vs. LAmin	4.129	4.474	-0.002	4.672	-0.002	106.909	1.002	0.009
%SP02 vs. LCpk	3.206	4.531	0	4.612	0	100.717	1.001	0.01

APPENDIX F – RISK RATIO MATLAB CODE

```
clear all
close all
clc

alpha=1.645;
[data,names]=xlsread('HospDataWithNoIDNoAlarm.xls'); names=names(1,:);
Time=data(:,1); HF=data(:,2); SPO2=data(:,3); Resp=data(:,4);
ArtSys=data(:,5);
ArtDias=data(:,6); ArtMedel=data(:,7); LAeq=data(:,8);
LAFmax=data(:,9); LCpk=data(:,10); LAFmin=data(:,11);

%LAeq vs HF
LAeq3035=LAeq(find(LAeq>30 & LAeq<35)); HFLAeq3035=HF(find(LAeq>30 &
LAeq<35));
LAeq3540=LAeq(find(LAeq>35 & LAeq<40)); HFLAeq3540=HF(find(LAeq>35 &
LAeq<40));
LAeq4045=LAeq(find(LAeq>40 & LAeq<45)); HFLAeq4045=HF(find(LAeq>40 &
LAeq<45));
LAeq4550=LAeq(find(LAeq>45 & LAeq<50)); HFLAeq4550=HF(find(LAeq>45 &
LAeq<50));
LAeq5055=LAeq(find(LAeq>50 & LAeq<55)); HFLAeq5055=HF(find(LAeq>50 &
LAeq<55));
LAeq5560=LAeq(find(LAeq>55 & LAeq<60)); HFLAeq5560=HF(find(LAeq>55 &
LAeq<60));
LAeq6065=LAeq(find(LAeq>60 & LAeq<65)); HFLAeq6065=HF(find(LAeq>60 &
LAeq<65));
LAeq6570=LAeq(find(LAeq>65 & LAeq<70)); HFLAeq6570=HF(find(LAeq>65 &
LAeq<70));
LAeq7075=LAeq(find(LAeq>70 & LAeq<75)); HFLAeq7075=HF(find(LAeq>70 &
LAeq<75));
LAeq7580=LAeq(find(LAeq>75 & LAeq<80)); HFLAeq7580=HF(find(LAeq>75 &
LAeq<80));
LAeq8085=LAeq(find(LAeq>80 & LAeq<85)); HFLAeq8085=HF(find(LAeq>80 &
LAeq<85));
LAeq8590=LAeq(find(LAeq>85 & LAeq<90)); HFLAeq8590=HF(find(LAeq>85 &
LAeq<90));
LAeq9095=LAeq(find(LAeq>90 & LAeq<95)); HFLAeq9095=HF(find(LAeq>90 &
LAeq<95));
LAeq95100=LAeq(find(LAeq>95 & LAeq<100)); HFLAeq95100=HF(find(LAeq>95 &
LAeq<100));
LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
HFLAeq100105=HF(find(LAeq>100105 & LAeq<100105));
LAeq105=LAeq(find(LAeq>105)); HFLAeq105=HF(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
LAeq4550Mean=nanmean(LAeq4550);
LAeq5055Mean=nanmean(LAeq5055);
LAeq5560Mean=nanmean(LAeq5560);
LAeq6065Mean=nanmean(LAeq6065);
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LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);

HFLAeq3035Mean=nanmean(HFLAeq3035);
HFLAeq3540Mean=nanmean(HFLAeq3540);
HFLAeq4045Mean=nanmean(HFLAeq4045);
HFLAeq4550Mean=nanmean(HFLAeq4550);
HFLAeq5055Mean=nanmean(HFLAeq5055);
HFLAeq5560Mean=nanmean(HFLAeq5560);
HFLAeq6065Mean=nanmean(HFLAeq6065);
HFLAeq6570Mean=nanmean(HFLAeq6570);
HFLAeq7075Mean=nanmean(HFLAeq7075);
HFLAeq7580Mean=nanmean(HFLAeq7580);
HFLAeq8085Mean=nanmean(HFLAeq8085);
HFLAeq8590Mean=nanmean(HFLAeq8590);
HFLAeq9095Mean=nanmean(HFLAeq9095);
HFLAeq95100Mean=nanmean(HFLAeq95100);
HFLAeq100105Mean=nanmean(HFLAeq100105);
HFLAeq105Mean=nanmean(HFLAeq105);

LengthLAeq3035=length(LAeq3035);
LengthLAeq3540=length(LAeq3540);
LengthLAeq4045=length(LAeq4045);
LengthLAeq4550=length(LAeq4550);
LengthLAeq5055=length(LAeq5055);
LengthLAeq5560=length(LAeq5560);
LengthLAeq6065=length(LAeq6065);
LengthLAeq6570=length(LAeq6570);
LengthLAeq7075=length(LAeq7075);
LengthLAeq7580=length(LAeq7580);
LengthLAeq8085=length(LAeq8085);
LengthLAeq8590=length(LAeq8590);
LengthLAeq9095=length(LAeq9095);
LengthLAeq95100=length(LAeq95100);
LengthLAeq100105=length(LAeq100105);
LengthLAeq105=length(LAeq105);

LengthHFLAeq3035=length(find(HFLAeq3035>HFLAeq3035Mean));
LengthHFLAeq3540=length(find(HFLAeq3540>HFLAeq3540Mean));
LengthHFLAeq4045=length(find(HFLAeq4045>HFLAeq4045Mean));
LengthHFLAeq4550=length(find(HFLAeq4550>HFLAeq4550Mean));
LengthHFLAeq5055=length(find(HFLAeq5055>HFLAeq5055Mean));
LengthHFLAeq5560=length(find(HFLAeq5560>HFLAeq5560Mean));
LengthHFLAeq6065=length(find(HFLAeq6065>HFLAeq6065Mean));
LengthHFLAeq6570=length(find(HFLAeq6570>HFLAeq6570Mean));
LengthHFLAeq7075=length(find(HFLAeq7075>HFLAeq7075Mean));
LengthHFLAeq7580=length(find(HFLAeq7580>HFLAeq7580Mean));
LengthHFLAeq8085=length(find(HFLAeq8085>HFLAeq8085Mean));
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LengthHFLAeq8590=length(find(HFLAeq8590>HFLAeq8590Mean));
LengthHFLAeq9095=length(find(HFLAeq9095>HFLAeq9095Mean));
LengthHFLAeq95100=length(find(HFLAeq95100>HFLAeq95100Mean));
LengthHFLAeq100105=length(find(HFLAeq100105>HFLAeq100105Mean));
LengthHFLAeq105=length(find(HFLAeq105>HFLAeq105Mean));


LAeqHFRiskRatio3035to3540=length(find(HFLAeq3540>HFLAeq3035Mean))/Lengt
hHFLAeq3540/(LengthHFLAeq3035/LengthLAeq3035)
se3035to3035=alpha*sqrt(((1-
LengthHFLAeq3035/LengthLAeq3035)/LengthHFLAeq3035)+(1-
length(find(HFLAeq3540>HFLAeq3035Mean))/LengthHFLAeq3540/length(find(HF
LAeq3540>HFLAeq3035Mean))));
confidence3035to3540=[exp(log(LAeqHFRiskRatio3035to3540)-se3035to3035)
exp(log(LAeqHFRiskRatio3035to3540+se3035to3035))]

LAeqHFRiskRatio3540to4045=length(find(HFLAeq4045>HFLAeq3540Mean))/Lengt
hHFLAeq4045/(LengthHFLAeq3540/LengthLAeq3540)
se3540to4045=alpha*sqrt(((1-
LengthHFLAeq3540/LengthLAeq3540)/LengthHFLAeq3540)+(1-
length(find(HFLAeq4045>HFLAeq3540Mean))/LengthHFLAeq4045/length(find(HF
LAeq4045>HFLAeq3540Mean))));
confidence3540to4045=[exp(log(LAeqHFRiskRatio3540to4045)-se3540to4045)
exp(log(LAeqHFRiskRatio3540to4045+se3540to4045))]

LAeqHFRiskRatio4045to4550=length(find(HFLAeq4550>HFLAeq4045Mean))/Lengt
hHFLAeq4550/(LengthHFLAeq4045/LengthLAeq4045)
se4045to4550=alpha*sqrt(((1-
LengthHFLAeq4045/LengthLAeq4045)/LengthHFLAeq4045)+(1-
length(find(HFLAeq4550>HFLAeq4045Mean))/LengthHFLAeq4550/length(find(HF
LAeq4550>HFLAeq4045Mean))));
confidence4045to4550=[exp(log(LAeqHFRiskRatio4045to4550)-se4045to4550)
exp(log(LAeqHFRiskRatio4045to4550+se4045to4550))]

LAeqHFRiskRatio4550to5055=length(find(HFLAeq5055>HFLAeq4550Mean))/Lengt
hHFLAeq5055/(LengthHFLAeq4550/LengthLAeq4550)
se4550to5055=alpha*sqrt(((1-
LengthHFLAeq4550/LengthLAeq4550)/LengthHFLAeq4550)+(1-
length(find(HFLAeq5055>HFLAeq4550Mean))/LengthHFLAeq5055/length(find(HF
LAeq5055>HFLAeq4550Mean))));
confidence4550to5055=[exp(log(LAeqHFRiskRatio4550to5055)-se4550to5055)
exp(log(LAeqHFRiskRatio4550to5055+se4550to5055))]

LAeqHFRiskRatio5055to5560=length(find(HFLAeq5560>HFLAeq5055Mean))/Lengt
hHFLAeq5560/(LengthHFLAeq5055/LengthLAeq5055)
se5055to5560=alpha*sqrt(((1-
LengthHFLAeq5055/LengthLAeq5055)/LengthHFLAeq5055)+(1-
length(find(HFLAeq5560>HFLAeq5055Mean))/LengthHFLAeq5560/length(find(HF
LAeq5560>HFLAeq5055Mean))));
confidence5055to5560=[exp(log(LAeqHFRiskRatio5055to5560)-se5055to5560)
exp(log(LAeqHFRiskRatio5055to5560+se5055to5560))]

LAeqHFRiskRatio5560to6065=length(find(HFLAeq6065>HFLAeq5560Mean))/Lengt
hHFLAeq6065/(LengthHFLAeq5560/LengthLAeq5560)
```

```
se5560to6065=alpha*sqrt(((1-
LengthHFLAeq5560/LengthLAeq5560)/LengthHFLAeq5560)+(1-
length(find(HFLAeq6065>HFLAeq5560Mean))/LengthHFLAeq6065/length(find(HF
LAeq6065>HFLAeq5560Mean))));
confidence5560to6065=[exp(log(LAeqHFRiskRatio5560to6065)-se5560to6065)
exp(log(LAeqHFRiskRatio5560to6065+se5560to6065))]

LAeqHFRiskRatio6065to6570=length(find(HFLAeq6570>HFLAeq6065Mean))/Lengt
hHFLAeq6570/(LengthHFLAeq6065/LengthLAeq6065)
se6065to6570=alpha*sqrt(((1-
LengthHFLAeq6065/LengthLAeq6065)/LengthHFLAeq6065)+(1-
length(find(HFLAeq6570>HFLAeq6065Mean))/LengthHFLAeq6570/length(find(HF
LAeq6570>HFLAeq6065Mean))));
confidence6065to6570=[exp(log(LAeqHFRiskRatio6065to6570)-se6065to6570)
exp(log(LAeqHFRiskRatio6065to6570+se6065to6570))]

LAeqHFRiskRatio6570to7075=length(find(HFLAeq7075>HFLAeq6570Mean))/Lengt
hHFLAeq7075/(LengthHFLAeq6570/LengthLAeq6570)
se6570to7075=alpha*sqrt(((1-
LengthHFLAeq6570/LengthLAeq6570)/LengthHFLAeq6570)+(1-
length(find(HFLAeq7075>HFLAeq6570Mean))/LengthHFLAeq7075/length(find(HF
LAeq7075>HFLAeq6570Mean))));
confidence6570to7075=[exp(log(LAeqHFRiskRatio6570to7075)-se6570to7075)
exp(log(LAeqHFRiskRatio6570to7075+se6570to7075))]

LAeqHFRiskRatio7075to7580=length(find(HFLAeq7580>HFLAeq7075Mean))/Lengt
hHFLAeq7580/(LengthHFLAeq7075/LengthLAeq7075)
se7075to7580=alpha*sqrt(((1-
LengthHFLAeq7075/LengthLAeq7075)/LengthHFLAeq7075)+(1-
length(find(HFLAeq7580>HFLAeq7075Mean))/LengthHFLAeq7580/length(find(HF
LAeq7580>HFLAeq7075Mean))));
confidence7075to7580=[exp(log(LAeqHFRiskRatio7075to7580)-se7075to7580)
exp(log(LAeqHFRiskRatio7075to7580+se7075to7580))]

LAeqHFRiskRatio7580to8085=length(find(HFLAeq8085>HFLAeq7580Mean))/Lengt
hHFLAeq8085/(LengthHFLAeq7580/LengthLAeq7580)
se7580to8085=alpha*sqrt(((1-
LengthHFLAeq7580/LengthLAeq7580)/LengthHFLAeq7580)+(1-
length(find(HFLAeq8085>HFLAeq7580Mean))/LengthHFLAeq8085/length(find(HF
LAeq8085>HFLAeq7580Mean))));
confidence7580to8085=[exp(log(LAeqHFRiskRatio7580to8085)-se7580to8085)
exp(log(LAeqHFRiskRatio7580to8085+se7580to8085))]

LAeqHFRiskRatio8085to8590=length(find(HFLAeq8590>HFLAeq8085Mean))/Lengt
hHFLAeq8590/(LengthHFLAeq8085/LengthLAeq8085)
se8085to8590=alpha*sqrt(((1-
LengthHFLAeq8085/LengthLAeq8085)/LengthHFLAeq8085)+(1-
length(find(HFLAeq8590>HFLAeq8085Mean))/LengthHFLAeq8590/length(find(HF
LAeq8590>HFLAeq8085Mean))));
confidence8085to8590=[exp(log(LAeqHFRiskRatio8085to8590)-se8085to8590)
exp(log(LAeqHFRiskRatio8085to8590+se8085to8590))]

LAeqHFRiskRatio8590to9095=length(find(HFLAeq9095>HFLAeq8590Mean))/Lengt
hHFLAeq9095/(LengthHFLAeq8590/LengthLAeq8590)
```

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se8590to9095=alpha*sqrt(((1-
LengthHFLAeq8590/LengthLAeq8590)/LengthHFLAeq8590)+(1-
length(find(HFLAeq9095>HFLAeq8590Mean))/LengthHFLAeq9095/length(find(HF
LAeq9095>HFLAeq8590Mean))));
confidence8590to9095=[exp(log(LAeqHFRiskRatio8590to9095)-se8590to9095)
exp(log(LAeqHFRiskRatio8590to9095+se8590to9095))]

LAeqHFRiskRatio9095to95100=length(find(HFLAeq95100>HFLAeq9095Mean))/Len
gthHFLAeq95100/(LengthHFLAeq9095/LengthLAeq9095)
se9095to95100=alpha*sqrt(((1-
LengthHFLAeq9095/LengthLAeq9095)/LengthHFLAeq9095)+(1-
length(find(HFLAeq95100>HFLAeq9095Mean))/LengthHFLAeq95100/length(find(
HFLAeq95100>HFLAeq9095Mean))));
confidence9095to95100=[exp(log(LAeqHFRiskRatio9095to95100)-
se9095to95100) exp(log(LAeqHFRiskRatio9095to95100+se9095to95100))]

LAeqHFRiskRatio95100to100105=length(find(HFLAeq100105>HFLAeq95100Mean))
/LengthHFLAeq100105/(LengthHFLAeq95100/LengthLAeq95100)
se95100to100105=alpha*sqrt(((1-
LengthHFLAeq95100/LengthLAeq95100)/LengthHFLAeq95100)+(1-
length(find(HFLAeq100105>HFLAeq95100Mean))/LengthHFLAeq100105/length(fi
nd(HFLAeq100105>HFLAeq95100Mean))));
confidence100105to100105=[exp(log(LAeqHFRiskRatio95100to100105)-
se95100to100105)
exp(log(LAeqHFRiskRatio95100to100105+se95100to100105))]

LAeqHFRiskRatio100105to105=length(find(HFLAeq105>HFLAeq100105Mean))/Len
gthHFLAeq105/(LengthHFLAeq100105/LengthLAeq100105)
se100105to105=alpha*sqrt(((1-
LengthHFLAeq100105/LengthLAeq100105)/LengthHFLAeq100105)+(1-
length(find(HFLAeq105>HFLAeq100105Mean))/LengthHFLAeq105/length(find(HF
LAeq105>HFLAeq100105Mean))));
confidence100105to105=[exp(log(LAeqHFRiskRatio100105to105)-
se100105to105) exp(log(LAeqHFRiskRatio100105to105+se100105to105))]


LAeq3035=LAeq(find(LAeq>30 & LAeq<35)); RespLAeq3035=Resp(find(LAeq>30
& LAeq<35));
LAeq3540=LAeq(find(LAeq>35 & LAeq<40)); RespLAeq3540=Resp(find(LAeq>35
& LAeq<40));
LAeq4045=LAeq(find(LAeq>40 & LAeq<45)); RespLAeq4045=Resp(find(LAeq>40
& LAeq<45));
LAeq4550=LAeq(find(LAeq>45 & LAeq<50)); RespLAeq4550=Resp(find(LAeq>45
& LAeq<50));
LAeq5055=LAeq(find(LAeq>50 & LAeq<55)); RespLAeq5055=Resp(find(LAeq>50
& LAeq<55));
LAeq5560=LAeq(find(LAeq>55 & LAeq<60)); RespLAeq5560=Resp(find(LAeq>55
& LAeq<60));
LAeq6065=LAeq(find(LAeq>60 & LAeq<65)); RespLAeq6065=Resp(find(LAeq>60
& LAeq<65));
LAeq6570=LAeq(find(LAeq>65 & LAeq<70)); RespLAeq6570=Resp(find(LAeq>65
& LAeq<70));
LAeq7075=LAeq(find(LAeq>70 & LAeq<75)); RespLAeq7075=Resp(find(LAeq>70
& LAeq<75));
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LAeq7580=LAeq(find(LAeq>75 & LAeq<80)); RespLAeq7580=Resp(find(LAeq>75
& LAeq<80));
LAeq8085=LAeq(find(LAeq>80 & LAeq<85)); RespLAeq8085=Resp(find(LAeq>80
& LAeq<85));
LAeq8590=LAeq(find(LAeq>85 & LAeq<90)); RespLAeq8590=Resp(find(LAeq>85
& LAeq<90));
LAeq9095=LAeq(find(LAeq>90 & LAeq<95)); RespLAeq9095=Resp(find(LAeq>90
& LAeq<95));
LAeq95100=LAeq(find(LAeq>95 & LAeq<100));
RespLAeq95100=Resp(find(LAeq>95 & LAeq<100));
LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
RespLAeq100105=Resp(find(LAeq>100105 & LAeq<100105));
LAeq105=LAeq(find(LAeq>105)); RespLAeq105=Resp(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
LAeq4550Mean=nanmean(LAeq4550);
LAeq5055Mean=nanmean(LAeq5055);
LAeq5560Mean=nanmean(LAeq5560);
LAeq6065Mean=nanmean(LAeq6065);
LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);

RespLAeq3035Mean=nanmean(RespLAeq3035);
RespLAeq3540Mean=nanmean(RespLAeq3540);
RespLAeq4045Mean=nanmean(RespLAeq4045);
RespLAeq4550Mean=nanmean(RespLAeq4550);
RespLAeq5055Mean=nanmean(RespLAeq5055);
RespLAeq5560Mean=nanmean(RespLAeq5560);
RespLAeq6065Mean=nanmean(RespLAeq6065);
RespLAeq6570Mean=nanmean(RespLAeq6570);
RespLAeq7075Mean=nanmean(RespLAeq7075);
RespLAeq7580Mean=nanmean(RespLAeq7580);
RespLAeq8085Mean=nanmean(RespLAeq8085);
RespLAeq8590Mean=nanmean(RespLAeq8590);
RespLAeq9095Mean=nanmean(RespLAeq9095);
RespLAeq95100Mean=nanmean(RespLAeq95100);
RespLAeq100105Mean=nanmean(RespLAeq100105);
RespLAeq105Mean=nanmean(RespLAeq105);

LengthLAeq3035=length(LAeq3035);
LengthLAeq3540=length(LAeq3540);
LengthLAeq4045=length(LAeq4045);
LengthLAeq4550=length(LAeq4550);
LengthLAeq5055=length(LAeq5055);
LengthLAeq5560=length(LAeq5560);
LengthLAeq6065=length(LAeq6065);
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LengthLAeq6570=length(LAeq6570);
LengthLAeq7075=length(LAeq7075);
LengthLAeq7580=length(LAeq7580);
LengthLAeq8085=length(LAeq8085);
LengthLAeq8590=length(LAeq8590);
LengthLAeq9095=length(LAeq9095);
LengthLAeq95100=length(LAeq95100);
LengthLAeq100105=length(LAeq100105);
LengthLAeq105=length(LAeq105);

LengthRespLAeq3035=length(find(RespLAeq3035>RespLAeq3035Mean));
LengthRespLAeq3540=length(find(RespLAeq3540>RespLAeq3540Mean));
LengthRespLAeq4045=length(find(RespLAeq4045>RespLAeq4045Mean));
LengthRespLAeq4550=length(find(RespLAeq4550>RespLAeq4550Mean));
LengthRespLAeq5055=length(find(RespLAeq5055>RespLAeq5055Mean));
LengthRespLAeq5560=length(find(RespLAeq5560>RespLAeq5560Mean));
LengthRespLAeq6065=length(find(RespLAeq6065>RespLAeq6065Mean));
LengthRespLAeq6570=length(find(RespLAeq6570>RespLAeq6570Mean));
LengthRespLAeq7075=length(find(RespLAeq7075>RespLAeq7075Mean));
LengthRespLAeq7580=length(find(RespLAeq7580>RespLAeq7580Mean));
LengthRespLAeq8085=length(find(RespLAeq8085>RespLAeq8085Mean));
LengthRespLAeq8590=length(find(RespLAeq8590>RespLAeq8590Mean));
LengthRespLAeq9095=length(find(RespLAeq9095>RespLAeq9095Mean));
LengthRespLAeq95100=length(find(RespLAeq95100>RespLAeq95100Mean));
LengthRespLAeq100105=length(find(RespLAeq100105>RespLAeq100105Mean));
LengthRespLAeq105=length(find(RespLAeq105>RespLAeq105Mean));


LAeqRespRiskRatio3035to3540=length(find(RespLAeq3540>RespLAeq3035Mean))
/LengthRespLAeq3540/(LengthRespLAeq3035/LengthLAeq3035)
se3035to3035=alpha*sqrt(((1-
LengthRespLAeq3035/LengthLAeq3035)/LengthRespLAeq3035)+(1-
length(find(RespLAeq3540>RespLAeq3035Mean))/LengthRespLAeq3540/length(f
ind(RespLAeq3540>RespLAeq3035Mean))));
confidence3035to3540=[exp(log(LAeqRespRiskRatio3035to3540)-
se3035to3035) exp(log(LAeqRespRiskRatio3035to3540+se3035to3035))]

LAeqRespRiskRatio3540to4045=length(find(RespLAeq4045>RespLAeq3540Mean))
/LengthRespLAeq4045/(LengthRespLAeq3540/LengthLAeq3540)
se3540to4045=alpha*sqrt(((1-
LengthRespLAeq3540/LengthLAeq3540)/LengthRespLAeq3540)+(1-
length(find(RespLAeq4045>RespLAeq3540Mean))/LengthRespLAeq4045/length(f
ind(RespLAeq4045>RespLAeq3540Mean))));
confidence3540to4045=[exp(log(LAeqRespRiskRatio3540to4045)-
se3540to4045) exp(log(LAeqRespRiskRatio3540to4045+se3540to4045))]

LAeqRespRiskRatio4045to4550=length(find(RespLAeq4550>RespLAeq4045Mean))
/LengthRespLAeq4550/(LengthRespLAeq4045/LengthLAeq4045)
se4045to4550=alpha*sqrt(((1-
LengthRespLAeq4045/LengthLAeq4045)/LengthRespLAeq4045)+(1-
length(find(RespLAeq4550>RespLAeq4045Mean))/LengthRespLAeq4550/length(f
ind(RespLAeq4550>RespLAeq4045Mean))));
confidence4045to4550=[exp(log(LAeqRespRiskRatio4045to4550)-
se4045to4550) exp(log(LAeqRespRiskRatio4045to4550+se4045to4550))]
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LAeqRespRiskRatio4550to5055=length(find(RespLAeq5055>RespLAeq4550Mean))
/LengthRespLAeq5055/(LengthRespLAeq4550/LengthLAeq4550)
se4550to5055=alpha*sqrt(((1-
LengthRespLAeq4550/LengthLAeq4550)/LengthRespLAeq4550)+(1-
length(find(RespLAeq5055>RespLAeq4550Mean))/LengthRespLAeq5055/length(f
ind(RespLAeq5055>RespLAeq4550Mean))));
confidence4550to5055=[exp(log(LAeqRespRiskRatio4550to5055)-
se4550to5055) exp(log(LAeqRespRiskRatio4550to5055+se4550to5055))]

LAeqRespRiskRatio5055to5560=length(find(RespLAeq5560>RespLAeq5055Mean))
/LengthRespLAeq5560/(LengthRespLAeq5055/LengthLAeq5055)
se5055to5560=alpha*sqrt(((1-
LengthRespLAeq5055/LengthLAeq5055)/LengthRespLAeq5055)+(1-
length(find(RespLAeq5560>RespLAeq5055Mean))/LengthRespLAeq5560/length(f
ind(RespLAeq5560>RespLAeq5055Mean))));
confidence5055to5560=[exp(log(LAeqRespRiskRatio5055to5560)-
se5055to5560) exp(log(LAeqRespRiskRatio5055to5560+se5055to5560))]

LAeqRespRiskRatio5560to6065=length(find(RespLAeq6065>RespLAeq5560Mean))
/LengthRespLAeq6065/(LengthRespLAeq5560/LengthLAeq5560)
se5560to6065=alpha*sqrt(((1-
LengthRespLAeq5560/LengthLAeq5560)/LengthRespLAeq5560)+(1-
length(find(RespLAeq6065>RespLAeq5560Mean))/LengthRespLAeq6065/length(f
ind(RespLAeq6065>RespLAeq5560Mean))));
confidence5560to6065=[exp(log(LAeqRespRiskRatio5560to6065)-
se5560to6065) exp(log(LAeqRespRiskRatio5560to6065+se5560to6065))]

LAeqRespRiskRatio6065to6570=length(find(RespLAeq6570>RespLAeq6065Mean))
/LengthRespLAeq6570/(LengthRespLAeq6065/LengthLAeq6065)
se6065to6570=alpha*sqrt(((1-
LengthRespLAeq6065/LengthLAeq6065)/LengthRespLAeq6065)+(1-
length(find(RespLAeq6570>RespLAeq6065Mean))/LengthRespLAeq6570/length(f
ind(RespLAeq6570>RespLAeq6065Mean))));
confidence6065to6570=[exp(log(LAeqRespRiskRatio6065to6570)-
se6065to6570) exp(log(LAeqRespRiskRatio6065to6570+se6065to6570))]

LAeqRespRiskRatio6570to7075=length(find(RespLAeq7075>RespLAeq6570Mean))
/LengthRespLAeq7075/(LengthRespLAeq6570/LengthLAeq6570)
se6570to7075=alpha*sqrt(((1-
LengthRespLAeq6570/LengthLAeq6570)/LengthRespLAeq6570)+(1-
length(find(RespLAeq7075>RespLAeq6570Mean))/LengthRespLAeq7075/length(f
ind(RespLAeq7075>RespLAeq6570Mean))));
confidence6570to7075=[exp(log(LAeqRespRiskRatio6570to7075)-
se6570to7075) exp(log(LAeqRespRiskRatio6570to7075+se6570to7075))]

LAeqRespRiskRatio7075to7580=length(find(RespLAeq7580>RespLAeq7075Mean))
/LengthRespLAeq7580/(LengthRespLAeq7075/LengthLAeq7075)
se7075to7580=alpha*sqrt(((1-
LengthRespLAeq7075/LengthLAeq7075)/LengthRespLAeq7075)+(1-
length(find(RespLAeq7580>RespLAeq7075Mean))/LengthRespLAeq7580/length(f
ind(RespLAeq7580>RespLAeq7075Mean))));
confidence7075to7580=[exp(log(LAeqRespRiskRatio7075to7580)-
se7075to7580) exp(log(LAeqRespRiskRatio7075to7580+se7075to7580))]
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LAeqRespRiskRatio7580to8085=length(find(RespLAeq8085>RespLAeq7580Mean))
/LengthRespLAeq8085/(LengthRespLAeq7580/LengthLAeq7580)
se7580to8085=alpha*sqrt(((1-
LengthRespLAeq7580/LengthLAeq7580)/LengthRespLAeq7580)+(1-
length(find(RespLAeq8085>RespLAeq7580Mean))/LengthRespLAeq8085/length(f
ind(RespLAeq8085>RespLAeq7580Mean))));
confidence7580to8085=[exp(log(LAeqRespRiskRatio7580to8085)-
se7580to8085) exp(log(LAeqRespRiskRatio7580to8085+se7580to8085))]

LAeqRespRiskRatio8085to8590=length(find(RespLAeq8590>RespLAeq8085Mean))
/LengthRespLAeq8590/(LengthRespLAeq8085/LengthLAeq8085)
se8085to8590=alpha*sqrt(((1-
LengthRespLAeq8085/LengthLAeq8085)/LengthRespLAeq8085)+(1-
length(find(RespLAeq8590>RespLAeq8085Mean))/LengthRespLAeq8590/length(f
ind(RespLAeq8590>RespLAeq8085Mean))));
confidence8085to8590=[exp(log(LAeqRespRiskRatio8085to8590)-
se8085to8590) exp(log(LAeqRespRiskRatio8085to8590+se8085to8590))]

LAeqRespRiskRatio8590to9095=length(find(RespLAeq9095>RespLAeq8590Mean))
/LengthRespLAeq9095/(LengthRespLAeq8590/LengthLAeq8590)
se8590to9095=alpha*sqrt(((1-
LengthRespLAeq8590/LengthLAeq8590)/LengthRespLAeq8590)+(1-
length(find(RespLAeq9095>RespLAeq8590Mean))/LengthRespLAeq9095/length(f
ind(RespLAeq9095>RespLAeq8590Mean))));
confidence8590to9095=[exp(log(LAeqRespRiskRatio8590to9095)-
se8590to9095) exp(log(LAeqRespRiskRatio8590to9095+se8590to9095))]

LAeqRespRiskRatio9095to95100=length(find(RespLAeq95100>RespLAeq9095Mean
))/LengthRespLAeq95100/(LengthRespLAeq9095/LengthLAeq9095)
se9095to95100=alpha*sqrt(((1-
LengthRespLAeq9095/LengthLAeq9095)/LengthRespLAeq9095)+(1-
length(find(RespLAeq95100>RespLAeq9095Mean))/LengthRespLAeq95100/length
(find(RespLAeq95100>RespLAeq9095Mean))));
confidence9095to95100=[exp(log(LAeqRespRiskRatio9095to95100)-
se9095to95100) exp(log(LAeqRespRiskRatio9095to95100+se9095to95100))]

LAeqRespRiskRatio95100to100105=length(find(RespLAeq100105>RespLAeq95100
Mean))/LengthRespLAeq100105/(LengthRespLAeq95100/LengthLAeq95100)
se95100to100105=alpha*sqrt(((1-
LengthRespLAeq95100/LengthLAeq95100)/LengthRespLAeq95100)+(1-
length(find(RespLAeq100105>RespLAeq95100Mean))/LengthRespLAeq100105/len
gth(find(RespLAeq100105>RespLAeq95100Mean))));
confidence100105to100105=[exp(log(LAeqRespRiskRatio95100to100105)-
se95100to100105)
exp(log(LAeqRespRiskRatio95100to100105+se95100to100105))]

LAeqRespRiskRatio100105to105=length(find(RespLAeq105>RespLAeq100105Mean
))/LengthRespLAeq105/(LengthRespLAeq100105/LengthLAeq100105)
se100105to105=alpha*sqrt(((1-
LengthRespLAeq100105/LengthLAeq100105)/LengthRespLAeq100105)+(1-
length(find(RespLAeq105>RespLAeq100105Mean))/LengthRespLAeq105/length(f
ind(RespLAeq105>RespLAeq100105Mean))));
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confidence100105to105=[exp(log(LAeqRespRiskRatio100105to105)-
se100105to105) exp(log(LAeqRespRiskRatio100105to105+se100105to105))]



LAeq3035=LAeq(find(LAeq>30 & LAeq<35)); SPO2LAeq3035=SPO2(find(LAeq>30
& LAeq<35));
LAeq3540=LAeq(find(LAeq>35 & LAeq<40)); SPO2LAeq3540=SPO2(find(LAeq>35
& LAeq<40));
LAeq4045=LAeq(find(LAeq>40 & LAeq<45)); SPO2LAeq4045=SPO2(find(LAeq>40
& LAeq<45));
LAeq4550=LAeq(find(LAeq>45 & LAeq<50)); SPO2LAeq4550=SPO2(find(LAeq>45
& LAeq<50));
LAeq5055=LAeq(find(LAeq>50 & LAeq<55)); SPO2LAeq5055=SPO2(find(LAeq>50
& LAeq<55));
LAeq5560=LAeq(find(LAeq>55 & LAeq<60)); SPO2LAeq5560=SPO2(find(LAeq>55
& LAeq<60));
LAeq6065=LAeq(find(LAeq>60 & LAeq<65)); SPO2LAeq6065=SPO2(find(LAeq>60
& LAeq<65));
LAeq6570=LAeq(find(LAeq>65 & LAeq<70)); SPO2LAeq6570=SPO2(find(LAeq>65
& LAeq<70));
LAeq7075=LAeq(find(LAeq>70 & LAeq<75)); SPO2LAeq7075=SPO2(find(LAeq>70
& LAeq<75));
LAeq7580=LAeq(find(LAeq>75 & LAeq<80)); SPO2LAeq7580=SPO2(find(LAeq>75
& LAeq<80));
LAeq8085=LAeq(find(LAeq>80 & LAeq<85)); SPO2LAeq8085=SPO2(find(LAeq>80
& LAeq<85));
LAeq8590=LAeq(find(LAeq>85 & LAeq<90)); SPO2LAeq8590=SPO2(find(LAeq>85
& LAeq<90));
LAeq9095=LAeq(find(LAeq>90 & LAeq<95)); SPO2LAeq9095=SPO2(find(LAeq>90
& LAeq<95));
LAeq95100=LAeq(find(LAeq>95 & LAeq<100));
SPO2LAeq95100=SPO2(find(LAeq>95 & LAeq<100));
LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
SPO2LAeq100105=SPO2(find(LAeq>100105 & LAeq<100105));
LAeq105=LAeq(find(LAeq>105)); SPO2LAeq105=SPO2(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
LAeq4550Mean=nanmean(LAeq4550);
LAeq5055Mean=nanmean(LAeq5055);
LAeq5560Mean=nanmean(LAeq5560);
LAeq6065Mean=nanmean(LAeq6065);
LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);
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SPO2LAeq3035Mean=nanmean(SPO2LAeq3035);
SPO2LAeq3540Mean=nanmean(SPO2LAeq3540);
SPO2LAeq4045Mean=nanmean(SPO2LAeq4045);
SPO2LAeq4550Mean=nanmean(SPO2LAeq4550);
SPO2LAeq5055Mean=nanmean(SPO2LAeq5055);
SPO2LAeq5560Mean=nanmean(SPO2LAeq5560);
SPO2LAeq6065Mean=nanmean(SPO2LAeq6065);
SPO2LAeq6570Mean=nanmean(SPO2LAeq6570);
SPO2LAeq7075Mean=nanmean(SPO2LAeq7075);
SPO2LAeq7580Mean=nanmean(SPO2LAeq7580);
SPO2LAeq8085Mean=nanmean(SPO2LAeq8085);
SPO2LAeq8590Mean=nanmean(SPO2LAeq8590);
SPO2LAeq9095Mean=nanmean(SPO2LAeq9095);
SPO2LAeq95100Mean=nanmean(SPO2LAeq95100);
SPO2LAeq100105Mean=nanmean(SPO2LAeq100105);
SPO2LAeq105Mean=nanmean(SPO2LAeq105);

LengthLAeq3035=length(LAeq3035);
LengthLAeq3540=length(LAeq3540);
LengthLAeq4045=length(LAeq4045);
LengthLAeq4550=length(LAeq4550);
LengthLAeq5055=length(LAeq5055);
LengthLAeq5560=length(LAeq5560);
LengthLAeq6065=length(LAeq6065);
LengthLAeq6570=length(LAeq6570);
LengthLAeq7075=length(LAeq7075);
LengthLAeq7580=length(LAeq7580);
LengthLAeq8085=length(LAeq8085);
LengthLAeq8590=length(LAeq8590);
LengthLAeq9095=length(LAeq9095);
LengthLAeq95100=length(LAeq95100);
LengthLAeq100105=length(LAeq100105);
LengthLAeq105=length(LAeq105);

LengthSPO2LAeq3035=length(find(SPO2LAeq3035>SPO2LAeq3035Mean));
LengthSPO2LAeq3540=length(find(SPO2LAeq3540>SPO2LAeq3540Mean));
LengthSPO2LAeq4045=length(find(SPO2LAeq4045>SPO2LAeq4045Mean));
LengthSPO2LAeq4550=length(find(SPO2LAeq4550>SPO2LAeq4550Mean));
LengthSPO2LAeq5055=length(find(SPO2LAeq5055>SPO2LAeq5055Mean));
LengthSPO2LAeq5560=length(find(SPO2LAeq5560>SPO2LAeq5560Mean));
LengthSPO2LAeq6065=length(find(SPO2LAeq6065>SPO2LAeq6065Mean));
LengthSPO2LAeq6570=length(find(SPO2LAeq6570>SPO2LAeq6570Mean));
LengthSPO2LAeq7075=length(find(SPO2LAeq7075>SPO2LAeq7075Mean));
LengthSPO2LAeq7580=length(find(SPO2LAeq7580>SPO2LAeq7580Mean));
LengthSPO2LAeq8085=length(find(SPO2LAeq8085>SPO2LAeq8085Mean));
LengthSPO2LAeq8590=length(find(SPO2LAeq8590>SPO2LAeq8590Mean));
LengthSPO2LAeq9095=length(find(SPO2LAeq9095>SPO2LAeq9095Mean));
LengthSPO2LAeq95100=length(find(SPO2LAeq95100>SPO2LAeq95100Mean));
LengthSPO2LAeq100105=length(find(SPO2LAeq100105>SPO2LAeq100105Mean));
LengthSPO2LAeq105=length(find(SPO2LAeq105>SPO2LAeq105Mean));


LAeqSPO2RiskRatio3035to3540=length(find(SPO2LAeq3540>SPO2LAeq3035Mean))
/LengthSPO2LAeq3540/(LengthSPO2LAeq3035/LengthLAeq3035)
```

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se3035to3035=alpha*sqrt(((1-
LengthSPO2LAeq3035/LengthLAeq3035)/LengthSPO2LAeq3035)+(1-
length(find(SPO2LAeq3540>SPO2LAeq3035Mean))/LengthSPO2LAeq3540/length(f
ind(SPO2LAeq3540>SPO2LAeq3035Mean))));
confidence3035to3540=[exp(log(LAeqSPO2RiskRatio3035to3540)-
se3035to3035) exp(log(LAeqSPO2RiskRatio3035to3540+se3035to3035))]

LAeqSPO2RiskRatio3540to4045=length(find(SPO2LAeq4045>SPO2LAeq3540Mean))
/LengthSPO2LAeq4045/(LengthSPO2LAeq3540/LengthLAeq3540)
se3540to4045=alpha*sqrt(((1-
LengthSPO2LAeq3540/LengthLAeq3540)/LengthSPO2LAeq3540)+(1-
length(find(SPO2LAeq4045>SPO2LAeq3540Mean))/LengthSPO2LAeq4045/length(f
ind(SPO2LAeq4045>SPO2LAeq3540Mean))));
confidence3540to4045=[exp(log(LAeqSPO2RiskRatio3540to4045)-
se3540to4045) exp(log(LAeqSPO2RiskRatio3540to4045+se3540to4045))]

LAeqSPO2RiskRatio4045to4550=length(find(SPO2LAeq4550>SPO2LAeq4045Mean))
/LengthSPO2LAeq4550/(LengthSPO2LAeq4045/LengthLAeq4045)
se4045to4550=alpha*sqrt(((1-
LengthSPO2LAeq4045/LengthLAeq4045)/LengthSPO2LAeq4045)+(1-
length(find(SPO2LAeq4550>SPO2LAeq4045Mean))/LengthSPO2LAeq4550/length(f
ind(SPO2LAeq4550>SPO2LAeq4045Mean))));
confidence4045to4550=[exp(log(LAeqSPO2RiskRatio4045to4550)-
se4045to4550) exp(log(LAeqSPO2RiskRatio4045to4550+se4045to4550))]

LAeqSPO2RiskRatio4550to5055=length(find(SPO2LAeq5055>SPO2LAeq4550Mean))
/LengthSPO2LAeq5055/(LengthSPO2LAeq4550/LengthLAeq4550)
se4550to5055=alpha*sqrt(((1-
LengthSPO2LAeq4550/LengthLAeq4550)/LengthSPO2LAeq4550)+(1-
length(find(SPO2LAeq5055>SPO2LAeq4550Mean))/LengthSPO2LAeq5055/length(f
ind(SPO2LAeq5055>SPO2LAeq4550Mean))));
confidence4550to5055=[exp(log(LAeqSPO2RiskRatio4550to5055)-
se4550to5055) exp(log(LAeqSPO2RiskRatio4550to5055+se4550to5055))]

LAeqSPO2RiskRatio5055to5560=length(find(SPO2LAeq5560>SPO2LAeq5055Mean))
/LengthSPO2LAeq5560/(LengthSPO2LAeq5055/LengthLAeq5055)
se5055to5560=alpha*sqrt(((1-
LengthSPO2LAeq5055/LengthLAeq5055)/LengthSPO2LAeq5055)+(1-
length(find(SPO2LAeq5560>SPO2LAeq5055Mean))/LengthSPO2LAeq5560/length(f
ind(SPO2LAeq5560>SPO2LAeq5055Mean))));
confidence5055to5560=[exp(log(LAeqSPO2RiskRatio5055to5560)-
se5055to5560) exp(log(LAeqSPO2RiskRatio5055to5560+se5055to5560))]

LAeqSPO2RiskRatio5560to6065=length(find(SPO2LAeq6065>SPO2LAeq5560Mean))
/LengthSPO2LAeq6065/(LengthSPO2LAeq5560/LengthLAeq5560)
se5560to6065=alpha*sqrt(((1-
LengthSPO2LAeq5560/LengthLAeq5560)/LengthSPO2LAeq5560)+(1-
length(find(SPO2LAeq6065>SPO2LAeq5560Mean))/LengthSPO2LAeq6065/length(f
ind(SPO2LAeq6065>SPO2LAeq5560Mean))));
confidence5560to6065=[exp(log(LAeqSPO2RiskRatio5560to6065)-
se5560to6065) exp(log(LAeqSPO2RiskRatio5560to6065+se5560to6065))]

LAeqSPO2RiskRatio6065to6570=length(find(SPO2LAeq6570>SPO2LAeq6065Mean))
/LengthSPO2LAeq6570/(LengthSPO2LAeq6065/LengthLAeq6065)
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se6065to6570=alpha*sqrt(((1-
LengthSPO2LAeq6065/LengthLAeq6065)/LengthSPO2LAeq6065)+(1-
length(find(SPO2LAeq6570>SPO2LAeq6065Mean))/LengthSPO2LAeq6570/length(f
ind(SPO2LAeq6570>SPO2LAeq6065Mean))));
confidence6065to6570=[exp(log(LAeqSPO2RiskRatio6065to6570)-
se6065to6570) exp(log(LAeqSPO2RiskRatio6065to6570+se6065to6570))]

LAeqSPO2RiskRatio6570to7075=length(find(SPO2LAeq7075>SPO2LAeq6570Mean))
/LengthSPO2LAeq7075/(LengthSPO2LAeq6570/LengthLAeq6570)
se6570to7075=alpha*sqrt(((1-
LengthSPO2LAeq6570/LengthLAeq6570)/LengthSPO2LAeq6570)+(1-
length(find(SPO2LAeq7075>SPO2LAeq6570Mean))/LengthSPO2LAeq7075/length(f
ind(SPO2LAeq7075>SPO2LAeq6570Mean))));
confidence6570to7075=[exp(log(LAeqSPO2RiskRatio6570to7075)-
se6570to7075) exp(log(LAeqSPO2RiskRatio6570to7075+se6570to7075))]

LAeqSPO2RiskRatio7075to7580=length(find(SPO2LAeq7580>SPO2LAeq7075Mean))
/LengthSPO2LAeq7580/(LengthSPO2LAeq7075/LengthLAeq7075)
se7075to7580=alpha*sqrt(((1-
LengthSPO2LAeq7075/LengthLAeq7075)/LengthSPO2LAeq7075)+(1-
length(find(SPO2LAeq7580>SPO2LAeq7075Mean))/LengthSPO2LAeq7580/length(f
ind(SPO2LAeq7580>SPO2LAeq7075Mean))));
confidence7075to7580=[exp(log(LAeqSPO2RiskRatio7075to7580)-
se7075to7580) exp(log(LAeqSPO2RiskRatio7075to7580+se7075to7580))]

LAeqSPO2RiskRatio7580to8085=length(find(SPO2LAeq8085>SPO2LAeq7580Mean))
/LengthSPO2LAeq8085/(LengthSPO2LAeq7580/LengthLAeq7580)
se7580to8085=alpha*sqrt(((1-
LengthSPO2LAeq7580/LengthLAeq7580)/LengthSPO2LAeq7580)+(1-
length(find(SPO2LAeq8085>SPO2LAeq7580Mean))/LengthSPO2LAeq8085/length(f
ind(SPO2LAeq8085>SPO2LAeq7580Mean))));
confidence7580to8085=[exp(log(LAeqSPO2RiskRatio7580to8085)-
se7580to8085) exp(log(LAeqSPO2RiskRatio7580to8085+se7580to8085))]

LAeqSPO2RiskRatio8085to8590=length(find(SPO2LAeq8590>SPO2LAeq8085Mean))
/LengthSPO2LAeq8590/(LengthSPO2LAeq8085/LengthLAeq8085)
se8085to8590=alpha*sqrt(((1-
LengthSPO2LAeq8085/LengthLAeq8085)/LengthSPO2LAeq8085)+(1-
length(find(SPO2LAeq8590>SPO2LAeq8085Mean))/LengthSPO2LAeq8590/length(f
ind(SPO2LAeq8590>SPO2LAeq8085Mean))));
confidence8085to8590=[exp(log(LAeqSPO2RiskRatio8085to8590)-
se8085to8590) exp(log(LAeqSPO2RiskRatio8085to8590+se8085to8590))]

LAeqSPO2RiskRatio8590to9095=length(find(SPO2LAeq9095>SPO2LAeq8590Mean))
/LengthSPO2LAeq9095/(LengthSPO2LAeq8590/LengthLAeq8590)
se8590to9095=alpha*sqrt(((1-
LengthSPO2LAeq8590/LengthLAeq8590)/LengthSPO2LAeq8590)+(1-
length(find(SPO2LAeq9095>SPO2LAeq8590Mean))/LengthSPO2LAeq9095/length(f
ind(SPO2LAeq9095>SPO2LAeq8590Mean))));
confidence8590to9095=[exp(log(LAeqSPO2RiskRatio8590to9095)-
se8590to9095) exp(log(LAeqSPO2RiskRatio8590to9095+se8590to9095))]

LAeqSPO2RiskRatio9095to95100=length(find(SPO2LAeq95100>SPO2LAeq9095Mean
))/LengthSPO2LAeq95100/(LengthSPO2LAeq9095/LengthLAeq9095)
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se9095to95100=alpha*sqrt(((1-
LengthSPO2LAeq9095/LengthLAeq9095)/LengthSPO2LAeq9095)+(1-
length(find(SPO2LAeq95100>SPO2LAeq9095Mean))/LengthSPO2LAeq95100/length
(find(SPO2LAeq95100>SPO2LAeq9095Mean))));
confidence9095to95100=[exp(log(LAeqSPO2RiskRatio9095to95100)-
se9095to95100) exp(log(LAeqSPO2RiskRatio9095to95100+se9095to95100))]

LAeqSPO2RiskRatio95100to100105=length(find(SPO2LAeq100105>SPO2LAeq95100
Mean))/LengthSPO2LAeq100105/(LengthSPO2LAeq95100/LengthLAeq95100)
se95100to100105=alpha*sqrt(((1-
LengthSPO2LAeq95100/LengthLAeq95100)/LengthSPO2LAeq95100)+(1-
length(find(SPO2LAeq100105>SPO2LAeq95100Mean))/LengthSPO2LAeq100105/len
gth(find(SPO2LAeq100105>SPO2LAeq95100Mean))));
confidence100105to100105=[exp(log(LAeqSPO2RiskRatio95100to100105)-
se95100to100105)
exp(log(LAeqSPO2RiskRatio95100to100105+se95100to100105))]

LAeqSPO2RiskRatio100105to105=length(find(SPO2LAeq105>SPO2LAeq100105Mean
))/LengthSPO2LAeq105/(LengthSPO2LAeq100105/LengthLAeq100105)
se100105to105=alpha*sqrt(((1-
LengthSPO2LAeq100105/LengthLAeq100105)/LengthSPO2LAeq100105)+(1-
length(find(SPO2LAeq105>SPO2LAeq100105Mean))/LengthSPO2LAeq105/length(f
ind(SPO2LAeq105>SPO2LAeq100105Mean))));
confidence100105to105=[exp(log(LAeqSPO2RiskRatio100105to105)-
se100105to105) exp(log(LAeqSPO2RiskRatio100105to105+se100105to105))]




LAeq3035=LAeq(find(LAeq>30 & LAeq<35));
ArtSysLAeq3035=ArtSys(find(LAeq>30 & LAeq<35));
LAeq3540=LAeq(find(LAeq>35 & LAeq<40));
ArtSysLAeq3540=ArtSys(find(LAeq>35 & LAeq<40));
LAeq4045=LAeq(find(LAeq>40 & LAeq<45));
ArtSysLAeq4045=ArtSys(find(LAeq>40 & LAeq<45));
LAeq4550=LAeq(find(LAeq>45 & LAeq<50));
ArtSysLAeq4550=ArtSys(find(LAeq>45 & LAeq<50));
LAeq5055=LAeq(find(LAeq>50 & LAeq<55));
ArtSysLAeq5055=ArtSys(find(LAeq>50 & LAeq<55));
LAeq5560=LAeq(find(LAeq>55 & LAeq<60));
ArtSysLAeq5560=ArtSys(find(LAeq>55 & LAeq<60));
LAeq6065=LAeq(find(LAeq>60 & LAeq<65));
ArtSysLAeq6065=ArtSys(find(LAeq>60 & LAeq<65));
LAeq6570=LAeq(find(LAeq>65 & LAeq<70));
ArtSysLAeq6570=ArtSys(find(LAeq>65 & LAeq<70));
LAeq7075=LAeq(find(LAeq>70 & LAeq<75));
ArtSysLAeq7075=ArtSys(find(LAeq>70 & LAeq<75));
LAeq7580=LAeq(find(LAeq>75 & LAeq<80));
ArtSysLAeq7580=ArtSys(find(LAeq>75 & LAeq<80));
LAeq8085=LAeq(find(LAeq>80 & LAeq<85));
ArtSysLAeq8085=ArtSys(find(LAeq>80 & LAeq<85));
LAeq8590=LAeq(find(LAeq>85 & LAeq<90));
ArtSysLAeq8590=ArtSys(find(LAeq>85 & LAeq<90));
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LAeq9095=LAeq(find(LAeq>90 & LAeq<95));
ArtSysLAeq9095=ArtSys(find(LAeq>90 & LAeq<95));
LAeq95100=LAeq(find(LAeq>95 & LAeq<100));
ArtSysLAeq95100=ArtSys(find(LAeq>95 & LAeq<100));
LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
ArtSysLAeq100105=ArtSys(find(LAeq>100105 & LAeq<100105));
LAeq105=LAeq(find(LAeq>105)); ArtSysLAeq105=ArtSys(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
LAeq4550Mean=nanmean(LAeq4550);
LAeq5055Mean=nanmean(LAeq5055);
LAeq5560Mean=nanmean(LAeq5560);
LAeq6065Mean=nanmean(LAeq6065);
LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);

ArtSysLAeq3035Mean=nanmean(ArtSysLAeq3035);
ArtSysLAeq3540Mean=nanmean(ArtSysLAeq3540);
ArtSysLAeq4045Mean=nanmean(ArtSysLAeq4045);
ArtSysLAeq4550Mean=nanmean(ArtSysLAeq4550);
ArtSysLAeq5055Mean=nanmean(ArtSysLAeq5055);
ArtSysLAeq5560Mean=nanmean(ArtSysLAeq5560);
ArtSysLAeq6065Mean=nanmean(ArtSysLAeq6065);
ArtSysLAeq6570Mean=nanmean(ArtSysLAeq6570);
ArtSysLAeq7075Mean=nanmean(ArtSysLAeq7075);
ArtSysLAeq7580Mean=nanmean(ArtSysLAeq7580);
ArtSysLAeq8085Mean=nanmean(ArtSysLAeq8085);
ArtSysLAeq8590Mean=nanmean(ArtSysLAeq8590);
ArtSysLAeq9095Mean=nanmean(ArtSysLAeq9095);
ArtSysLAeq95100Mean=nanmean(ArtSysLAeq95100);
ArtSysLAeq100105Mean=nanmean(ArtSysLAeq100105);
ArtSysLAeq105Mean=nanmean(ArtSysLAeq105);

LengthLAeq3035=length(LAeq3035);
LengthLAeq3540=length(LAeq3540);
LengthLAeq4045=length(LAeq4045);
LengthLAeq4550=length(LAeq4550);
LengthLAeq5055=length(LAeq5055);
LengthLAeq5560=length(LAeq5560);
LengthLAeq6065=length(LAeq6065);
LengthLAeq6570=length(LAeq6570);
LengthLAeq7075=length(LAeq7075);
LengthLAeq7580=length(LAeq7580);
LengthLAeq8085=length(LAeq8085);
LengthLAeq8590=length(LAeq8590);
LengthLAeq9095=length(LAeq9095);
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LengthLAeq95100=length(LAeq95100);
LengthLAeq100105=length(LAeq100105);
LengthLAeq105=length(LAeq105);

LengthArtSysLAeq3035=length(find(ArtSysLAeq3035>ArtSysLAeq3035Mean));
LengthArtSysLAeq3540=length(find(ArtSysLAeq3540>ArtSysLAeq3540Mean));
LengthArtSysLAeq4045=length(find(ArtSysLAeq4045>ArtSysLAeq4045Mean));
LengthArtSysLAeq4550=length(find(ArtSysLAeq4550>ArtSysLAeq4550Mean));
LengthArtSysLAeq5055=length(find(ArtSysLAeq5055>ArtSysLAeq5055Mean));
LengthArtSysLAeq5560=length(find(ArtSysLAeq5560>ArtSysLAeq5560Mean));
LengthArtSysLAeq6065=length(find(ArtSysLAeq6065>ArtSysLAeq6065Mean));
LengthArtSysLAeq6570=length(find(ArtSysLAeq6570>ArtSysLAeq6570Mean));
LengthArtSysLAeq7075=length(find(ArtSysLAeq7075>ArtSysLAeq7075Mean));
LengthArtSysLAeq7580=length(find(ArtSysLAeq7580>ArtSysLAeq7580Mean));
LengthArtSysLAeq8085=length(find(ArtSysLAeq8085>ArtSysLAeq8085Mean));
LengthArtSysLAeq8590=length(find(ArtSysLAeq8590>ArtSysLAeq8590Mean));
LengthArtSysLAeq9095=length(find(ArtSysLAeq9095>ArtSysLAeq9095Mean));
LengthArtSysLAeq95100=length(find(ArtSysLAeq95100>ArtSysLAeq95100Mean))
;
LengthArtSysLAeq100105=length(find(ArtSysLAeq100105>ArtSysLAeq100105Mea
n));
LengthArtSysLAeq105=length(find(ArtSysLAeq105>ArtSysLAeq105Mean));


LAeqArtSysRiskRatio3035to3540=length(find(ArtSysLAeq3540>ArtSysLAeq3035
Mean))/LengthArtSysLAeq3540/(LengthArtSysLAeq3035/LengthLAeq3035)
se3035to3035=alpha*sqrt(((1-
LengthArtSysLAeq3035/LengthLAeq3035)/LengthArtSysLAeq3035)+(1-
length(find(ArtSysLAeq3540>ArtSysLAeq3035Mean))/LengthArtSysLAeq3540/le
ngth(find(ArtSysLAeq3540>ArtSysLAeq3035Mean))));
confidence3035to3540=[exp(log(LAeqArtSysRiskRatio3035to3540)-
se3035to3035) exp(log(LAeqArtSysRiskRatio3035to3540+se3035to3035))]

LAeqArtSysRiskRatio3540to4045=length(find(ArtSysLAeq4045>ArtSysLAeq3540
Mean))/LengthArtSysLAeq4045/(LengthArtSysLAeq3540/LengthLAeq3540)
se3540to4045=alpha*sqrt(((1-
LengthArtSysLAeq3540/LengthLAeq3540)/LengthArtSysLAeq3540)+(1-
length(find(ArtSysLAeq4045>ArtSysLAeq3540Mean))/LengthArtSysLAeq4045/le
ngth(find(ArtSysLAeq4045>ArtSysLAeq3540Mean))));
confidence3540to4045=[exp(log(LAeqArtSysRiskRatio3540to4045)-
se3540to4045) exp(log(LAeqArtSysRiskRatio3540to4045+se3540to4045))]

LAeqArtSysRiskRatio4045to4550=length(find(ArtSysLAeq4550>ArtSysLAeq4045
Mean))/LengthArtSysLAeq4550/(LengthArtSysLAeq4045/LengthLAeq4045)
se4045to4550=alpha*sqrt(((1-
LengthArtSysLAeq4045/LengthLAeq4045)/LengthArtSysLAeq4045)+(1-
length(find(ArtSysLAeq4550>ArtSysLAeq4045Mean))/LengthArtSysLAeq4550/le
ngth(find(ArtSysLAeq4550>ArtSysLAeq4045Mean))));
confidence4045to4550=[exp(log(LAeqArtSysRiskRatio4045to4550)-
se4045to4550) exp(log(LAeqArtSysRiskRatio4045to4550+se4045to4550))]

LAeqArtSysRiskRatio4550to5055=length(find(ArtSysLAeq5055>ArtSysLAeq4550
Mean))/LengthArtSysLAeq5055/(LengthArtSysLAeq4550/LengthLAeq4550)
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se4550to5055=alpha*sqrt(((1-
LengthArtSysLAeq4550/LengthLAeq4550)/LengthArtSysLAeq4550)+(1-
length(find(ArtSysLAeq5055>ArtSysLAeq4550Mean))/LengthArtSysLAeq5055/le
ngth(find(ArtSysLAeq5055>ArtSysLAeq4550Mean))));
confidence4550to5055=[exp(log(LAeqArtSysRiskRatio4550to5055)-
se4550to5055) exp(log(LAeqArtSysRiskRatio4550to5055+se4550to5055))]

LAeqArtSysRiskRatio5055to5560=length(find(ArtSysLAeq5560>ArtSysLAeq5055
Mean))/LengthArtSysLAeq5560/(LengthArtSysLAeq5055/LengthLAeq5055)
se5055to5560=alpha*sqrt(((1-
LengthArtSysLAeq5055/LengthLAeq5055)/LengthArtSysLAeq5055)+(1-
length(find(ArtSysLAeq5560>ArtSysLAeq5055Mean))/LengthArtSysLAeq5560/le
ngth(find(ArtSysLAeq5560>ArtSysLAeq5055Mean))));
confidence5055to5560=[exp(log(LAeqArtSysRiskRatio5055to5560)-
se5055to5560) exp(log(LAeqArtSysRiskRatio5055to5560+se5055to5560))]

LAeqArtSysRiskRatio5560to6065=length(find(ArtSysLAeq6065>ArtSysLAeq5560
Mean))/LengthArtSysLAeq6065/(LengthArtSysLAeq5560/LengthLAeq5560)
se5560to6065=alpha*sqrt(((1-
LengthArtSysLAeq5560/LengthLAeq5560)/LengthArtSysLAeq5560)+(1-
length(find(ArtSysLAeq6065>ArtSysLAeq5560Mean))/LengthArtSysLAeq6065/le
ngth(find(ArtSysLAeq6065>ArtSysLAeq5560Mean))));
confidence5560to6065=[exp(log(LAeqArtSysRiskRatio5560to6065)-
se5560to6065) exp(log(LAeqArtSysRiskRatio5560to6065+se5560to6065))]

LAeqArtSysRiskRatio6065to6570=length(find(ArtSysLAeq6570>ArtSysLAeq6065
Mean))/LengthArtSysLAeq6570/(LengthArtSysLAeq6065/LengthLAeq6065)
se6065to6570=alpha*sqrt(((1-
LengthArtSysLAeq6065/LengthLAeq6065)/LengthArtSysLAeq6065)+(1-
length(find(ArtSysLAeq6570>ArtSysLAeq6065Mean))/LengthArtSysLAeq6570/le
ngth(find(ArtSysLAeq6570>ArtSysLAeq6065Mean))));
confidence6065to6570=[exp(log(LAeqArtSysRiskRatio6065to6570)-
se6065to6570) exp(log(LAeqArtSysRiskRatio6065to6570+se6065to6570))]

LAeqArtSysRiskRatio6570to7075=length(find(ArtSysLAeq7075>ArtSysLAeq6570
Mean))/LengthArtSysLAeq7075/(LengthArtSysLAeq6570/LengthLAeq6570)
se6570to7075=alpha*sqrt(((1-
LengthArtSysLAeq6570/LengthLAeq6570)/LengthArtSysLAeq6570)+(1-
length(find(ArtSysLAeq7075>ArtSysLAeq6570Mean))/LengthArtSysLAeq7075/le
ngth(find(ArtSysLAeq7075>ArtSysLAeq6570Mean))));
confidence6570to7075=[exp(log(LAeqArtSysRiskRatio6570to7075)-
se6570to7075) exp(log(LAeqArtSysRiskRatio6570to7075+se6570to7075))]

LAeqArtSysRiskRatio7075to7580=length(find(ArtSysLAeq7580>ArtSysLAeq7075
Mean))/LengthArtSysLAeq7580/(LengthArtSysLAeq7075/LengthLAeq7075)
se7075to7580=alpha*sqrt(((1-
LengthArtSysLAeq7075/LengthLAeq7075)/LengthArtSysLAeq7075)+(1-
length(find(ArtSysLAeq7580>ArtSysLAeq7075Mean))/LengthArtSysLAeq7580/le
ngth(find(ArtSysLAeq7580>ArtSysLAeq7075Mean))));
confidence7075to7580=[exp(log(LAeqArtSysRiskRatio7075to7580)-
se7075to7580) exp(log(LAeqArtSysRiskRatio7075to7580+se7075to7580))]

LAeqArtSysRiskRatio7580to8085=length(find(ArtSysLAeq8085>ArtSysLAeq7580
Mean))/LengthArtSysLAeq8085/(LengthArtSysLAeq7580/LengthLAeq7580)
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se7580to8085=alpha*sqrt(((1-
LengthArtSysLAeq7580/LengthLAeq7580)/LengthArtSysLAeq7580)+(1-
length(find(ArtSysLAeq8085>ArtSysLAeq7580Mean))/LengthArtSysLAeq8085/le
ngth(find(ArtSysLAeq8085>ArtSysLAeq7580Mean))));
confidence7580to8085=[exp(log(LAeqArtSysRiskRatio7580to8085)-
se7580to8085) exp(log(LAeqArtSysRiskRatio7580to8085+se7580to8085))]

LAeqArtSysRiskRatio8085to8590=length(find(ArtSysLAeq8590>ArtSysLAeq8085
Mean))/LengthArtSysLAeq8590/(LengthArtSysLAeq8085/LengthLAeq8085)
se8085to8590=alpha*sqrt(((1-
LengthArtSysLAeq8085/LengthLAeq8085)/LengthArtSysLAeq8085)+(1-
length(find(ArtSysLAeq8590>ArtSysLAeq8085Mean))/LengthArtSysLAeq8590/le
ngth(find(ArtSysLAeq8590>ArtSysLAeq8085Mean))));
confidence8085to8590=[exp(log(LAeqArtSysRiskRatio8085to8590)-
se8085to8590) exp(log(LAeqArtSysRiskRatio8085to8590+se8085to8590))]

LAeqArtSysRiskRatio8590to9095=length(find(ArtSysLAeq9095>ArtSysLAeq8590
Mean))/LengthArtSysLAeq9095/(LengthArtSysLAeq8590/LengthLAeq8590)
se8590to9095=alpha*sqrt(((1-
LengthArtSysLAeq8590/LengthLAeq8590)/LengthArtSysLAeq8590)+(1-
length(find(ArtSysLAeq9095>ArtSysLAeq8590Mean))/LengthArtSysLAeq9095/le
ngth(find(ArtSysLAeq9095>ArtSysLAeq8590Mean))));
confidence8590to9095=[exp(log(LAeqArtSysRiskRatio8590to9095)-
se8590to9095) exp(log(LAeqArtSysRiskRatio8590to9095+se8590to9095))]

LAeqArtSysRiskRatio9095to95100=length(find(ArtSysLAeq95100>ArtSysLAeq90
95Mean))/LengthArtSysLAeq95100/(LengthArtSysLAeq9095/LengthLAeq9095)
se9095to95100=alpha*sqrt(((1-
LengthArtSysLAeq9095/LengthLAeq9095)/LengthArtSysLAeq9095)+(1-
length(find(ArtSysLAeq95100>ArtSysLAeq9095Mean))/LengthArtSysLAeq95100/
length(find(ArtSysLAeq95100>ArtSysLAeq9095Mean))));
confidence9095to95100=[exp(log(LAeqArtSysRiskRatio9095to95100)-
se9095to95100) exp(log(LAeqArtSysRiskRatio9095to95100+se9095to95100))]

LAeqArtSysRiskRatio95100to100105=length(find(ArtSysLAeq100105>ArtSysLAe
q95100Mean))/LengthArtSysLAeq100105/(LengthArtSysLAeq95100/LengthLAeq95
100)
se95100to100105=alpha*sqrt(((1-
LengthArtSysLAeq95100/LengthLAeq95100)/LengthArtSysLAeq95100)+(1-
length(find(ArtSysLAeq100105>ArtSysLAeq95100Mean))/LengthArtSysLAeq1001
05/length(find(ArtSysLAeq100105>ArtSysLAeq95100Mean))));
confidence100105to100105=[exp(log(LAeqArtSysRiskRatio95100to100105)-
se95100to100105)
exp(log(LAeqArtSysRiskRatio95100to100105+se95100to100105))]

LAeqArtSysRiskRatio100105to105=length(find(ArtSysLAeq105>ArtSysLAeq1001
05Mean))/LengthArtSysLAeq105/(LengthArtSysLAeq100105/LengthLAeq100105)
se100105to105=alpha*sqrt(((1-
LengthArtSysLAeq100105/LengthLAeq100105)/LengthArtSysLAeq100105)+(1-
length(find(ArtSysLAeq105>ArtSysLAeq100105Mean))/LengthArtSysLAeq105/le
ngth(find(ArtSysLAeq105>ArtSysLAeq100105Mean))));
confidence100105to105=[exp(log(LAeqArtSysRiskRatio100105to105)-
se100105to105) exp(log(LAeqArtSysRiskRatio100105to105+se100105to105))]
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```
LAeq3035=LAeq(find(LAeq>30 & LAeq<35));
ArtDiasLAeq3035=ArtDias(find(LAeq>30 & LAeq<35));
LAeq3540=LAeq(find(LAeq>35 & LAeq<40));
ArtDiasLAeq3540=ArtDias(find(LAeq>35 & LAeq<40));
LAeq4045=LAeq(find(LAeq>40 & LAeq<45));
ArtDiasLAeq4045=ArtDias(find(LAeq>40 & LAeq<45));
LAeq4550=LAeq(find(LAeq>45 & LAeq<50));
ArtDiasLAeq4550=ArtDias(find(LAeq>45 & LAeq<50));
LAeq5055=LAeq(find(LAeq>50 & LAeq<55));
ArtDiasLAeq5055=ArtDias(find(LAeq>50 & LAeq<55));
LAeq5560=LAeq(find(LAeq>55 & LAeq<60));
ArtDiasLAeq5560=ArtDias(find(LAeq>55 & LAeq<60));
LAeq6065=LAeq(find(LAeq>60 & LAeq<65));
ArtDiasLAeq6065=ArtDias(find(LAeq>60 & LAeq<65));
LAeq6570=LAeq(find(LAeq>65 & LAeq<70));
ArtDiasLAeq6570=ArtDias(find(LAeq>65 & LAeq<70));
LAeq7075=LAeq(find(LAeq>70 & LAeq<75));
ArtDiasLAeq7075=ArtDias(find(LAeq>70 & LAeq<75));
LAeq7580=LAeq(find(LAeq>75 & LAeq<80));
ArtDiasLAeq7580=ArtDias(find(LAeq>75 & LAeq<80));
LAeq8085=LAeq(find(LAeq>80 & LAeq<85));
ArtDiasLAeq8085=ArtDias(find(LAeq>80 & LAeq<85));
LAeq8590=LAeq(find(LAeq>85 & LAeq<90));
ArtDiasLAeq8590=ArtDias(find(LAeq>85 & LAeq<90));
LAeq9095=LAeq(find(LAeq>90 & LAeq<95));
ArtDiasLAeq9095=ArtDias(find(LAeq>90 & LAeq<95));
LAeq95100=LAeq(find(LAeq>95 & LAeq<100));
ArtDiasLAeq95100=ArtDias(find(LAeq>95 & LAeq<100));
LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
ArtDiasLAeq100105=ArtDias(find(LAeq>100105 & LAeq<100105));
LAeq105=LAeq(find(LAeq>105)); ArtDiasLAeq105=ArtDias(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
LAeq4550Mean=nanmean(LAeq4550);
LAeq5055Mean=nanmean(LAeq5055);
LAeq5560Mean=nanmean(LAeq5560);
LAeq6065Mean=nanmean(LAeq6065);
LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);

ArtDiasLAeq3035Mean=nanmean(ArtDiasLAeq3035);
ArtDiasLAeq3540Mean=nanmean(ArtDiasLAeq3540);
ArtDiasLAeq4045Mean=nanmean(ArtDiasLAeq4045);
ArtDiasLAeq4550Mean=nanmean(ArtDiasLAeq4550);
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ArtDiasLAeq5055Mean=nanmean(ArtDiasLAeq5055);
ArtDiasLAeq5560Mean=nanmean(ArtDiasLAeq5560);
ArtDiasLAeq6065Mean=nanmean(ArtDiasLAeq6065);
ArtDiasLAeq6570Mean=nanmean(ArtDiasLAeq6570);
ArtDiasLAeq7075Mean=nanmean(ArtDiasLAeq7075);
ArtDiasLAeq7580Mean=nanmean(ArtDiasLAeq7580);
ArtDiasLAeq8085Mean=nanmean(ArtDiasLAeq8085);
ArtDiasLAeq8590Mean=nanmean(ArtDiasLAeq8590);
ArtDiasLAeq9095Mean=nanmean(ArtDiasLAeq9095);
ArtDiasLAeq95100Mean=nanmean(ArtDiasLAeq95100);
ArtDiasLAeq100105Mean=nanmean(ArtDiasLAeq100105);
ArtDiasLAeq105Mean=nanmean(ArtDiasLAeq105);

LengthLAeq3035=length(LAeq3035);
LengthLAeq3540=length(LAeq3540);
LengthLAeq4045=length(LAeq4045);
LengthLAeq4550=length(LAeq4550);
LengthLAeq5055=length(LAeq5055);
LengthLAeq5560=length(LAeq5560);
LengthLAeq6065=length(LAeq6065);
LengthLAeq6570=length(LAeq6570);
LengthLAeq7075=length(LAeq7075);
LengthLAeq7580=length(LAeq7580);
LengthLAeq8085=length(LAeq8085);
LengthLAeq8590=length(LAeq8590);
LengthLAeq9095=length(LAeq9095);
LengthLAeq95100=length(LAeq95100);
LengthLAeq100105=length(LAeq100105);
LengthLAeq105=length(LAeq105);

LengthArtDiasLAeq3035=length(find(ArtDiasLAeq3035>ArtDiasLAeq3035Mean))
;
LengthArtDiasLAeq3540=length(find(ArtDiasLAeq3540>ArtDiasLAeq3540Mean))
;
LengthArtDiasLAeq4045=length(find(ArtDiasLAeq4045>ArtDiasLAeq4045Mean))
;
LengthArtDiasLAeq4550=length(find(ArtDiasLAeq4550>ArtDiasLAeq4550Mean))
;
LengthArtDiasLAeq5055=length(find(ArtDiasLAeq5055>ArtDiasLAeq5055Mean))
;
LengthArtDiasLAeq5560=length(find(ArtDiasLAeq5560>ArtDiasLAeq5560Mean))
;
LengthArtDiasLAeq6065=length(find(ArtDiasLAeq6065>ArtDiasLAeq6065Mean))
;
LengthArtDiasLAeq6570=length(find(ArtDiasLAeq6570>ArtDiasLAeq6570Mean))
;
LengthArtDiasLAeq7075=length(find(ArtDiasLAeq7075>ArtDiasLAeq7075Mean))
;
LengthArtDiasLAeq7580=length(find(ArtDiasLAeq7580>ArtDiasLAeq7580Mean))
;
LengthArtDiasLAeq8085=length(find(ArtDiasLAeq8085>ArtDiasLAeq8085Mean))
;
LengthArtDiasLAeq8590=length(find(ArtDiasLAeq8590>ArtDiasLAeq8590Mean))
;
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LengthArtDiasLAeq9095=length(find(ArtDiasLAeq9095>ArtDiasLAeq9095Mean))
;
LengthArtDiasLAeq95100=length(find(ArtDiasLAeq95100>ArtDiasLAeq95100Mea
n));
LengthArtDiasLAeq100105=length(find(ArtDiasLAeq100105>ArtDiasLAeq100105
Mean));
LengthArtDiasLAeq105=length(find(ArtDiasLAeq105>ArtDiasLAeq105Mean));


LAeqArtDiasRiskRatio3035to3540=length(find(ArtDiasLAeq3540>ArtDiasLAeq3
035Mean))/LengthArtDiasLAeq3540/(LengthArtDiasLAeq3035/LengthLAeq3035)
se3035to3035=alpha*sqrt(((1-
LengthArtDiasLAeq3035/LengthLAeq3035)/LengthArtDiasLAeq3035)+(1-
length(find(ArtDiasLAeq3540>ArtDiasLAeq3035Mean))/LengthArtDiasLAeq3540
/length(find(ArtDiasLAeq3540>ArtDiasLAeq3035Mean))));
confidence3035to3540=[exp(log(LAeqArtDiasRiskRatio3035to3540)-
se3035to3035) exp(log(LAeqArtDiasRiskRatio3035to3540+se3035to3035))]

LAeqArtDiasRiskRatio3540to4045=length(find(ArtDiasLAeq4045>ArtDiasLAeq3
540Mean))/LengthArtDiasLAeq4045/(LengthArtDiasLAeq3540/LengthLAeq3540)
se3540to4045=alpha*sqrt(((1-
LengthArtDiasLAeq3540/LengthLAeq3540)/LengthArtDiasLAeq3540)+(1-
length(find(ArtDiasLAeq4045>ArtDiasLAeq3540Mean))/LengthArtDiasLAeq4045
/length(find(ArtDiasLAeq4045>ArtDiasLAeq3540Mean))));
confidence3540to4045=[exp(log(LAeqArtDiasRiskRatio3540to4045)-
se3540to4045) exp(log(LAeqArtDiasRiskRatio3540to4045+se3540to4045))]

LAeqArtDiasRiskRatio4045to4550=length(find(ArtDiasLAeq4550>ArtDiasLAeq4
045Mean))/LengthArtDiasLAeq4550/(LengthArtDiasLAeq4045/LengthLAeq4045)
se4045to4550=alpha*sqrt(((1-
LengthArtDiasLAeq4045/LengthLAeq4045)/LengthArtDiasLAeq4045)+(1-
length(find(ArtDiasLAeq4550>ArtDiasLAeq4045Mean))/LengthArtDiasLAeq4550
/length(find(ArtDiasLAeq4550>ArtDiasLAeq4045Mean))));
confidence4045to4550=[exp(log(LAeqArtDiasRiskRatio4045to4550)-
se4045to4550) exp(log(LAeqArtDiasRiskRatio4045to4550+se4045to4550))]

LAeqArtDiasRiskRatio4550to5055=length(find(ArtDiasLAeq5055>ArtDiasLAeq4
550Mean))/LengthArtDiasLAeq5055/(LengthArtDiasLAeq4550/LengthLAeq4550)
se4550to5055=alpha*sqrt(((1-
LengthArtDiasLAeq4550/LengthLAeq4550)/LengthArtDiasLAeq4550)+(1-
length(find(ArtDiasLAeq5055>ArtDiasLAeq4550Mean))/LengthArtDiasLAeq5055
/length(find(ArtDiasLAeq5055>ArtDiasLAeq4550Mean))));
confidence4550to5055=[exp(log(LAeqArtDiasRiskRatio4550to5055)-
se4550to5055) exp(log(LAeqArtDiasRiskRatio4550to5055+se4550to5055))]

LAeqArtDiasRiskRatio5055to5560=length(find(ArtDiasLAeq5560>ArtDiasLAeq5
055Mean))/LengthArtDiasLAeq5560/(LengthArtDiasLAeq5055/LengthLAeq5055)
se5055to5560=alpha*sqrt(((1-
LengthArtDiasLAeq5055/LengthLAeq5055)/LengthArtDiasLAeq5055)+(1-
length(find(ArtDiasLAeq5560>ArtDiasLAeq5055Mean))/LengthArtDiasLAeq5560
/length(find(ArtDiasLAeq5560>ArtDiasLAeq5055Mean))));
confidence5055to5560=[exp(log(LAeqArtDiasRiskRatio5055to5560)-
se5055to5560) exp(log(LAeqArtDiasRiskRatio5055to5560+se5055to5560))]
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LAeqArtDiasRiskRatio5560to6065=length(find(ArtDiasLAeq6065>ArtDiasLAeq5
560Mean))/LengthArtDiasLAeq6065/(LengthArtDiasLAeq5560/LengthLAeq5560)
se5560to6065=alpha*sqrt(((1-
LengthArtDiasLAeq5560/LengthLAeq5560)/LengthArtDiasLAeq5560)+(1-
length(find(ArtDiasLAeq6065>ArtDiasLAeq5560Mean))/LengthArtDiasLAeq6065
/length(find(ArtDiasLAeq6065>ArtDiasLAeq5560Mean))));
confidence5560to6065=[exp(log(LAeqArtDiasRiskRatio5560to6065)-
se5560to6065) exp(log(LAeqArtDiasRiskRatio5560to6065+se5560to6065))]

LAeqArtDiasRiskRatio6065to6570=length(find(ArtDiasLAeq6570>ArtDiasLAeq6
065Mean))/LengthArtDiasLAeq6570/(LengthArtDiasLAeq6065/LengthLAeq6065)
se6065to6570=alpha*sqrt(((1-
LengthArtDiasLAeq6065/LengthLAeq6065)/LengthArtDiasLAeq6065)+(1-
length(find(ArtDiasLAeq6570>ArtDiasLAeq6065Mean))/LengthArtDiasLAeq6570
/length(find(ArtDiasLAeq6570>ArtDiasLAeq6065Mean))));
confidence6065to6570=[exp(log(LAeqArtDiasRiskRatio6065to6570)-
se6065to6570) exp(log(LAeqArtDiasRiskRatio6065to6570+se6065to6570))]

LAeqArtDiasRiskRatio6570to7075=length(find(ArtDiasLAeq7075>ArtDiasLAeq6
570Mean))/LengthArtDiasLAeq7075/(LengthArtDiasLAeq6570/LengthLAeq6570)
se6570to7075=alpha*sqrt(((1-
LengthArtDiasLAeq6570/LengthLAeq6570)/LengthArtDiasLAeq6570)+(1-
length(find(ArtDiasLAeq7075>ArtDiasLAeq6570Mean))/LengthArtDiasLAeq7075
/length(find(ArtDiasLAeq7075>ArtDiasLAeq6570Mean))));
confidence6570to7075=[exp(log(LAeqArtDiasRiskRatio6570to7075)-
se6570to7075) exp(log(LAeqArtDiasRiskRatio6570to7075+se6570to7075))]

LAeqArtDiasRiskRatio7075to7580=length(find(ArtDiasLAeq7580>ArtDiasLAeq7
075Mean))/LengthArtDiasLAeq7580/(LengthArtDiasLAeq7075/LengthLAeq7075)
se7075to7580=alpha*sqrt(((1-
LengthArtDiasLAeq7075/LengthLAeq7075)/LengthArtDiasLAeq7075)+(1-
length(find(ArtDiasLAeq7580>ArtDiasLAeq7075Mean))/LengthArtDiasLAeq7580
/length(find(ArtDiasLAeq7580>ArtDiasLAeq7075Mean))));
confidence7075to7580=[exp(log(LAeqArtDiasRiskRatio7075to7580)-
se7075to7580) exp(log(LAeqArtDiasRiskRatio7075to7580+se7075to7580))]

LAeqArtDiasRiskRatio7580to8085=length(find(ArtDiasLAeq8085>ArtDiasLAeq7
580Mean))/LengthArtDiasLAeq8085/(LengthArtDiasLAeq7580/LengthLAeq7580)
se7580to8085=alpha*sqrt(((1-
LengthArtDiasLAeq7580/LengthLAeq7580)/LengthArtDiasLAeq7580)+(1-
length(find(ArtDiasLAeq8085>ArtDiasLAeq7580Mean))/LengthArtDiasLAeq8085
/length(find(ArtDiasLAeq8085>ArtDiasLAeq7580Mean))));
confidence7580to8085=[exp(log(LAeqArtDiasRiskRatio7580to8085)-
se7580to8085) exp(log(LAeqArtDiasRiskRatio7580to8085+se7580to8085))]

LAeqArtDiasRiskRatio8085to8590=length(find(ArtDiasLAeq8590>ArtDiasLAeq8
085Mean))/LengthArtDiasLAeq8590/(LengthArtDiasLAeq8085/LengthLAeq8085)
se8085to8590=alpha*sqrt(((1-
LengthArtDiasLAeq8085/LengthLAeq8085)/LengthArtDiasLAeq8085)+(1-
length(find(ArtDiasLAeq8590>ArtDiasLAeq8085Mean))/LengthArtDiasLAeq8590
/length(find(ArtDiasLAeq8590>ArtDiasLAeq8085Mean))));
confidence8085to8590=[exp(log(LAeqArtDiasRiskRatio8085to8590)-
se8085to8590) exp(log(LAeqArtDiasRiskRatio8085to8590+se8085to8590))]
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LAeqArtDiasRiskRatio8590to9095=length(find(ArtDiasLAeq9095>ArtDiasLAeq8
590Mean))/LengthArtDiasLAeq9095/(LengthArtDiasLAeq8590/LengthLAeq8590)
se8590to9095=alpha*sqrt(((1-
LengthArtDiasLAeq8590/LengthLAeq8590)/LengthArtDiasLAeq8590)+(1-
length(find(ArtDiasLAeq9095>ArtDiasLAeq8590Mean))/LengthArtDiasLAeq9095
/length(find(ArtDiasLAeq9095>ArtDiasLAeq8590Mean))));
confidence8590to9095=[exp(log(LAeqArtDiasRiskRatio8590to9095)-
se8590to9095) exp(log(LAeqArtDiasRiskRatio8590to9095+se8590to9095))]

LAeqArtDiasRiskRatio9095to95100=length(find(ArtDiasLAeq95100>ArtDiasLAe
q9095Mean))/LengthArtDiasLAeq95100/(LengthArtDiasLAeq9095/LengthLAeq909
5)
se9095to95100=alpha*sqrt(((1-
LengthArtDiasLAeq9095/LengthLAeq9095)/LengthArtDiasLAeq9095)+(1-
length(find(ArtDiasLAeq95100>ArtDiasLAeq9095Mean))/LengthArtDiasLAeq951
00/length(find(ArtDiasLAeq95100>ArtDiasLAeq9095Mean))));
confidence9095to95100=[exp(log(LAeqArtDiasRiskRatio9095to95100)-
se9095to95100) exp(log(LAeqArtDiasRiskRatio9095to95100+se9095to95100))]

LAeqArtDiasRiskRatio95100to100105=length(find(ArtDiasLAeq100105>ArtDias
LAeq95100Mean))/LengthArtDiasLAeq100105/(LengthArtDiasLAeq95100/LengthL
Aeq95100)
se95100to100105=alpha*sqrt(((1-
LengthArtDiasLAeq95100/LengthLAeq95100)/LengthArtDiasLAeq95100)+(1-
length(find(ArtDiasLAeq100105>ArtDiasLAeq95100Mean))/LengthArtDiasLAeq1
00105/length(find(ArtDiasLAeq100105>ArtDiasLAeq95100Mean))));
confidence100105to100105=[exp(log(LAeqArtDiasRiskRatio95100to100105)-
se95100to100105)
exp(log(LAeqArtDiasRiskRatio95100to100105+se95100to100105))]

LAeqArtDiasRiskRatio100105to105=length(find(ArtDiasLAeq105>ArtDiasLAeq1
00105Mean))/LengthArtDiasLAeq105/(LengthArtDiasLAeq100105/LengthLAeq100
105)
se100105to105=alpha*sqrt(((1-
LengthArtDiasLAeq100105/LengthLAeq100105)/LengthArtDiasLAeq100105)+(1-
length(find(ArtDiasLAeq105>ArtDiasLAeq100105Mean))/LengthArtDiasLAeq105
/length(find(ArtDiasLAeq105>ArtDiasLAeq100105Mean))));
confidence100105to105=[exp(log(LAeqArtDiasRiskRatio100105to105)-
se100105to105) exp(log(LAeqArtDiasRiskRatio100105to105+se100105to105))]




LAeq3035=LAeq(find(LAeq>30 & LAeq<35));
ArtMedelLAeq3035=ArtMedel(find(LAeq>30 & LAeq<35));
LAeq3540=LAeq(find(LAeq>35 & LAeq<40));
ArtMedelLAeq3540=ArtMedel(find(LAeq>35 & LAeq<40));
LAeq4045=LAeq(find(LAeq>40 & LAeq<45));
ArtMedelLAeq4045=ArtMedel(find(LAeq>40 & LAeq<45));
LAeq4550=LAeq(find(LAeq>45 & LAeq<50));
ArtMedelLAeq4550=ArtMedel(find(LAeq>45 & LAeq<50));
LAeq5055=LAeq(find(LAeq>50 & LAeq<55));
ArtMedelLAeq5055=ArtMedel(find(LAeq>50 & LAeq<55));
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LAeq5560=LAeq(find(LAeq>55 & LAeq<60));
ArtMedelLAeq5560=ArtMedel(find(LAeq>55 & LAeq<60));
LAeq6065=LAeq(find(LAeq>60 & LAeq<65));
ArtMedelLAeq6065=ArtMedel(find(LAeq>60 & LAeq<65));
LAeq6570=LAeq(find(LAeq>65 & LAeq<70));
ArtMedelLAeq6570=ArtMedel(find(LAeq>65 & LAeq<70));
LAeq7075=LAeq(find(LAeq>70 & LAeq<75));
ArtMedelLAeq7075=ArtMedel(find(LAeq>70 & LAeq<75));
LAeq7580=LAeq(find(LAeq>75 & LAeq<80));
ArtMedelLAeq7580=ArtMedel(find(LAeq>75 & LAeq<80));
LAeq8085=LAeq(find(LAeq>80 & LAeq<85));
ArtMedelLAeq8085=ArtMedel(find(LAeq>80 & LAeq<85));
LAeq8590=LAeq(find(LAeq>85 & LAeq<90));
ArtMedelLAeq8590=ArtMedel(find(LAeq>85 & LAeq<90));
LAeq9095=LAeq(find(LAeq>90 & LAeq<95));
ArtMedelLAeq9095=ArtMedel(find(LAeq>90 & LAeq<95));
LAeq95100=LAeq(find(LAeq>95 & LAeq<100));
ArtMedelLAeq95100=ArtMedel(find(LAeq>95 & LAeq<100));
LAeq100105=LAeq(find(LAeq>100105 & LAeq<100105));
ArtMedelLAeq100105=ArtMedel(find(LAeq>100105 & LAeq<100105));
LAeq105=LAeq(find(LAeq>105)); ArtMedelLAeq105=ArtMedel(find(LAeq>105));

LAeq3035Mean=nanmean(LAeq3035);
LAeq3540Mean=nanmean(LAeq3540);
LAeq4045Mean=nanmean(LAeq4045);
LAeq4550Mean=nanmean(LAeq4550);
LAeq5055Mean=nanmean(LAeq5055);
LAeq5560Mean=nanmean(LAeq5560);
LAeq6065Mean=nanmean(LAeq6065);
LAeq6570Mean=nanmean(LAeq6570);
LAeq7075Mean=nanmean(LAeq7075);
LAeq7580Mean=nanmean(LAeq7580);
LAeq8085Mean=nanmean(LAeq8085);
LAeq8590Mean=nanmean(LAeq8590);
LAeq9095Mean=nanmean(LAeq9095);
LAeq95100Mean=nanmean(LAeq95100);
LAeq100105Mean=nanmean(LAeq100105);
LAeq105Mean=nanmean(LAeq105);

ArtMedelLAeq3035Mean=nanmean(ArtMedelLAeq3035);
ArtMedelLAeq3540Mean=nanmean(ArtMedelLAeq3540);
ArtMedelLAeq4045Mean=nanmean(ArtMedelLAeq4045);
ArtMedelLAeq4550Mean=nanmean(ArtMedelLAeq4550);
ArtMedelLAeq5055Mean=nanmean(ArtMedelLAeq5055);
ArtMedelLAeq5560Mean=nanmean(ArtMedelLAeq5560);
ArtMedelLAeq6065Mean=nanmean(ArtMedelLAeq6065);
ArtMedelLAeq6570Mean=nanmean(ArtMedelLAeq6570);
ArtMedelLAeq7075Mean=nanmean(ArtMedelLAeq7075);
ArtMedelLAeq7580Mean=nanmean(ArtMedelLAeq7580);
ArtMedelLAeq8085Mean=nanmean(ArtMedelLAeq8085);
ArtMedelLAeq8590Mean=nanmean(ArtMedelLAeq8590);
ArtMedelLAeq9095Mean=nanmean(ArtMedelLAeq9095);
ArtMedelLAeq95100Mean=nanmean(ArtMedelLAeq95100);
ArtMedelLAeq100105Mean=nanmean(ArtMedelLAeq100105);
ArtMedelLAeq105Mean=nanmean(ArtMedelLAeq105);
```

```
LengthLAeq3035=length(LAeq3035);
LengthLAeq3540=length(LAeq3540);
LengthLAeq4045=length(LAeq4045);
LengthLAeq4550=length(LAeq4550);
LengthLAeq5055=length(LAeq5055);
LengthLAeq5560=length(LAeq5560);
LengthLAeq6065=length(LAeq6065);
LengthLAeq6570=length(LAeq6570);
LengthLAeq7075=length(LAeq7075);
LengthLAeq7580=length(LAeq7580);
LengthLAeq8085=length(LAeq8085);
LengthLAeq8590=length(LAeq8590);
LengthLAeq9095=length(LAeq9095);
LengthLAeq95100=length(LAeq95100);
LengthLAeq100105=length(LAeq100105);
LengthLAeq105=length(LAeq105);

LengthArtMedelLAeq3035=length(find(ArtMedelLAeq3035>ArtMedelLAeq3035Mea
n));
LengthArtMedelLAeq3540=length(find(ArtMedelLAeq3540>ArtMedelLAeq3540Mea
n));
LengthArtMedelLAeq4045=length(find(ArtMedelLAeq4045>ArtMedelLAeq4045Mea
n));
LengthArtMedelLAeq4550=length(find(ArtMedelLAeq4550>ArtMedelLAeq4550Mea
n));
LengthArtMedelLAeq5055=length(find(ArtMedelLAeq5055>ArtMedelLAeq5055Mea
n));
LengthArtMedelLAeq5560=length(find(ArtMedelLAeq5560>ArtMedelLAeq5560Mea
n));
LengthArtMedelLAeq6065=length(find(ArtMedelLAeq6065>ArtMedelLAeq6065Mea
n));
LengthArtMedelLAeq6570=length(find(ArtMedelLAeq6570>ArtMedelLAeq6570Mea
n));
LengthArtMedelLAeq7075=length(find(ArtMedelLAeq7075>ArtMedelLAeq7075Mea
n));
LengthArtMedelLAeq7580=length(find(ArtMedelLAeq7580>ArtMedelLAeq7580Mea
n));
LengthArtMedelLAeq8085=length(find(ArtMedelLAeq8085>ArtMedelLAeq8085Mea
n));
LengthArtMedelLAeq8590=length(find(ArtMedelLAeq8590>ArtMedelLAeq8590Mea
n));
LengthArtMedelLAeq9095=length(find(ArtMedelLAeq9095>ArtMedelLAeq9095Mea
n));
LengthArtMedelLAeq95100=length(find(ArtMedelLAeq95100>ArtMedelLAeq95100
Mean));
LengthArtMedelLAeq100105=length(find(ArtMedelLAeq100105>ArtMedelLAeq100
105Mean));
LengthArtMedelLAeq105=length(find(ArtMedelLAeq105>ArtMedelLAeq105Mean))
;


LAeqArtMedelRiskRatio3035to3540=length(find(ArtMedelLAeq3540>ArtMedelLA
eq3035Mean))/LengthArtMedelLAeq3540/(LengthArtMedelLAeq3035/LengthLAeq3
035)
```

```
se3035to3035=alpha*sqrt(((1-
LengthArtMedelLAeq3035/LengthLAeq3035)/LengthArtMedelLAeq3035)+(1-
length(find(ArtMedelLAeq3540>ArtMedelLAeq3035Mean))/LengthArtMedelLAeq3
540/length(find(ArtMedelLAeq3540>ArtMedelLAeq3035Mean))));
confidence3035to3540=[exp(log(LAeqArtMedelRiskRatio3035to3540)-
se3035to3035) exp(log(LAeqArtMedelRiskRatio3035to3540+se3035to3035))]

LAeqArtMedelRiskRatio3540to4045=length(find(ArtMedelLAeq4045>ArtMedelLA
eq3540Mean))/LengthArtMedelLAeq4045/(LengthArtMedelLAeq3540/LengthLAeq3
540)
se3540to4045=alpha*sqrt(((1-
LengthArtMedelLAeq3540/LengthLAeq3540)/LengthArtMedelLAeq3540)+(1-
length(find(ArtMedelLAeq4045>ArtMedelLAeq3540Mean))/LengthArtMedelLAeq4
045/length(find(ArtMedelLAeq4045>ArtMedelLAeq3540Mean))));
confidence3540to4045=[exp(log(LAeqArtMedelRiskRatio3540to4045)-
se3540to4045) exp(log(LAeqArtMedelRiskRatio3540to4045+se3540to4045))]

LAeqArtMedelRiskRatio4045to4550=length(find(ArtMedelLAeq4550>ArtMedelLA
eq4045Mean))/LengthArtMedelLAeq4550/(LengthArtMedelLAeq4045/LengthLAeq4
045)
se4045to4550=alpha*sqrt(((1-
LengthArtMedelLAeq4045/LengthLAeq4045)/LengthArtMedelLAeq4045)+(1-
length(find(ArtMedelLAeq4550>ArtMedelLAeq4045Mean))/LengthArtMedelLAeq4
550/length(find(ArtMedelLAeq4550>ArtMedelLAeq4045Mean))));
confidence4045to4550=[exp(log(LAeqArtMedelRiskRatio4045to4550)-
se4045to4550) exp(log(LAeqArtMedelRiskRatio4045to4550+se4045to4550))]

LAeqArtMedelRiskRatio4550to5055=length(find(ArtMedelLAeq5055>ArtMedelLA
eq4550Mean))/LengthArtMedelLAeq5055/(LengthArtMedelLAeq4550/LengthLAeq4
550)
se4550to5055=alpha*sqrt(((1-
LengthArtMedelLAeq4550/LengthLAeq4550)/LengthArtMedelLAeq4550)+(1-
length(find(ArtMedelLAeq5055>ArtMedelLAeq4550Mean))/LengthArtMedelLAeq5
055/length(find(ArtMedelLAeq5055>ArtMedelLAeq4550Mean))));
confidence4550to5055=[exp(log(LAeqArtMedelRiskRatio4550to5055)-
se4550to5055) exp(log(LAeqArtMedelRiskRatio4550to5055+se4550to5055))]

LAeqArtMedelRiskRatio5055to5560=length(find(ArtMedelLAeq5560>ArtMedelLA
eq5055Mean))/LengthArtMedelLAeq5560/(LengthArtMedelLAeq5055/LengthLAeq5
055)
se5055to5560=alpha*sqrt(((1-
LengthArtMedelLAeq5055/LengthLAeq5055)/LengthArtMedelLAeq5055)+(1-
length(find(ArtMedelLAeq5560>ArtMedelLAeq5055Mean))/LengthArtMedelLAeq5
560/length(find(ArtMedelLAeq5560>ArtMedelLAeq5055Mean))));
confidence5055to5560=[exp(log(LAeqArtMedelRiskRatio5055to5560)-
se5055to5560) exp(log(LAeqArtMedelRiskRatio5055to5560+se5055to5560))]

LAeqArtMedelRiskRatio5560to6065=length(find(ArtMedelLAeq6065>ArtMedelLA
eq5560Mean))/LengthArtMedelLAeq6065/(LengthArtMedelLAeq5560/LengthLAeq5
560)
se5560to6065=alpha*sqrt(((1-
LengthArtMedelLAeq5560/LengthLAeq5560)/LengthArtMedelLAeq5560)+(1-
length(find(ArtMedelLAeq6065>ArtMedelLAeq5560Mean))/LengthArtMedelLAeq6
065/length(find(ArtMedelLAeq6065>ArtMedelLAeq5560Mean))));
```

```
confidence5560to6065=[exp(log(LAeqArtMedelRiskRatio5560to6065)-
se5560to6065) exp(log(LAeqArtMedelRiskRatio5560to6065+se5560to6065))]

LAeqArtMedelRiskRatio6065to6570=length(find(ArtMedelLAeq6570>ArtMedelLA
eq6065Mean))/LengthArtMedelLAeq6570/(LengthArtMedelLAeq6065/LengthLAeq6
065)
se6065to6570=alpha*sqrt(((1-
LengthArtMedelLAeq6065/LengthLAeq6065)/LengthArtMedelLAeq6065)+(1-
length(find(ArtMedelLAeq6570>ArtMedelLAeq6065Mean))/LengthArtMedelLAeq6
570/length(find(ArtMedelLAeq6570>ArtMedelLAeq6065Mean))));
confidence6065to6570=[exp(log(LAeqArtMedelRiskRatio6065to6570)-
se6065to6570) exp(log(LAeqArtMedelRiskRatio6065to6570+se6065to6570))]

LAeqArtMedelRiskRatio6570to7075=length(find(ArtMedelLAeq7075>ArtMedelLA
eq6570Mean))/LengthArtMedelLAeq7075/(LengthArtMedelLAeq6570/LengthLAeq6
570)
se6570to7075=alpha*sqrt(((1-
LengthArtMedelLAeq6570/LengthLAeq6570)/LengthArtMedelLAeq6570)+(1-
length(find(ArtMedelLAeq7075>ArtMedelLAeq6570Mean))/LengthArtMedelLAeq7
075/length(find(ArtMedelLAeq7075>ArtMedelLAeq6570Mean))));
confidence6570to7075=[exp(log(LAeqArtMedelRiskRatio6570to7075)-
se6570to7075) exp(log(LAeqArtMedelRiskRatio6570to7075+se6570to7075))]

LAeqArtMedelRiskRatio7075to7580=length(find(ArtMedelLAeq7580>ArtMedelLA
eq7075Mean))/LengthArtMedelLAeq7580/(LengthArtMedelLAeq7075/LengthLAeq7
075)
se7075to7580=alpha*sqrt(((1-
LengthArtMedelLAeq7075/LengthLAeq7075)/LengthArtMedelLAeq7075)+(1-
length(find(ArtMedelLAeq7580>ArtMedelLAeq7075Mean))/LengthArtMedelLAeq7
580/length(find(ArtMedelLAeq7580>ArtMedelLAeq7075Mean))));
confidence7075to7580=[exp(log(LAeqArtMedelRiskRatio7075to7580)-
se7075to7580) exp(log(LAeqArtMedelRiskRatio7075to7580+se7075to7580))]

LAeqArtMedelRiskRatio7580to8085=length(find(ArtMedelLAeq8085>ArtMedelLA
eq7580Mean))/LengthArtMedelLAeq8085/(LengthArtMedelLAeq7580/LengthLAeq7
580)
se7580to8085=alpha*sqrt(((1-
LengthArtMedelLAeq7580/LengthLAeq7580)/LengthArtMedelLAeq7580)+(1-
length(find(ArtMedelLAeq8085>ArtMedelLAeq7580Mean))/LengthArtMedelLAeq8
085/length(find(ArtMedelLAeq8085>ArtMedelLAeq7580Mean))));
confidence7580to8085=[exp(log(LAeqArtMedelRiskRatio7580to8085)-
se7580to8085) exp(log(LAeqArtMedelRiskRatio7580to8085+se7580to8085))]

LAeqArtMedelRiskRatio8085to8590=length(find(ArtMedelLAeq8590>ArtMedelLA
eq8085Mean))/LengthArtMedelLAeq8590/(LengthArtMedelLAeq8085/LengthLAeq8
085)
se8085to8590=alpha*sqrt(((1-
LengthArtMedelLAeq8085/LengthLAeq8085)/LengthArtMedelLAeq8085)+(1-
length(find(ArtMedelLAeq8590>ArtMedelLAeq8085Mean))/LengthArtMedelLAeq8
590/length(find(ArtMedelLAeq8590>ArtMedelLAeq8085Mean))));
confidence8085to8590=[exp(log(LAeqArtMedelRiskRatio8085to8590)-
se8085to8590) exp(log(LAeqArtMedelRiskRatio8085to8590+se8085to8590))]
```

```
LAeqArtMedelRiskRatio8590to9095=length(find(ArtMedelLAeq9095>ArtMedelLA
eq8590Mean))/LengthArtMedelLAeq9095/(LengthArtMedelLAeq8590/LengthLAeq8
590)
se8590to9095=alpha*sqrt(((1-
LengthArtMedelLAeq8590/LengthLAeq8590)/LengthArtMedelLAeq8590)+(1-
length(find(ArtMedelLAeq9095>ArtMedelLAeq8590Mean))/LengthArtMedelLAeq9
095/length(find(ArtMedelLAeq9095>ArtMedelLAeq8590Mean))));
confidence8590to9095=[exp(log(LAeqArtMedelRiskRatio8590to9095)-
se8590to9095) exp(log(LAeqArtMedelRiskRatio8590to9095+se8590to9095))]

LAeqArtMedelRiskRatio9095to95100=length(find(ArtMedelLAeq95100>ArtMedel
LAeq9095Mean))/LengthArtMedelLAeq95100/(LengthArtMedelLAeq9095/LengthLA
eq9095)
se9095to95100=alpha*sqrt(((1-
LengthArtMedelLAeq9095/LengthLAeq9095)/LengthArtMedelLAeq9095)+(1-
length(find(ArtMedelLAeq95100>ArtMedelLAeq9095Mean))/LengthArtMedelLAeq
95100/length(find(ArtMedelLAeq95100>ArtMedelLAeq9095Mean))));
confidence9095to95100=[exp(log(LAeqArtMedelRiskRatio9095to95100)-
se9095to95100)
exp(log(LAeqArtMedelRiskRatio9095to95100+se9095to95100))]

LAeqArtMedelRiskRatio95100to100105=length(find(ArtMedelLAeq100105>ArtMe
delLAeq95100Mean))/LengthArtMedelLAeq100105/(LengthArtMedelLAeq95100/Le
ngthLAeq95100)
se95100to100105=alpha*sqrt(((1-
LengthArtMedelLAeq95100/LengthLAeq95100)/LengthArtMedelLAeq95100)+(1-
length(find(ArtMedelLAeq100105>ArtMedelLAeq95100Mean))/LengthArtMedelLA
eq100105/length(find(ArtMedelLAeq100105>ArtMedelLAeq95100Mean))));
confidence100105to100105=[exp(log(LAeqArtMedelRiskRatio95100to100105)-
se95100to100105)
exp(log(LAeqArtMedelRiskRatio95100to100105+se95100to100105))]

LAeqArtMedelRiskRatio100105to105=length(find(ArtMedelLAeq105>ArtMedelLA
eq100105Mean))/LengthArtMedelLAeq105/(LengthArtMedelLAeq100105/LengthLA
eq100105)
se100105to105=alpha*sqrt(((1-
LengthArtMedelLAeq100105/LengthLAeq100105)/LengthArtMedelLAeq100105)+(1
-
length(find(ArtMedelLAeq105>ArtMedelLAeq100105Mean))/LengthArtMedelLAeq
105/length(find(ArtMedelLAeq105>ArtMedelLAeq100105Mean))));
confidence100105to105=[exp(log(LAeqArtMedelRiskRatio100105to105)-
se100105to105)
exp(log(LAeqArtMedelRiskRatio100105to105+se100105to105))]



clear all
close all
clc

alpha=1.96;

%Sil vs SPO2
[data,names]=xlsread('SPO2Sil.xlsx');
SPO2=data(:,3);
```

```
Sil=data(:,4);

eq=41
Sil49=Sil(find(Sil<=eq)); SPO2Sil49=SPO2(find(Sil<=eq));
Sil50=Sil(find(Sil>eq)); SPO2Sil50=SPO2(find(Sil>eq));


Sil49Mean=nanmean(Sil49);
Sil50Mean=nanmean(Sil50);

SPO2Sil49Mean=nanmean(SPO2Sil49);
SPO2Sil50Mean=nanmean(SPO2Sil50);

LengthSil49=length(Sil49);
LengthSil50=length(Sil50);

LengthSPO2Sil49=length(find(SPO2Sil49>SPO2Sil50Mean));
LengthSPO2Sil50=length(find(SPO2Sil50>SPO2Sil50Mean));

p1=length(find(SPO2Sil50>SPO2Sil49Mean))/length(SPO2Sil50);
p2=(length(find(SPO2Sil49>SPO2Sil49Mean))/length(SPO2Sil49));
SilSPO2RiskRatio=p1/p2
N1=length(SPO2Sil50);
N2=length(SPO2Sil49);
se=alpha*sqrt((1-p1)/(N1*p1)+(1-p2)/N2*p2);
CI=[exp(log(SilSPO2RiskRatio)-alpha*se)
exp(log(SilSPO2RiskRatio)+alpha*se)]


%Loud vs SPO2
[data,names]=xlsread('SPO2Loud.xlsx');
SPO2=data(:,3);
Loud=data(:,4);

Max=6
Loud49=Loud(find(Loud<=Max)); SPO2Loud49=SPO2(find(Loud<=Max));
Loud50=Loud(find(Loud>Max)); SPO2Loud50=SPO2(find(Loud>Max));


Loud49Mean=nanmean(Loud49);
Loud50Mean=nanmean(Loud50);

SPO2Loud49Mean=nanmean(SPO2Loud49);
SPO2Loud50Mean=nanmean(SPO2Loud50);

LengthLoud49=length(Loud49);
LengthLoud50=length(Loud50);

LengthSPO2Loud49=length(find(SPO2Loud49>SPO2Loud50Mean));
LengthSPO2Loud50=length(find(SPO2Loud50>SPO2Loud50Mean));

p1=length(find(SPO2Loud50>SPO2Loud49Mean))/length(SPO2Loud50);
```

```
p2=(length(find(SPO2Loud49>SPO2Loud49Mean))/length(SPO2Loud49));
LoudSPO2RiskRatio=p1/p2
N1=length(SPO2Loud50);
N2=length(SPO2Loud49);
se=alpha*sqrt((1-p1)/(N1*p1)+(1-p2)/N2*p2);
CI=[exp(log(LoudSPO2RiskRatio)-alpha*se)
exp(log(LoudSPO2RiskRatio)+alpha*se)]

%Sharp vs SPO2
[data,names]=xlsread('SPO2Sharp.xlsx'); SPO2=data(:,3);
Sharp=data(:,4);

Pk=2
Sharp49=Sharp(find(Sharp<=Pk)); SPO2Sharp49=SPO2(find(Sharp<=Pk));
Sharp50=Sharp(find(Sharp>Pk)); SPO2Sharp50=SPO2(find(Sharp>Pk));


Sharp49Mean=nanmean(Sharp49);
Sharp50Mean=nanmean(Sharp50);

SPO2Sharp49Mean=nanmean(SPO2Sharp49);
SPO2Sharp50Mean=nanmean(SPO2Sharp50);

LengthSharp49=length(Sharp49);
LengthSharp50=length(Sharp50);

LengthSPO2Sharp49=length(find(SPO2Sharp49>SPO2Sharp50Mean));
LengthSPO2Sharp50=length(find(SPO2Sharp50>SPO2Sharp50Mean));

p1=length(find(SPO2Sharp50>SPO2Sharp49Mean))/length(SPO2Sharp50);
p2=(length(find(SPO2Sharp49>SPO2Sharp49Mean))/length(SPO2Sharp49));
SharpSPO2RiskRatio=p1/p2
N1=length(SPO2Sharp50);
N2=length(SPO2Sharp49);
se=alpha*sqrt((1-p1)/(N1*p1)+(1-p2)/N2*p2);
CI=[exp(log(SharpSPO2RiskRatio)-alpha*se)
exp(log(SharpSPO2RiskRatio)+alpha*se)]

%Fluct vs SPO2
[data,names]=xlsread('SPO2Fluct.xlsx'); SPO2=data(:,3);
Fluct=data(:,4);

Min=.028
Fluct49=Fluct(find(Fluct<=Min)); SPO2Fluct49=SPO2(find(Fluct<=Min));
Fluct50=Fluct(find(Fluct>Min)); SPO2Fluct50=SPO2(find(Fluct>Min));


Fluct49Mean=nanmean(Fluct49);
Fluct50Mean=nanmean(Fluct50);

SPO2Fluct49Mean=nanmean(SPO2Fluct49);
SPO2Fluct50Mean=nanmean(SPO2Fluct50);
```

```
LengtSPO2luct49=length(Fluct49);
LengtSPO2luct50=length(Fluct50);

LengthSPO2Fluct49=length(find(SPO2Fluct49>SPO2Fluct50Mean));
LengthSPO2Fluct50=length(find(SPO2Fluct50>SPO2Fluct50Mean));

p1=length(find(SPO2Fluct50>SPO2Fluct49Mean))/length(SPO2Fluct50);
p2=(length(find(SPO2Fluct49>SPO2Fluct49Mean))/length(SPO2Fluct49));
FluctSPO2RiskRatio=p1/p2
N1=length(SPO2Fluct50);
N2=length(SPO2Fluct49);
se=alpha*sqrt((1-p1)/(N1*p1)+(1-p2)/N2*p2);
CI=[exp(log(FluctSPO2RiskRatio)-alpha*se)
exp(log(FluctSPO2RiskRatio)+alpha*se)]

%Rough vs SPO2
[data,names]=xlsread('SPO2Rough.xlsx'); SPO2=data(:,3);
Rough=data(:,4);

Min=.93
Rough49=Rough(find(Rough<=Min)); SPO2Rough49=SPO2(find(Rough<=Min));
Rough50=Rough(find(Rough>Min)); SPO2Rough50=SPO2(find(Rough>Min));


Rough49Mean=nanmean(Rough49);
Rough50Mean=nanmean(Rough50);

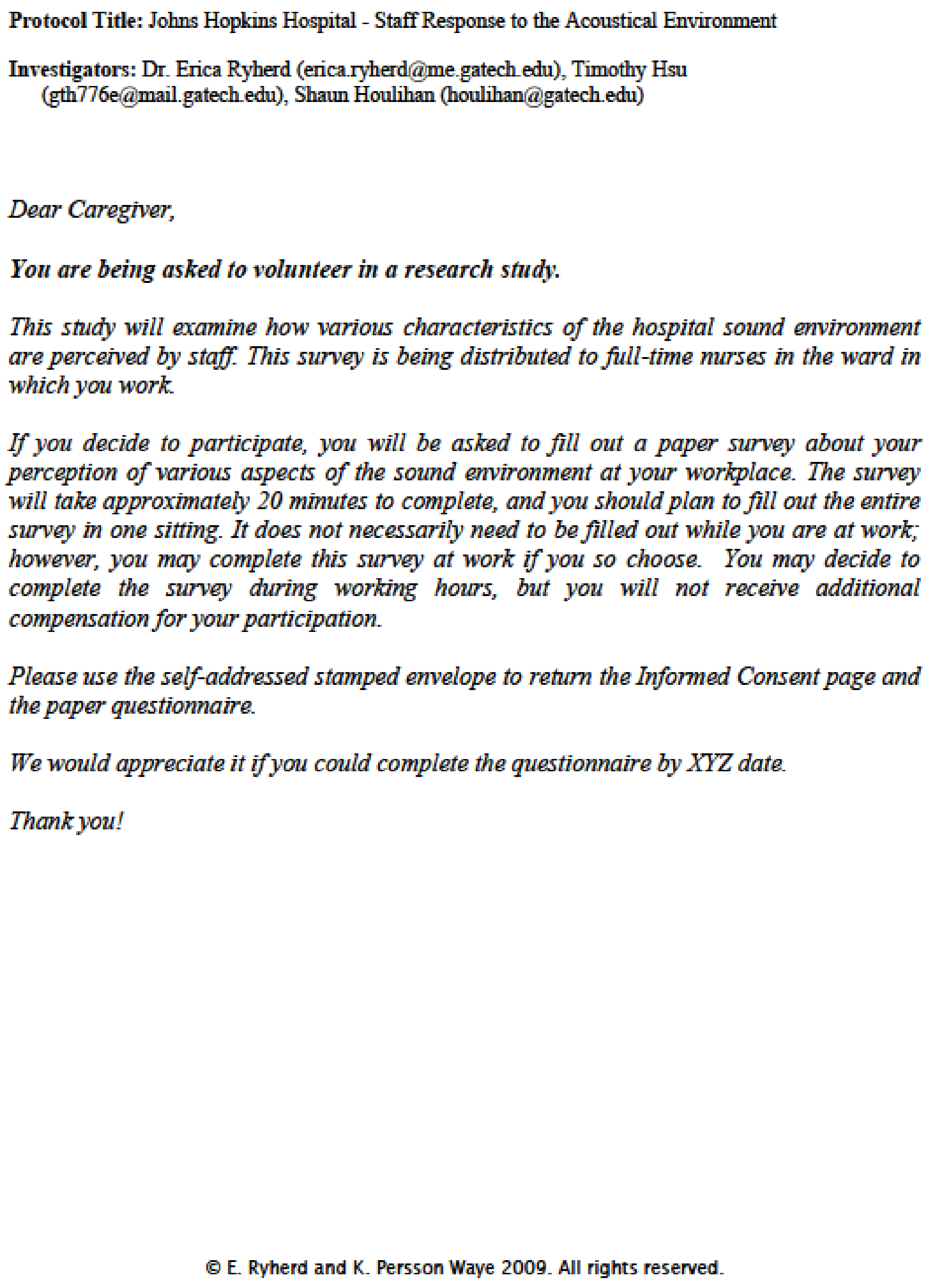
SPO2Rough49Mean=nanmean(SPO2Rough49);
SPO2Rough50Mean=nanmean(SPO2Rough50);

LengthRough49=length(Rough49);
LengthRough50=length(Rough50);

LengthSPO2Rough49=length(find(SPO2Rough49>SPO2Rough50Mean));
LengthSPO2Rough50=length(find(SPO2Rough50>SPO2Rough50Mean));

p1=length(find(SPO2Rough50>SPO2Rough49Mean))/length(SPO2Rough50);
p2=(length(find(SPO2Rough49>SPO2Rough49Mean))/length(SPO2Rough49));
RoughSPO2RiskRatio=p1/p2
N1=length(SPO2Rough50);
N2=length(SPO2Rough49);
se=alpha*sqrt((1-p1)/(N1*p1)+(1-p2)/N2*p2);
CI=[exp(log(RoughSPO2RiskRatio)-alpha*se)
exp(log(RoughSPO2RiskRatio)+alpha*se)]
```

APPENDIX G – JOHNS HOPKINS QUESTIONNAIRE



Protocol Title: Johns Hopkins Hospital - Staff Response to the Acoustical Environment

Investigators: Dr. Erica Ryherd (erica.ryherd@me.gatech.edu), Timothy Hsu (gth776e@mail.gatech.edu), Shaun Houlihan (houlihan@gatech.edu)

Dear Caregiver,

You are being asked to volunteer in a research study.

This study will examine how various characteristics of the hospital sound environment are perceived by staff. This survey is being distributed to full-time nurses in the ward in which you work.

If you decide to participate, you will be asked to fill out a paper survey about your perception of various aspects of the sound environment at your workplace. The survey will take approximately 20 minutes to complete, and you should plan to fill out the entire survey in one sitting. It does not necessarily need to be filled out while you are at work; however, you may complete this survey at work if you so choose. You may decide to complete the survey during working hours, but you will not receive additional compensation for your participation.

Please use the self-addressed stamped envelope to return the Informed Consent page and the paper questionnaire.

We would appreciate it if you could complete the questionnaire by XYZ date.

Thank you!

13. For the following items, indicate how much it the particular sound source bothers you.

	Not at all	A little	A fair amount	A lot	A great deal
Ventilation & air conditioning	☐	☐	☐	☐	☐
Staff talking	☐	☐	☐	☐	☐
Visitors talking	☐	☐	☐	☐	☐
Patients talking	☐	☐	☐	☐	☐
Distress sounds from patients (i.e coughing)	☐	☐	☐	☐	☐
Operational sounds of medical equipment (non-alarm)	☐	☐	☐	☐	☐
Alarms	☐	☐	☐	☐	☐
Footfall noise	☐	☐	☐	☐	☐
Noise from rolling carts	☐	☐	☐	☐	☐
Noise from cleaning equipment	☐	☐	☐	☐	☐
External traffic noise (cars, planes, etc)	☐	☐	☐	☐	☐
Construction noise	☐	☐	☐	☐	☐
Other, what? ____________________	☐	☐	☐	☐	☐

Protocol Title: Johns Hopkins Hospital - Staff Response to the Acoustical Environment

Investigators: Dr. Erica Ryherd (erica.ryherd@me.gatech.edu), Timothy Hsu (gth776e@mail.gatech.edu), Marie Swisher (swishma@jhmi.edu)

Questionnaire

1. Which ward are you currently located at within Weinberg?

5A	5B	5C	5D
☐	☐	☐	☐

2. What is your job title? ____

3. Gender: ☐ Male ☐ Female

4. Age: ______ years old

5. Do you work: ☐ Full-time ☐ Part-time

6. What are your normal working hours?

Morning	Afternoon	Night	Combination of morning, afternoon, and night shifts
☐	☐	☐	☐

7. In an ordinary work week, how many total hours do you work in your ward?

_______ hours

8. How many total hours do you spend on your ward in an ordinary work day?

0-7 hours	8-11 hours	12 or more hours
☐	☐	☐

9. How many years have you worked as a nurse during your entire career?

Less than 1 year	1 to 5 years	6 to 10 years	11 or more years
☐	☐	☐	☐

10. How many years have you worked at your current ward (Weinberg 5A/B/C/D)?

Less than 1 year	1 to 5 years	6 to 10 years	11 or more years
☐	☐	☐	☐

11. Do you notice that the sound environment changes as you go from one location in in your ward to another location in your ward?

☐ No

☐ Yes → What locations do you find to be the most

troublesome and why?________________________

☐ I don't know

12. Does the current visual environment positively or negatively affect how you perceive the sound environment in your ward?

Negatively	Positively	Neither
☐	☐	☐

14. Rate your level of agreement with the following statements, describing how you usually experience the sound environment in your ward.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The sound environment makes it difficult to hear during telephone conversations	☐	☐	☐	☐	☐
I have to consistently raise my voice in order to communicate with others[1]	☐	☐	☐	☐	☐
I have trouble communicating with other staff because of the sound environment[2]	☐	☐	☐	☐	☐
I have trouble communicating with the patients because of the sound environment[2]	☐	☐	☐	☐	☐
The background noise helps keep my conversations from being overheard by others	☐	☐	☐	☐	☐
I tend to rush through work in louder environments so as to escape the noise	☐	☐	☐	☐	☐
The sound environment causes me to make mistakes	☐	☐	☐	☐	☐
The sound environment is a source of stress[2]	☐	☐	☐	☐	☐
The sound environment negatively influences my ability to perform my job tasks	☐	☐	☐	☐	☐
The sound environment is a small problem compared to other work environment problems	☐	☐	☐	☐	☐

15. How much do you believe the sound environment at your ward contributes to this symptom during or just after work?

	Not at all	A little	A fair amount	A lot	A great deal
Headache	☐	☐	☐	☐	☐
Concentration problems	☐	☐	☐	☐	☐
Tiredness	☐	☐	☐	☐	☐
Irritation	☐	☐	☐	☐	☐
Feeling unsociable/ want to be left alone	☐	☐	☐	☐	☐
Trouble staying motivated	☐	☐	☐	☐	☐
Ringing in the ears	☐	☐	☐	☐	☐
Sore throat/ voice strain	☐	☐	☐	☐	☐
Other, what? ____________________	☐	☐	☐	☐	☐

16-20. The remaining questions are not specific to your ward. Fill out these questions based on your experiences in everyday life.

16. Do you have any known hearing impairments?

☐ No

☐ Yes → Type?________________________

☐ I don't know

17. In everyday life, do you have difficulties understanding speech in an environment where there are several others talking at the same time?

☐ No ☐ Yes

18. In everyday life, how often on average do you ask someone to repeat something because you did not fully understand the first time?

Never	Rarely	Sometimes	Often	Very Often
☐	☐	☐	☐	☐

19. How do you think your hearing is?

Very bad	Bad	Normal	Good	Very Good
☐	☐	☐	☐	☐

20. In general, how sensitive are you to noise?[3]

Not at all	A little	Moderately	Considerable	Extremely
☐	☐	☐	☐	☐

<u>Adaptations</u>
[1] From Busch-Vishniac et. al (2005)
[2] From Macleod et. al (2007)
[3] Taken from CAN-168 from Fields' catalog (2001)

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