THE CENTER FOR HEALTH DESIGN® Research Coalition

VALIDATING ACOUSTIC GUIDELINES
FOR HEALTHCARE FACILITIES

Evidence-Based Design Meets Evidence-Based Medicine: The Sound Sleep Study

FINAL REPORT FUNDED BY:

THE CENTER FOR HEALTH DESIGN

RESEARCH PROJECT FUNDED BY

THE CENTER FOR HEALTH DESIGN

FACILITY GUIDELINES INSTITUTE

THE ACADEMY OF ARCHITECTURE FOR HEALTH FOUNDATION

Principal Investigators

Jo M. Solet, PhD
Behavioral Medicine
Harvard Medical School, Division of Sleep Medicine
Cambridge Health Alliance
Corresponding Author

Orfeu M. Buxton, PhD
Neuroscience
Harvard Medical School, Division of Sleep Medicine
Brigham and Women's Hospital

Jeffrey M. Ellenbogen, MD
Neurology
Harvard Medical School, Division of Sleep Medicine
Massachusetts General Hospital

Co-Investigators

Wei Wang, PhD
Statistics
Harvard Medical School, Division of Sleep Medicine
Brigham and Women's Hospital

Andy Carballiera, BM
Acoustics
Cavanaugh Tocci Associates, Inc.
Berklee College of Music

Acknowledgements from the Research Team

Research Team

Jo M. Solet, PhD
Orfeu M. Buxton, PhD
Jeffrey M. Ellenbogen, MD
Wei Wang, PhD
Andy Carballiera, BM

Acknowledgements from the Research Team

Research Institutions:

Harvard Medical School, Division of Sleep Medicine, Boston, Massachusetts
Cambridge Health Alliance, Cambridge, Massachusetts
Brigham and Women's Hospital, Boston, Massachusetts
Massachusetts General Hospital, Boston, Massachusetts

Institutional Review Boards:

Cambridge Health Alliance
Brigham and Women's Hospital
Massachusetts General Hospital

Acoustics Consultants:

Cavanaugh Tocci Associates, Inc., Sudbury, Massachusetts
Gregory Tocci, PE, FASA, INCE Bd Cert.

Sleep Laboratory Staff Members:

Dan Cooper
Vanessa Castro
Carolina Smales
Margaret Merlino
Patrick Sorenson
Farre Nixon

Head Librarian, Cambridge Health Alliance:
Jenny Lee Olsen

Clinical Audiologist Consultant, Brigham and Women's Hospital
Margaret R. Toro, AuD, CCC-A

The Center for Health Design:
Anjali Joseph, PhD, EDAC
Paul Barach, MD, MPH
Bart Franey
Frank Weinberg
Carolyn Quist, MA, EDAC

Facilities Guidelines Institute:
Pamela Blumgart
Kurt Rockstroh, AIA, ACHA
Doug Erickson, FASHE, CHFM, HFDP
Martin H. Cohen, FAIA, FACHA

Academy of Architecture for Health Foundation:
George Tingwald, MD, AIA, ACHA

Research Sponsors

- Academy of Architecture for Health Foundation (AAHF)
- Facilities Guidelines Institute: Healthcare Guidelines Review Committee (FGI/HGRC)
- The Center for Health Design, through its Research Coalition

About The American Institute of Architects Academy of Architecture for Health

The AIA Academy of Architecture for Health is a Knowledge Community of the American Institute of Architects. The mission of the Academy is to improve the quality of healthcare through design by developing, documenting, and disseminating knowledge; educating healthcare architects and other related constituencies; advancing the practice of healthcare architecture; improving the design of healthcare environments; and promoting research.

About The Academy of Architecture for Health Foundation

The mission of the Academy of Architecture for Health Foundation is to support the AIA Academy of Architecture for Health and to enhance the knowledge and effectiveness of those who create healthcare environments through the funding of critical educational and research activities.

About Facility Guidelines Institute

The Facility Guidelines Institute (FGI) is a not-for-profit corporation founded in 1998 to provide continuity in the development of the "Guidelines for Design and

Construction of Healthcare Facilities" (hereafter *"Guidelines")* and to ensure that the document is kept current. FGI functions as a contractual coordinating entity, provides budget management for "*Guidelines"* development, provides formal interpretations of the "*Guidelines"*, and is focused on enhancing the content and format of the *"Guidelines"* to encourage its application and use. Funding research projects related to *"Guidelines"* development is one of the important functions performed by FGI in support of its mission, which is to *"Promote the process of producing consensus-based guidelines, ADVISED BY RESEARCH, to advance quality healthcare."*

FGI's Research and Development Subcommittee manages the process of reviewing and recommending proposals related to important research initiatives identified by the Health Guidelines Revision Committee (HGRC)—the formal voting entity for the *"Guidelines"* revision process. As part of the 2010 edition cycle—the third edition of the *"Guidelines"* managed by FGI—noise concerns in healthcare facilities were identified as one of the most important issues requiring attention. The research proposal submitted by Jo M. Solet, PhD and her collaborating team from Harvard Medical School, Division of Sleep Medicine, provided an exciting opportunity for FGI to fund research important to improving the content of the *"Guidelines"* and to advance quality healthcare. FGI anticipates that this is the first of several noise related research initiatives that will be funded, in whole or in part, through FGI as they work to constantly improve the content of the *"Guidelines"* as a dynamic and current document.

For an in depth history of the *"Guidelines"* and more information on FGI, go to the website at www.fgiguidelines.org

About The Center for Health Design

THE CENTER FOR HEALTH DESIGN®

The Center for Health Design (CHD) formed in 1993, is a nonprofit research and advocacy organization of forward-thinking healthcare, elder care, design and construction professionals, and product manufacturers who are leading the quest to improve the quality of healthcare facilities and create new environments for healthy aging. The CHD Research Coalition promotes the dissemination of evidence-based design research that contributes to therapeutic, safe, efficient, and ef-

fective healthcare settings. The group is comprised of experienced researchers, design practitioners, and healthcare administrators. They help develop requests for proposals, select appropriate teams to conduct each research study, monitor the progress of research studies, and critique the drafts of the final reports.

CHD's Research Coalition funds exist to support cutting edge research in evidence-based design (EBD) that fill critical gaps in the field. Also, by rewarding funds to EBD research, the group strives to grow the network of researchers who are engaged in EBD. All research studies funded by the Research Coalition are put through a peer-review process.

CHD Research Coalition

Paul Barach, MD, MPH, *Co-chair*
Frank Weinberg, *Co-chair*
Frank Becker, PhD
Roger Call, AIA, ACHA, LEED AP
Bart Franey, *Co-Chair Emeritus*
Debra Harris, PhD, RID, AAHID
Kathy Hathorn, MA
Anjali Joseph, PhD, EDAC
Roger Leib, AIA, ACHA, LEED AP
Debra Levin, MA, EDAC
Eileen Malone, RN, MSN, MS, EDAC
Mark Patterson, AIA AAH, LEED AP
Debajyoti Pati, PhD, FIIA, LEED AP
Jane Rohde, AIA, ACHA, AAHID, IIDA, NCARB, LEED AP
Mardelle Shepley, DArch, AIA, EDAC
W. H. (Tib) Tusler, FAIA, FACHA, *Chairman Emeritus*
Roger Ulrich, PhD, EDAC
Jean Young, ASID, CID, AAHID
Frank Zilm, DArch, FAIA, FACHA
Craig Zimring, PhD, EDAC

The Center for Health Design (CHD) is a 501(c)(3) organization.

Published by The Center for Health Design
www.healthdesign.org

How to cite this paper:
Solet, J. M., Buxton. O.M., Ellenbogen, J.M., Wang, W., and Carballiera, A. (2010). Evidence-based design meets evidence-based medicine: The sound sleep study. Concord, CA: The Center for Health Design.

Corresponding author: Jo M. Solet, PhD
Phone: 617-547-3373
Joanne_Solet@HMS.Harvard.edu
15 Berkeley Street
Cambridge, MA 02138 USA

Keywords: *acoustic arousal thresholds, sleep disruption, hospital noise, healthcare quality*

Executive Summary

National healthcare quality surveys have found that noise in hospitals is an urgent concern. The purpose of this study was to demonstrate the impact of hospital noise on all stages of human sleep by developing sleep arousal probability threshold curves for specific hospital-based sounds. Most hospital sound sources were recorded on-site corresponding to specific categories identified in the American Institute of Architects' Draft Interim Guideline on Sound and Vibration in Healthcare Facilities. Fourteen sounds were chosen and calibrated for dynamic presentation. They were transmitted through an array of speakers positioned in a hospital sleep laboratory room. Sounds were delivered in rising 5 decibel-step exposures from 40 to 70 dB(A), with steady 32 dB(A) night background levels from air-handling equipment.

Noise-related sleep arousals were recorded and quantified using current American Association of Sleep Medicine EEG criteria. These arousals were summed for each sleep stage by sound type at each decibel step level and then plotted as arousal probability thresholds. The results provide evidence that repeated arousals occur from common hospital noises at typical decibel levels even in healthy young adults. The reported responses varied with the sound stimulus characteristics and across different sleep stages.

The Problem

Healthcare quality surveys report patient sleep disruption from noise as a very common and serious complaint. Disrupted and/or limited sleep has been demonstrated to have adverse impacts on several important health measures and outcomes including blood pressure, weight gain, heart disease, pain, stress levels, and inflammation. However, no quantification of the relationship of common hospital sounds to patient arousal has been available to guide policy, design and technical innovation.

The Stakeholders

Patients and Families: The most vulnerable patients are the youngest and sickest, those admitted for the longest periods, or those exposed to high hospital census.

Caregivers and Staff: Their challenge is to offer compassionate care and to make critical time sensitive decisions in high stress environments.

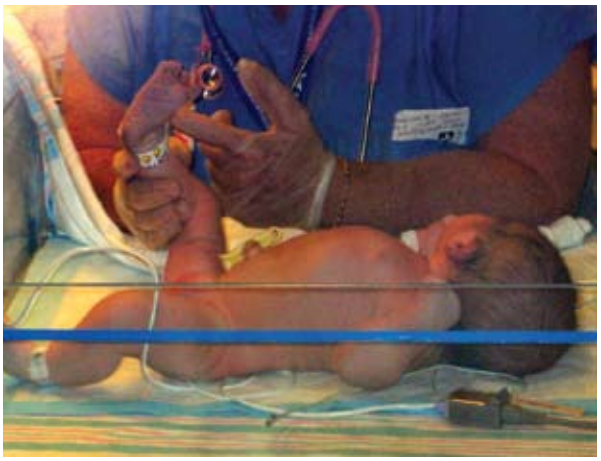


FIGURE 1
The stakeholders, neonate

FIGURE 2
The stakeholders, elderly woman (photo source: Jo M. Solet)

Government Regulators: They are responsible for structuring the funding of care, especially for older patients. As a wave of baby boomers reaches the age when health typically declines, expanded need for care is anticipated.

Hospital Board and Management: Leaders must balance budgets in the face of rising expenses while delivering quality care.

Employers and Insurers: They seek cost effective care, placing patients in settings where insurance dollars translate into clinical outcomes.

Research Methods and Materials

Twelve sleeping fully-monitored healthy adult human subjects were exposed to a series of 14 hospital sounds, including voices, derived from the recording of an in-patient medical-surgical unit. The sounds were delivered in rising decibel level steps during all stages of sleep at a Harvard Medical School affiliated sleep laboratory.

Summary of Research Project Steps

The research steps of this project included:

- Record real hospital sounds to develop a "virtual hospital" soundscape.
- Expose subjects, during all sleep stages, to soundscape components.
- Quantify specific physiological and cognitive responses.
- Demonstrate sleep arousal probability thresholds.
- Organize outcome data to inform the Acoustic Guidelines.

Summary of Research Project Requirements

The selection, screening, and physiological measurement of sleep disrupted participants in this study required:

- Adult human subjects who had no medical or psychological problems, including sleep and hearing disorders.
- Robust methodology for presenting adequate numbers of scientifically valid reproducible sound stimulus exposures to subjects during 2 full nights of sleep monitoring.
- Analysis of all subject arousals attributable to sound stimulus exposures, controlling for depth of sleep at stimulus presentation and loudness of sound (with repeated measures for statistical precision).

Key Findings and Recommendations

The combined responses of all sleeping subjects are reported as sleep-stage-specific arousal probability curves. The curves demonstrate the percentage of those subjects experiencing lightened sleep or full arousal for each of 14 sounds (stimuli) at stepwise decibel levels from 40 to 70 dB(A).

A. Phone and intravenous infusion pump alarms, which are intentionally designed to be alerting, were effective in evoking the highest arousal probabilities.

Recommendations:

- Answer IV alarms promptly and lower background sound levels so important alarm signals can be easily discerned.
- Reduce telephone ring tone volume to prevent transmission beyond the patient rooms.
- Set telephones to stop after a specific number of rings.

B. Staff conversations, as well as voice paging, were also shown to be highly alerting. The threshold curves for voice stimuli are consistent with the arousal recollections reported by our subjects and documented as troublesome in healthcare quality surveys. Voice level exposures can be modified behaviorally as well as through design and construction solutions. Some variation was identified among sleep stages, with light sleep (NREM2) showing the least protection from voices as well as other acoustic disruptions.

Recommendations:

- Materials and surfaces should be chosen to limit sound transmission from nurses' stations.
- Special consulting spaces should be allocated for nurses in which voice-based information can be transferred away from open hall areas, yet not far from nursing stations.
- Protocols such as dimming hall lights at night as a "quiet cue" should be incorporated as part of behavioral protocols to limit sleep disruption by staff voices.

C. Exterior noises, those coming from outside the hospital building (jets, helicopters, road traffic) were found to be the least arousing stimuli at levels tested. Jets and helicopters may actually be experienced by patients at levels louder than those tested here. Further, the vibration and low frequency components experienced with actual exposures were not fully duplicated in our study and may in reality impact sleep arousal.

Recommendations:

- Site considerations are critical to reduce air, train, and road traffic noise exposure.
- When site options are limited, enhanced building envelope solutions must be put in place to protect patients.
- Increasing concerns with regard to low frequency sounds, such as those attributed to airplane over flights and wind turbines, call for additional consideration of protective building envelopes, especially in rural areas where ambient noise levels have historically been low.

D. With regard to other stimuli, those with shifting contours (towel dispenser, door close, toilet flush, ice machine) tended to be more arousing than those with continuous contours (traffic and laundry cart).

Recommendations:

- Ice machines should be architecturally isolated from patient areas or dramatically re-engineered.
- Quieter or low-tech alternatives for automatic hand towel dispensers (often described as disruptive by patients) should be substituted.
- Proper door hardware will limit latch noises; door gasket selection will better protect patients from hall and nurses' station noise, as well as blocking transfer out of noise generated within that patient room.
- Policy regarding keeping patient doors open should be re-examined. Other options should be considered, including systems-level solutions such as telemetry to a common station and assignment of staff to specific patients, allowing them to be individually alerted to patient needs.

Conclusion

Our results provide evidence in support of incorporation of minimum acoustic standards as part of the *Guidelines for Design and Construction of Health Care Facilities.* An estimated $240 billion price tag has been placed on healthcare construction for the period 2009 through 2013 (Jones, 2009). In this context the cost implications of additional requirements call for justification.

We are now witnessing a transformation in healthcare reimbursement to a "pay for performance" model. Design and construction mandates related to acoustics can be expected to enhance performance through more accurate communication, increased speech privacy and HIPAA compliance, lowered staff stress levels, decreased medical errors, and limited patient sleep disruption. Together these should produce better clinical outcomes, reduce staff turnover rates, and provide advantages in the competitive marketplace, all of which carry positive cost implications.

Contents

List of Figures

1. Introduction

1.1 Hospital Room Noise and Quality of Care Indicators

Healthcare quality surveys report patient sleep disruption from noise as a very common and serious complaint, yet no quantification of the relationship of common hospital sounds to patient arousal has been available to guide innovation and quality improvement.

Two partner agencies in the Department of Health and Human Services—The Center for Medicare and Medicaid Services (CMS) and the Agency for Healthcare Research and Quality (AHRQ)—have together developed a comprehensive survey for "Hospital Consumer Assessment of Healthcare Providers" known as "HCAHPS". Formally endorsed by the private National Quality Forum (NQF), the purpose of this survey is to standardize collection and encourage public reporting of patients' perspectives on care in hospitals. Reporting of patient assessments is intended to provide greater transparency and accountability as well as incentives for improvement.

This 27-item survey, launched as a national initiative, includes demographics of the reporting patients, broad ratings of satisfaction, and very specific questions related to perceived quality of care, including communication with doctors and nurses, information about medications and discharge, pain control, and ratings of room cleanliness and quiet. Patients are given alternative rating options of "never, sometimes, usually, and always" for questions which include "During this hospital stay, how often was the area around your room quiet at night?"

The first data from the HCAHPS survey became available in March 2008 and were analyzed by the Department of Health Policy and Management at The Harvard School of Public Health and The Division of General Medicine at Brigham and Women's Hospital, together with the Boston Veterans Affairs Healthcare System. On average, 36% of patients reported on 60% of US hospitals. Jha et al, reporting in the October 30, 2008 *New England Journal of Medicine*, reviewed the findings and provided analyses based on certain hospital characteristics, including nursing staff ratios, academic/teaching connections, and profit/not-for-profit status. For all

hospital categories, **the rating of "quiet room" as "always" was lower than any of the other quality indicators at between 50.8 and 55.2% of respondents**. This finding confirms quality surveys and validates overwhelming numbers of patient self-reports regarding disturbing degrees of hospital noise which degrade clinical outcomes through multiple mechanisms, which are listed below.

- Stress responses
- Medical errors
- Lost privacy
- Sleep disruption

1.2 Hospital Noise and Clinical Outcomes

More than just an annoyance factor, frequent failure to provide patients with quiet rooms affects clinical outcomes through several mechanisms, including increased physiological arousal and stress responses, medical errors, interference with speech privacy and sleep disruption. Sleep disruption has been linked to numerous events and conditions including increased falls, elevated physiological indicators of inflammation, altered glucose metabolism, elevated blood pressure, and increased pain. Prior in situ research studies analyzing the effect of *improved* acoustic environments on hospitalized patients have included decreased re-hospitalization rates, improved sympathetic arousal and higher patient satisfaction ratings, as compared with "ordinary" hospital environments. See Bibliography: Sleep and Health.

FIGURE 1
Consequences of poor sleep

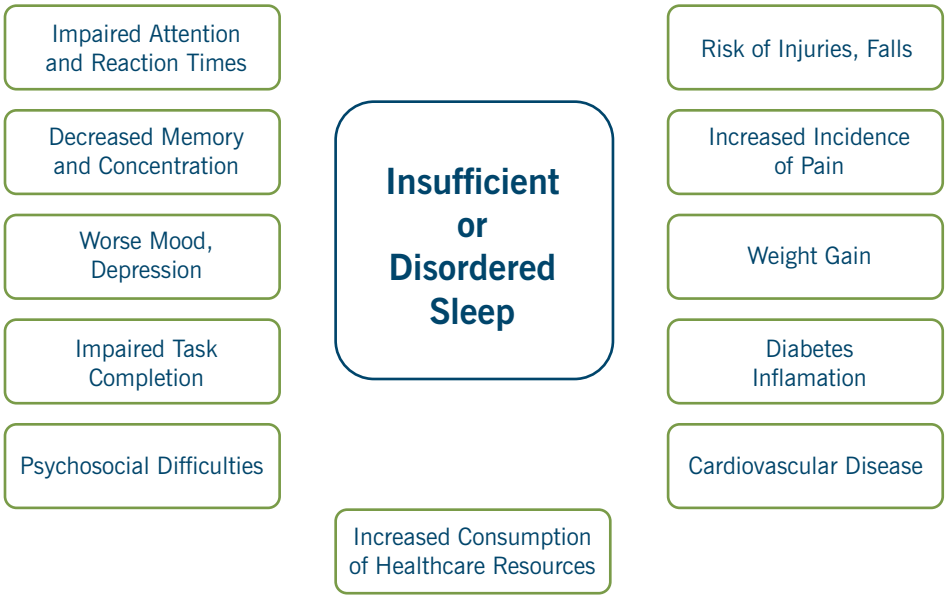


Figure 1 shows the multiple consequences over time of disrupted or limited sleep. In many medical settings not only are the patients sleep deprived, so are the some of the caregivers.

1.3 This Study

No determination has been made in the healthcare quality literature of what functionality constitutes a good acoustic environment for sleep in the hospital. Arousal probability threshold "benchmarks" for quality have not been established. Broad decibel-level guidelines include the Environmental Protection Agency (EPA) recommended maximum noise levels of 40 dB(A) in hospitals, and the World Health Organization (WHO) recommended maximum levels of 30 to 40 dB(A) in patients' rooms at night. The 2010 *Guidelines for Design and Construction of Health Care Facilities* include updated recommendations and minimum standards for acoustics in specific hospital environments. The purpose of this study was to demonstrate the impact of hospital noise on all stages of human sleep by developing sleep arousal probability threshold curves to specific hospital-based sounds.

1.4 Sleep Science Key Concepts

The arousal effect of a diverse set of acoustic insults impacting sleep can be measured and interpreted through exposure of sleeping human subjects, based on the following concepts from sleep science:

- The architecture of sleep is built of sleep cycles of approximately 90 minutes each. The composition of the cycles changes during a normal night's sleep.
- A greater proportion of deep sleep (NREM3) occurs earlier in the night and a greater proportion of dream sleep toward morning.
- Healthy young adults have 50 to 80 minutes of the deeper stages of sleep per night. The amount of this deep, more protected sleep decreases with normal aging.
- Arousal from sleep requires a greater intensity of stimulus during the deeper most protected stages of sleep.
- Valid quantification of the arousing nature of acoustic insults requires simultaneous measurement of sleep stages and brain arousal patterns through electroencephalogram recordings during presentation of well-defined stimuli.

2. Methods

2.1 Project Phases

The research project was conducted in three phases:

- Phase 1: Recordings of actual hospital sound sources were captured
- Phase 2: Pilot study tested methodology
- Phase 3: 12 subjects were exposed to the 14 sound stimulus protocol

Phase 1: Sound Recordings

Acoustic insults relevant to a real healthcare environment have not before been quantified in a controlled laboratory setting. Recordings of actual hospital sound sources were captured onsite at Somerville Hospital, part of the Cambridge Health Alliance, on an in-patient medical unit in Somerville, Massachusetts. The unit was selected because of a parallel research project to study altered night care routines to decrease noise and to limit patient sleep disruptions by staff. The fourteen acoustic "event" sound sources, the majority of which were derived from the recorded soundscape, (see Figure 2) correspond to specific categories identified in the AIA Draft Interim Guideline on Sound and Vibration in Healthcare Facilities.

FIGURE 2
Recorded acoustic "events" for subject exposure

EVENTS

C – Calibration
1 – Door
2 – Helicopter
3 – Ice machine
4 – IV Alarm
5 – Jet
6 – Laundry Cart
7 – Phone
8 – Snoring
9 – Toilet
10 – Traffic
11 – Towel dispenser (electric)
12 – Bad conversation
13 – Good conversation
14 – Paging

Technical Review of Acoustic Methodology and Derivation of Stimuli

Each Phase 1 sound source recording or "acoustic event" was truncated to 10 seconds and then spatialized within the Nuendo DAW (Digital Audio Workstation) environment. This imparted spatial qualities to the virtual sound experience, especially to some stimuli which were dynamic. For example, Door Close would always be expected to occur at the same place within the room, so its spatial position in the sound-field was held constant. Conversely, a significant component of the sound of an airplane is movement through space. The DAW environment allowed simulation of the spatial position of the sound sources, presenting sleeping subjects with the motion component of the soundfield that has not always been well-developed and applied in previous studies.

Decibel Exposure Levels

After the reference level was set, the sources were scaled downwards in 5 dB(A) increments, yielding 7 files per source, corresponding to reference exposure levels of 40, 45, 50, 55, 60, 65 and 70 dB(A). These sound files were played back through the loudspeaker array. Sound sources were presented from the lowest exposure level (40 dB(A)Leq,10-sec) and ramped upward until an arousal was detected, at which point a subject recovery period was initiated, lasting until the sleep stage was judged to be steady.

Subjects were exposed to the 14 stimuli described earlier using an array of four studio monitor loudspeakers (type Event PS6). The speakers were arranged in a modified ITU-R BS775-1 pattern (see Figure 3), omitting the center loudspeaker (which is typically reserved for the dialogue channel in film). Stimuli were delivered to the speakers via an 8-channel audio interface device connected to a laptop computer. The equivalent sound level ($LA_{eq,10\text{-}sec}$) was employed in delivery, consistent with other reported research on the clinical effects of noise. In order to control the overall noise dose received by each sleeping subject, the playback system was carefully calibrated. This was accomplished by playing a pink noise signal through each loudspeaker at equal sound pressure level until a pre-determined sound level was reached.

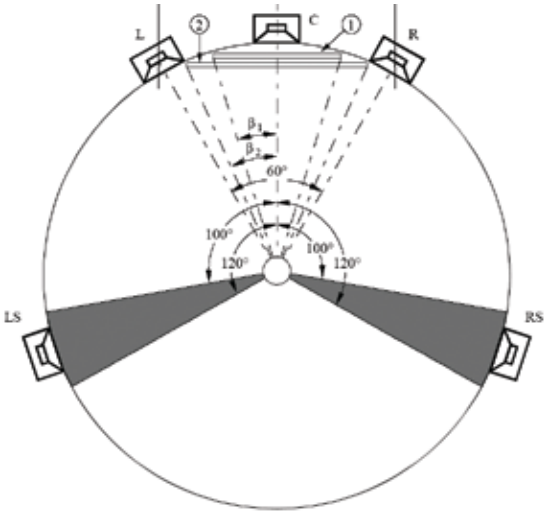


FIGURE 3
4.0 surround configuration (quadro) Sound files were played back through the loudspeaker array.

Pink noise was generated digitally and the resulting audio file was scaled to the reference A-weighted sound pressure level. In the case of the current work, a digital sound file with equivalent sound level of -16 dB(A)(FS) corresponds to an airborne equivalent sound level of 74 dB(A)(SPL).

Once the calibration reference was established, each sound source was normalized, such that its equivalent sound level ($LA_{eq,10\text{-}sec}$), as compared to the calibration reference level, was 70 dB(A). Because both the integrated equivalent sound level and the length of the stimuli exposures were held constant, the stimuli were effectively normalized for "noise dose", an integration of the equivalent sound level over time.

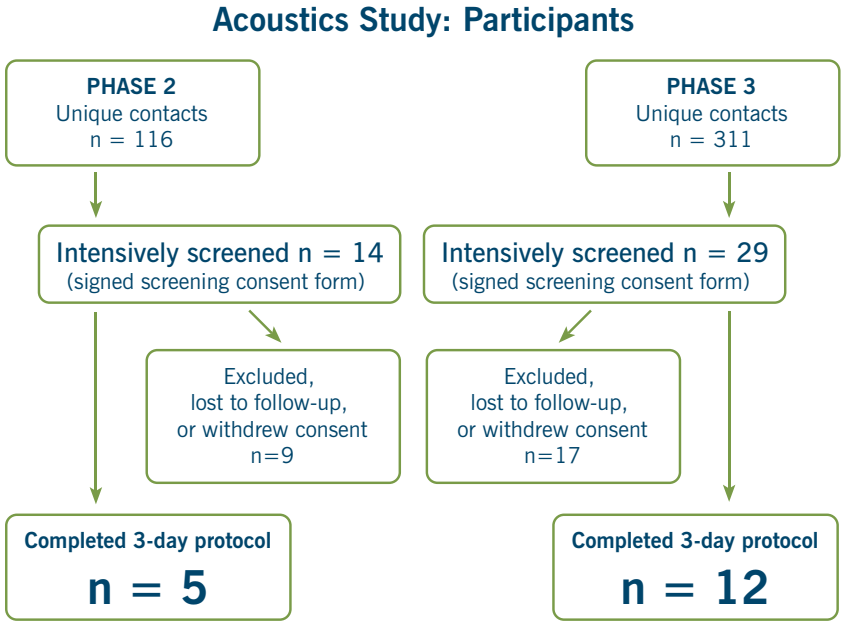
Phase 2 (Pilot Study) Recruitment and Institutional Review Board Approval

All recruitment and study procedures for Phase 2 were approved by the Human Research Committees of the Brigham and Women's Hospital (BWH) and the Cambridge Health Alliance (CHA) and conducted according to the principles of human research subject protections expressed in the Declaration of Helsinki. Through April 2008, 5 subjects completed the phase 2 pilot study at Brigham and Women's Hospital, all of whom met specific criteria initially through phone interview and then through careful in-person screening. The phase 2 pilot study led to the addition of voice stimuli to the pilot protocol and incorporation of enhanced technology and lower ambient sound levels in place for Phase 3. See Figure 4 for a chart of subjects evaluated in Phase 2 and Phase 3 of the study.

FIGURE 4
Subject participation for Phases 2 and 3

Phase 2:
Pilot study tested methodology

Phase 3
Subjects were exposed to 14 sound stimulus events



Phase 3 Recruitment and Institutional Review Board Approval

All recruitment and study procedures for Phase 3 were approved by the Human Research Committees of the Brigham and Women's Hospital, Massachusetts General Hospital (MGH) and the Cambridge Health Alliance and were conducted according to the principles of human research subject protections expressed in the Declaration of Helsinki.

On each visit, the subjects answered direct questions about their ongoing health and current medical conditions. Their sleep and wake patterns from the beginning of the screening procedures until the completion of the study were fully reviewed. A licensed physician performed physical exams at screening interviews and at admission. On each inpatient day, study subjects received careful monitoring of vital signs by registered nurses who were available for direct-response and oversight.

FIGURE 5
Summary of completed phase 3 subjects (11/08)

PHASE 3				
UNIQUE SUBJECT CONTACTS	**SIGNED SCF**	**SIGNED RCF**	**DISEMPANELED**	**COMPLETED**
311	29	14	1	12

SCF= Screening Consent Form
RCF=Research Consent Form

Twelve subjects completed Phase 3 at the Massachusetts General Hospital (MGH) Sleep Laboratory, all of whom met specific identified criteria first through phone interview and then through in-person screening. One subject was excluded due to possible cardiac irregularities. See Figures 5 and 6 for information on Phase 3 subject contacts and participants.

FIGURE 6
Phase 3 subject demographics

Summary Of Demographics For Phase 3 Subjects			
SUBJECT #	**GENDER**	**AGE**	**RACE & ETHNICITY**
1	Female	23	Asian
2	Male	25	Asian
3	Male	29	Black, Non-Hispanic
4	Male	30	White, Hispanic
5	Female	30	White, Non-Hispanic
6	Male	20	White, Non-Hispanic
7	Male	25	White, Non-Hispanic
8	Female	46	White, Non-Hispanic
9	Female	22	White, Non-Hispanic
10	Female	26	White, Non-Hispanic
11	Female	22	White, Non-Hispanic
12	Female	21	White, Unknown

Subject Screening Criteria

The following subject-screening criteria were used for Phase 2 (Pilot Study) and Phase 3:

- *Sleep/Wake History*. Volunteers must currently maintain a regular sleep/wake schedule (±2 hr average bedtime) and express willingness to continue to follow a regular sleep-wake schedule.
- *Drug/Alcohol Use.* Volunteers must be drug-free (including nicotine). No medications (prescription or over the counter) that significantly affect circadian rhythms or sleep allowed. Subjects must report no history of drug or alcohol dependency. A comprehensive toxicological analysis of urine for prescription medication, non-prescription medication, drugs of abuse, and caffeine, nicotine, and alcohol metabolites was carried out for verification of reported non-use at screening and at admission.
- *Evaluation of Medical Suitability.* Only healthy men and women were selected for this study. Subjects were free from any acute, chronic, or debilitating medical conditions. Normality was established on the basis of clinical history and a physical examination conducted by a licensed physician. Any subject with symptoms of active illness, such as fever, infection, or hypertension, was excluded.

- *Evaluation of auditory function.* Subjects with significant impairments of the auditory system were excluded, using a defined normal Hearing Level (HL) threshold through standard audiometric screening of each ear. All subjects were tested at 25 db at 500, 1000, 2000, and 4000 Hz.
- *Evaluation of Psychiatric/Psychological Suitability.* Individuals with a history of psychiatric illnesses or psychiatric disorders were excluded. Individuals who were unaware of specific psychiatric diagnoses but had a history of treatment with antidepressant, neuroleptic medications, or major tranquilizers were excluded from the study. Subjects were also questioned to demonstrate their full understanding of the requirements, demands, and risks of the study and informed of the option to withdraw at any time.

Technical Information on Special Equipment

Phase 3 PSG recordings were collected at the MGH Sleep Laboratory through use of GRASS systems for PSG/EEG sleep recording and TWIN software. Phase 3 recordings included the addition of frontal (F3 and F4) EEG leads for scoring and staging, using established criteria from the American Academy of Sleep Medicine. This equipment also afforded the opportunity, using infrared video recordings, to document subjects' body positions, allowing for recognition of partial obstruction of the ear (such as ear against pillow), as a possible co-variant for later analyses. All surface electrodes (Beckman Instrument Company, Schiller Park, Illinois) for recording electroencephalograms (EEG), electrooculograms (EOG), electromyograms (EMG), and electrocardiograms (ECG) were applied at least 2 hours prior to the scheduled sleep period.

General Study Pre-admission Procedures—Outpatient

During a pre-study period, subjects slept at home on a regular schedule for at least 4 days prior to their sleep study (bedtime ±2 hr). Subjects wore wrist actigraphy monitors that recorded activity levels as consistent with sleep or wakefulness. They also completed sleep diaries to ensure compliance with the required schedule.

General Study Procedures and Methods—Inpatient

Immediately following their pre-study period for Phases 2--at Brigham and Womens' Hospital (BWH)--and 3--at Massachussetts General Hospital (MGH)--subjects were admitted to the sleep laboratory rooms in the late afternoon or early evening. Subjects stayed in the labs and slept overnight, starting at approximately their normal bedtimes for an 8.5 hour duration. They were instructed not to nap during scheduled wake times and to continue wearing wrist actigraphy monitors to verify sleep-wake schedules. Inpatient environment and conditions included nurses and/or technicians present 24 hours a day to carry out the protocol, interact with the volunteers, perform polysomnographic (PSG) recording of sleep electroencephalograms (EEG), check vital signs, deliver meals, monitor performance testing, and ensure wakefulness was maintained during scheduled wake times. Light levels were approximately 90 lux while subjects were awake and less than 1 lux during sleep. A project leader or co-investigator visited the subjects at least once daily to allow for adverse event reporting and to undertake routine procedures ensuring accurate data collection. Neurobehavioral performance and subjective sleepiness were assessed at regular intervals during the scheduled waking period.

Technical Information on Sleep Laboratory Environment

For Phase 3 at MGH, a fully dedicated sleep lab room (see Figure 7) was used in which the exposure layout was held completely constant across subjects. Because recommended background sound levels for testing should ideally be at least 10 dB(A) below the signal level, a sound attenuation plenum was designed and installed remediating sound from the air handling equipment. In addition, it was recommended that the heat pump HVAC unit serving the space be mounted on neoprene vibration isolation pads and run continuously (not intermittently) in order to reduce changes and structure-borne sound. Complete silence is neither possible to achieve in a real hospital setting nor actually as protective of sleep or privacy for patients as a low to moderate continuous background sound level like that achieved in the sleep lab for this study.

During late night hours when sleeping subjects were being tested, sound from outside the building was minimal; background sound levels were roughly 32 dB(A) with the plenum installed. During the day when study subjects were awake, the background level with plenum was roughly 35 dB(A), due to outside noise from activity transmitted into the lab through the large glass window.

On the first night (quiet baseline night), sleep was not disturbed for an 8.5 hr period, unless technical issues arose that required immediate attention. EEG recordings of sleep were collected. On the subsequent two nights, acoustic event stimuli were presented. On all three nights, sleep disruption and EEG arousals were quantified by PSG recordings from skin surface electrodes per current AASM criteria for sleep/wake and cortical arousal determination.

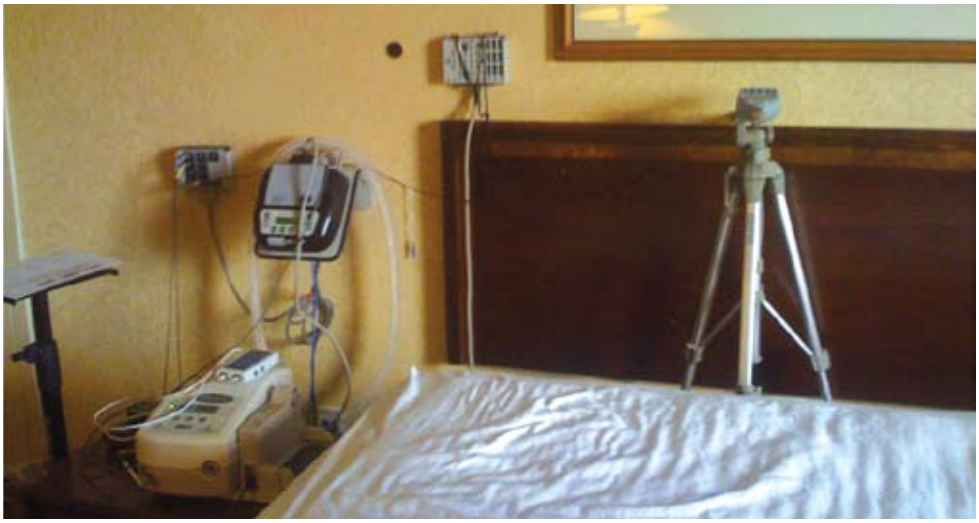


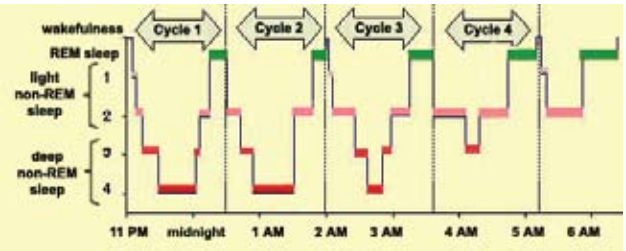
FIGURE 7
Sleep laboratory room with equipment in place

Sound Stimulus Presentations

A sleep specialist in attendance across the sleep periods presented the soundscape-derived acoustic "events" (see Figure 2) in counter-balanced, randomized order in real time, following EEG-defined evidence of entry to each sleep stage from NREM stage 2, stage 3, and REM (rapid eye movement - dream sleep) sleep. Data for each of the stimuli were manually scored by the sleep specialist for presence of cortical arousal on the EEG and frank awakenings lasting at least one epoch (30 seconds), contemporaneous with the presentation of an acoustic stimulus.

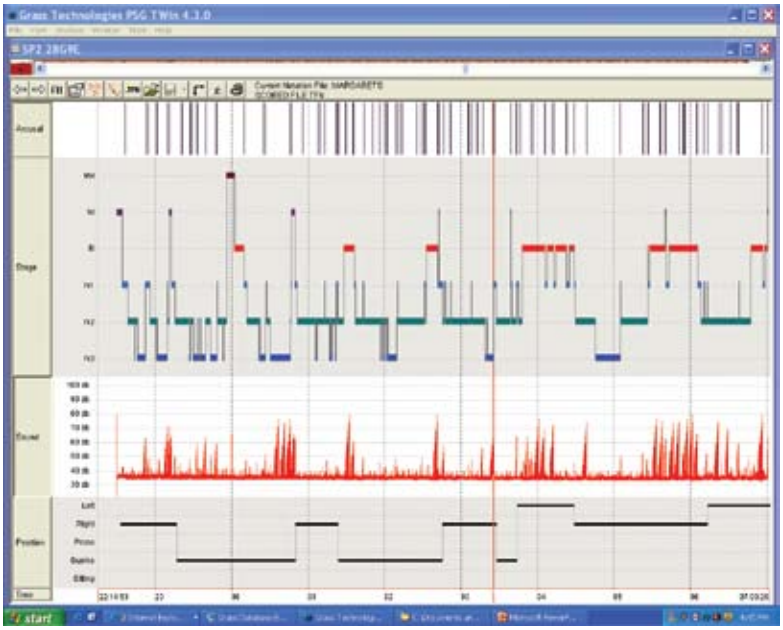
Physiological monitoring was used to identify specific sound levels that produced sleep changes, including sub-threshold arousals, those that did not fully awaken but nonetheless inhibited and disrupted the deeper stages of sleep. Analyses were undertaken independently (without Phase 2 Pilot Study subjects) for the Phase 3 advanced protocol group of 12 subjects, using 14 stimuli to derive arousal probability threshold curves.

FIGURE 8
Sleep cycles across the night (hypnogram)



A hypnogram is a diagram of normal sleep architecture. Figure 8, reading from left to right, shows a typical single night of sleep beginning at 11PM, with 4 sleep cycles, each lasting 90 minutes. Reading from the top down—moving from wakefulness to deep sleep—through stages 1-4, sleep is becoming increasingly deep, with the red troughs showing the deep sleep (NREM3), which is the deepest sleep, more of which occurs in the early sleep cycles. Green lines represent rapid eye movement or REM sleep in which dreaming occurs. Note that REM sleep is increasing through cycles during the night. Some brief arousals or lightening of sleep during the night are normal and often not remembered.

FIGURE 9
Data readout



Technical Information on Sound Level Logging during Stimulus Presentations

During stimulus presentations, the sound level in the sleep lab room was logged in 1-second increments using an environmental sound monitor (Rion Type NL-31 with Type 1 microphone) as a front-end to sleep recording software. The sound monitor was installed on a tripod roughly 6 inches above the forehead of the sleeping subject and was programmed to output a DC voltage proportional to the A-weighted fast response sound level (LAF). This signal was inserted into the sleep recording software and calibrated using a 1 kHz sine wave. The 1-second data were then combined into 30-second segments to correspond to the epoch timing used in the sleep data recording software (GRASS, Astro-MED, Inc.).

The variables tracked in this research study are listed down the left margin of Figure 9 (arousal, sleep stage, sound, position). These variables track from the left side of the diagram to the right across time through sleep cycles during the night.

Sources, Stimuli, and Soundscape Derivation

The sound sources developed and captured through recordings in Phase 1 and presented during Pilot Phase 2 and Phase 3 were sorted into broad categories: Patient Room, Interior of Hospital and Patient Room, Interior Hospital, Exterior Hospital—according to their sources/locations and in relation to the proposed Acoustic Guidelines as shown in the Sound Stimulus Key (Figure 10). This key was then used to guide graphing the summed arousals on the arousal probability threshold curves below (Figures 11 to 13).

FIGURE 10
Sound stimulus key

Stimulus	Source	FGI Guidelines Category	Characteristics	Color	Shape
IV Alarm	Electronic	Patient Room	High salience; alerting	Red1	Triangle up
Phone Ringing	Electronic	Patient Room	High salience; alerting	Red1	Triangle down
Bad Conversation	Human voice	Int. Hosp/Patient Room	High salience	Red2	Square
Good Conversation	Human voice	Int. Hosp/Patient Room	High salience	Red2	Diamond
Paging (overhead PA)	Human voice	Int. Hosp/Patient Room	High salience	Red2	Circle
Snoring	Human	Int. Hosp/Patient Room	Shifting contours	Orange	Circle
Towel Dispenser (electric)	Machine	Interior Hospital	Shifting contours	Orange	Circle
Door (squeaky open/close)	Machine	Int. Hosp/Patient Room	Shifting contours	Green1	Square
Toilet	Flush	Int. Hosp/Patient Room	Shifting contours	Green1	Circle
Ice Machine	Machine	Interior Hospital	Shifting contours	Green1	Diamond
Laundry Cart	Rolling	Interior Hospital	Relatively continuous	Green2	Triangle down
Traffic	Engine	Exterior Hospital	Relatively continuous	Blue1	Diamond
Helicopter	Engine	Exterior Hospital	Relatively continuous	Blue2	Circle
Jet	Engine	Exterior Hospital	Relatively continuous	Blue3	Square

3. Results

3.1 Number of Self-Reported Awakenings and Recollections of Stimulus Presentations

Recollections of arousal sources:

Both voices and non-voice sounds: 7

Voices only: 8

Non-voice sounds only: 15

Non-sound attributions: 5

Technical Information on Sleep Arousal Scoring

EEG arousals were defined using the current American Academy of Sleep Medicine criteria: "Score arousal during sleep stages N, N2, N3, or R if there is an abrupt shift of EEG frequency including alpha, theta, and/or frequencies greater than 16 Hz [but not spindles] that lasts at least 3 seconds, with at least 10 seconds of stable sleep preceding the change. Scoring of arousal during REM requires concurrent increases in sub-mental EMG lasting at least 1 second."

When these criteria were met, an arousal was documented. These defined sleep disruptions did not require a full "awakening". At times, stimulus presentations at specific decibel levels did result in subjects awakening briefly from sleep. Arousals were summed for all exposed subjects and have been plotted as color-coded stimulus points for 3 sleep stages: non-REM stage 2, REM, and non-REM stage 3 (SWS).

Each of the 12 Phase 3 subjects were questioned in the morning after their first sham/baseline quiet night of sleep and again after each of 2 acoustic event exposure nights about whether they had been awakened. When the answer was "yes," they were asked the cause of the awakening. When causes included sounds, subjects were asked to try to identify those sounds and describe how intense the sounds were. All the reported recollections and attributions were tallied. On the baseline nights, sleeping in the acoustically prepared quiet sleep lab room, no arousals were attributed to noise. On the 2 exposure nights, noise reports were higher but still reported at a much lower rate of arousals than evidenced through examining their EEGs. As has already been confirmed for human sleep, self-report typically underestimates the degree of sleep disruption as compared with documentation through monitoring brain wave changes. Arousal sources presented in this study often could not be identified by subjects---only vaguely characterized. Furthermore, a handful of the stimuli were not be characterized except by directionality.

Of the total of 24 reports provided by the 12 subjects on 2 stimulus exposure nights, there were 35 recollections. Fifteen of the reports included recollections of human voices. Eight identified more than one voice (as in conversations). One described "someone paging a doctor". There were 15 recollections of awakening by non-voice sounds, including 6 of machine sounds, 1 recollection of a natural sound, (thunder and lightning—not actually among the stimuli), 3 recollections attributing sound locations, and 8 of unidentifiable sounds. There were also non-sound attributions for awakening: sleeping in a new bed, uncomfortable bed/sleep position, dreams, moving position in bed, and need to use the restroom.

Voices which comprised only 3 of 14 stimuli (2 conversations, 1 paging) were reported disproportionately more than they were administered. It is possible that because voices are familiar and can be easily identified and named, they were remembered and reported more often than unfamiliar sounds. It appears that even while sleeping we maintain some attunement to voices because they have special salience for

communication. This fits well with patient satisfaction reports where complaints of voices and staff activity at night are especially common.

3.2 Arousal Probability Threshold Curves

Arousal probability threshold curves indicate the likelihood of arousal for each sound stimulus presented at each given decibel level by administering an equalized sound dose on the A scale, weighted for human perception, dB(A) Leq. As noted earlier, escalation continued in 5-decibel steps at 30-second intervals in the absence of an intervening arousal within a given stage of sleep up to 70 dB(A).

Figures 11, 12, and 13 demonstrate 3 sleep-stage-specific arousal threshold groups. Each point represents a sound exposure of 10-second duration for the specific named stimulus, plotted against the percent of total subjects aroused at that decibel level in the named sleep stage—NREM2 (Figure 11), and NREM3 (Figure 12), and REM (Figure 13). The Sound Stimulus Key (see Figure 10) for interpreting the curves organizes the tested stimuli by Source, Category, and Characteristics, with groups identified using similar colors and individual stimuli within groups differentiated with geometric shapes.

FIGURE 11
Arousal probability threshold curve for non-REM2 (light sleep). X axis signifies A-weighted equivalent sound level measured over 10-seconds

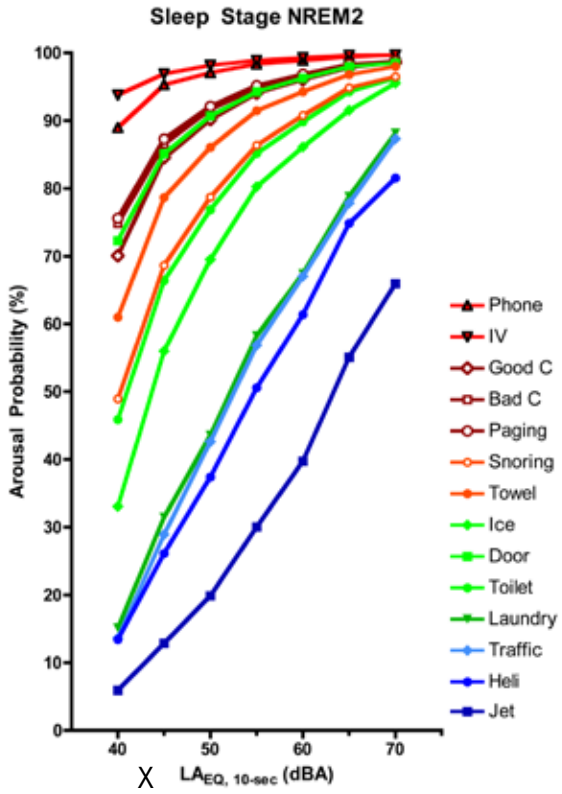


FIGURE 12
Arousal probability threshold curve for NREM3 (deep sleep). X axis signifies A-weighted equivalent sound level measured over 10-seconds.

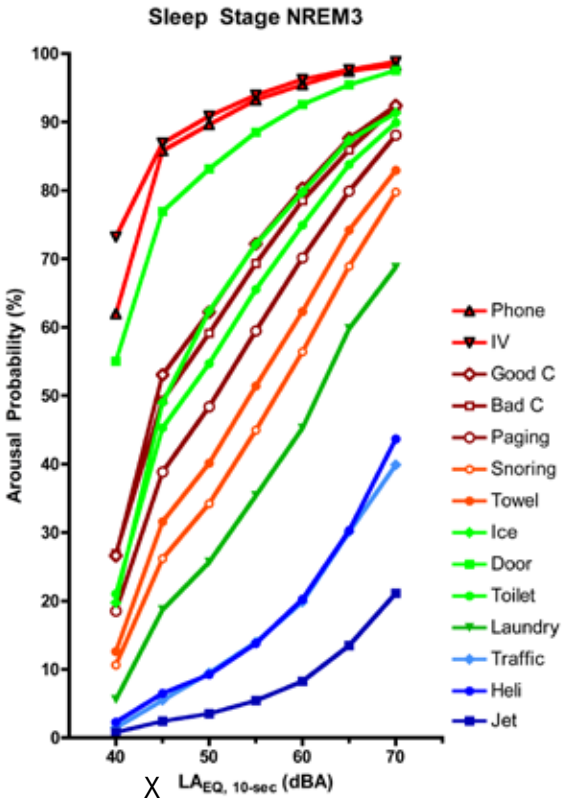
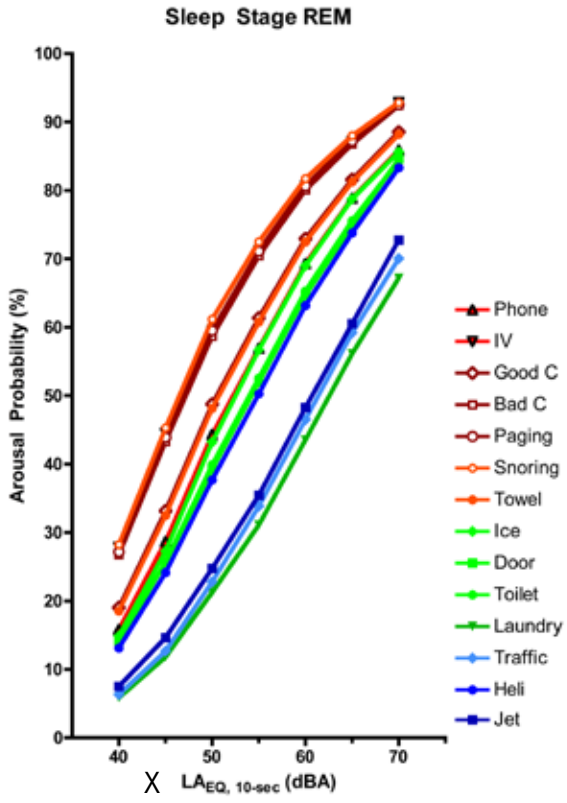


FIGURE 13
Arousal probability threshold curve for REM (rapid eye movement sleep). X axis signifies A-weighted equivalent sound level measured over 10-seconds.



3.3 Interpretation of the Arousal Probability Threshold Curves

The combined responses of all sleeping subjects are reported here as sleep stage specific arousal probability curves. These curves show the percent of those subjects (along the vertical axis) experiencing lightened sleep or full arousal for each of 14 color coded sounds delivered at stepwise decibel levels (along the horizontal axis) from 40 to 70 dB(A). Phone and IV alarms (shown in red) which are designed to be alerting, were effective in evoking the highest arousal probabilities, Voices (shown in dark red) were also highly alerting, even at lower tested decibel ranges, consistent with subjective data from healthcare quality survey reports. Given the salience of the human voice for communication, this response may convey an adaptive advantage in most circumstances. In general, like voices, other sounds with shifting contours (shown in orange and light green) such as snoring and electric towel dispenser, which changed during the course of the 10 second exposures, were more alerting than more continuous sounds such as traffic and laundry cart (green and acqua).

Some sound stimuli, jet and helicopter (blue and dark blue), had dynamic components which were spatialized through our speaker system to duplicate the perception of motion. At times upon awakening patients were able to recollect motion or position of a sound source, even when unable to specifically identify it.

Variation was identified among the sleep stages:

Light sleep, NREM2, (Figure 11) in which hospitalized patients spend most of their sleep time, showed the greatest vulnerability to acoustic disruption. It was less protected than either dream sleep, REM, (Figure 13) or deep sleep, NREM3 (Figure 14), especially with regard to continuous sounds with low frequency components such as jet and helicopter. Curves were less compressed in NREM2 than in REM sleep but more compressed than in NREM3 (Figure 12).

Deep sleep (NREM3) (Figure 12), the amount of which decreases with normal aging, showed the most protection from acoustic disruption. Rapid eye movement (REM) (Figure 13) or dream sleep showed a compressed pattern of threshold curves in which stimuli had effects more similar to each other, that is sound events were less differentiated in producing arousal than was seen in the other stages. This interesting finding deserves further exploration.

Our results confirm the wisdom of incorporating acoustic standards into guidelines for the construction of healthcare facilities to protect patient sleep from these and other common hospital sounds. It should be noted that while national surveys identify hospital noise as an urgent quality of care concern**, no benchmark for excellence has yet been established for sleep protection from disruption by noise for the inpatient population.**

4. Discussion

4.1 Specific Findings and Recommendations

Certain electronic sounds—(phone and IV alarms)—intentionally designed to be alerting, were very effective in evoking high arousal probabilities from sleeping subjects. Staff remediation efforts can include setting IV alarm signals lower and answering promptly. Because nurses do not typically leave their stations to answer patient room telephones, there is no need for the ring tones to be so loud that they reach beyond the patient rooms. In some healthcare settings, phones do not automatically stop after a specific number of rings and no "try again later" messages are offered to callers. Phones should be easily accessible to patients; signal levels and durations should be limited.

Staff conversations (charted as good c, bad c--related to prognosis conveyed), as well as voice paging, were also shown to be highly alerting. The threshold curves for voice stimuli are consistent with the arousal recollections reported by our subjects and documented as troublesome in healthcare quality surveys. Perhaps for evolutionary reasons to preserve safety, voices can be alerting even during sleep. Voice level exposures can be modified both behaviorally and through design and construction solutions. Special consulting spaces can be allocated for nurses in which voice-based information can be transferred away from open hall areas, yet not far from nursing stations. While television sounds were not specifically studied, policies limiting TV hours and provision of headphones, especially in shared rooms, are highly advised.

Exterior noises, outside the building, (jets, helicopters, road traffic) were found to be the least arousing stimuli at levels tested. However, the vibration components experienced with exposure to airplanes and helicopters could not be duplicated in our study and may in reality impact sleep arousal. There is some compelling information from European studies of sleepers near trains and airports describing associated health risks of such noises (elevated blood pressure) which do in reality at times reach or exceed the decibel levels associated in the present study with arousals. Site considerations are critical to reduce air, train, and road traffic noise exposure. When site options are limited, enhanced building envelope solutions must be put in place

to protect patients. Increasing concerns with regard to low frequency sounds, such as those attributed to wind turbines, will call for additional consideration of protective building envelopes especially in rural areas where ambient noise levels are anticipated to be low and envelope requirements have historically been less stringent.

Intermittent stimuli (ringing phone) in actuality delivered higher **peak** decibel levels than more continuous acoustic events in order for silent periods to balance in achieving the same "noise dose" during the 10-second duration subject exposures. Thus they cannot be fully equated with those relatively continuous stimuli in our study at the same "average" dB(A) Leq. step levels. The effect of intermittency on arousal is worthy of further examination. (See Limitations of Study, Average Noise Dose).

Recommendations

Multiple channels are available for improving the acoustics in the environment of care:

- Site exterior noise
- Design and configuration
- Acoustical surfaces and materials
- Paging and call systems
- Clinical alarms and equipment
- Staff behavioral protocols

With regard to other stimuli, those with shifting contours (towel dispensers, door close, toilet flush, ice machine) also tended to be more arousing than those with continuous contours. Clearly ice machines should be architecturally isolated from patient areas or dramatically re-engineered. While automatic towel dispensers are "hands free" they are often described as disruptive by patients; quieter or low-tech alternatives can be explored. Proper door hardware will limit latch noises; door gasket selection will better protect patients from hall and nurses' station noise, as well as blocking transfer of noise generated within that patient room. In many healthcare settings, policy still includes keeping patient doors open to allow for visual monitoring and easy accessibility by care-givers. However, where there is a line of vision, sound will also travel. Better patient-monitoring technology, a systems-level solution such as telemetry to a common station, or assignment of staff to specific patients allowing them to be individually alerted may help close that "open door policy", at least at night. Door policy must be balanced against isolating patients. (See the section, "Additional Considerations" below.)

4.2 Sleep Architecture and Differential Relevance of Curves

Older adults are known to experience decreased depth of non-rapid eye movement sleep (NREM), as well as lesser amounts of deep sleep (NREM3), They therefore spend greater amounts of their sleep time in less protected lighter sleep stages. The arousal probability curve presented here for NREM2 sleep (Figure 13) can be assumed to be especially relevant for older individuals. Based on the expected amount of time in lighter stages of sleep, older individuals, typical of many hospitalized

patients, would be more frequently and more easily aroused on a typical night (assuming normal hearing capacity) than our young subjects. NREM sleep stage 2 may therefore be the most instructive for organizing remediation of noise disruption and for undertaking design, materials, equipment and operational innovation.

4.3 Implications for the *Guidelines for Design and Construction of Health Care Facilities*

The 2010 *Guidelines for Design and Construction of Health Care Facilities* (*Guidelines)* publication cycle for the first time offers minimum acceptable guidelines for a protective acoustic environment, in consideration of sleep, privacy, and accurate communication. The research results presented in this report confirm the necessity of providing these protections and delineate which tested sounds from a "live" healthcare facility are most disruptive of patients' sleep. This study also confirms the wisdom of the 2006 Facility Guidelines Institute (FGI) mandate for single bed-rooms to limit patient exposure to disruptive sounds from roommates, their visitors, caregivers, and equipment. A quieter environment is also more protective of staff, reducing stress and burnout, enhancing communication, and reducing medical errors—all of which contribute to higher quality healthcare. FGI anticipates that this is the first of several noise related research initiatives that will be funded, in whole or in part, through FGI as they work to constantly improve the content of the *Guidelines* as a dynamic and current document.

5. Limitations of the Study

This study was specifically designed with the goal of informing guidelines to improve the acoustic environment experienced by patients and therefore to limit sleep disruption. It is the only controlled laboratory study of which we are aware that uses a series of sounds derived from a real hospital environment as stimuli administered to fully monitored sleeping subjects. While ecologically sound, certain limitations remain and must be acknowledged.

5.1 Average Noise Dose

Our stimuli were calibrated to provide average noise doses at specific decibel levels using the A weighted scale, which is most sensitive to the range of human hearing. Because of the specific qualities of certain sound stimuli, such as the intermittency of the telephone signal, the actual peak sound levels are balanced against quieter or silent periods in providing an average noise dose. Therefore the peak level of some sound stimuli is necessarily higher than those with more even and continuous levels that have a smaller decibel range. Specific characteristics of sounds such as familiarity, intermittency, dynamic range, motion, and low frequency content deserve further investigation as variables affecting arousal from sleep. (See the section, “Continuing Efforts”.)

5.2 Stimulus Duration

All our stimuli were organized into 10-second exposures. While this eliminated the need to consider stimulus duration as a variable that complicates analyses, in the natural hospital setting, hall conversations, ice machine disgorgement, and airplane over-flights, for example, may vary in duration at different times as well as from each other. Longer stimuli at the same decibel level could produce higher arousal probabilities.

5.3 Stimulus Co-occurence

While each of our stimuli was administered individually during all sleep stages with stepwise increases in volume up to 70 db(A) until arousal occurred, in the natural hospital setting such stimuli may co-occur. When they do co-occur, the noise "dose" and the probability of producing arousal rises. This means study results cannot simply be used to calculate the appropriate decibel levels for each of our stimuli as stable criteria for product innovation; sounds must be understood in combination and in context.

5.4 Special Characteristics of Hospitalized Patients

Our Phase 3 study exposed 12 subjects, each screened for good health and normal hearing, to acoustic stimulus-induced arousals. These subjects were younger than many hospitalized patients for whom noise-induced sleep disruptions are likely to be compounded by co-existing sleep-disrupting factors. Along with expected age-related sleep changes diminishing the amount of more protected deep sleep (NREM3), many hospitalized patients suffer negative impacts on sleep from pain, anxiety, and depression. Epidemiological studies have confirmed that sleep disorders are also more common in older age groups. Many patients arrive with an accumulated sleep debt, sometimes related to the condition for which they have been admitted. Patients may also be suffering from traumatic events or struggling with difficult diagnoses. Most have little ability to control or interpret their immediate environments. Ambiguous sounds under such circumstances may be experienced as alerting, even alarming. We present arousal probability thresholds for different sleep stages absent these additional complicating factors.

6. Additional Considerations

6.1 Infection Control

One of the most frequently cited concerns about acoustic improvement in healthcare facilities relates to surface materials such as wall panels, carpeting, and ceiling tiles, that are viewed as potentially compromising infection control—a rising concern especially because of resistant pathogens. Absorbing sound, rather than reflecting it, can safely be part of acoustic enhancement when appropriate products are chosen and when the specific patient population is considered. The requirements for spaces for immuno-compromised patients will be more stringent, just as air exchange needs are greater. Certain acoustic remedies such as blocking and masking sound, room and work-station design configurations, filling direct sound leakage paths, and altered care protocols are improvements that can be made without negative implications for infection control. See the 2007 CHD publication: *Limiting the spread of Infection in the Healthcare Environment, Assessment of Materials Commonly Utilized in Healthcare: Implications for Bacterial Survival and Transmission*. For an example of special materials visit: http://www.armstrong.com/commceilingsna/article11200.html

6.2 Cost

An estimated $240 billion price tag has been placed on healthcare construction for the period 2009 through 2013 (Jones, 2009).

In a January 2008 Recommendation for the Guidelines for the Design and Construction of Healthcare Facilities, a group of participating architects, engineers, and construction company executives, including R. Brown and T. Gormley, raised concerns to the leadership of the Facilities Guidelines Institute about the increasing design mandates and their effects on rising costs of healthcare construction. They cited the need to provide more information to help decision-makers balance requirements for specific functional programs against the limitations of available capital. In arguing for attention to fiscal responsibility, they maintained that improvements in design and construction anticipated to support better care must be made with significant attention to cost impact. Further, they recognized that cost-benefit analyses are

especially difficult when projects include not just construction costs, but a range of factors including operational cost differences related to geographical location, facility size, and case mix. The initial FGI mandate to improve acoustical environments in healthcare facilities, to which this research report is directed, is a justified area for their analyses. Recent development of advanced computer modeling systems for acoustics provide opportunities to more adequately predict success of design and construction solutions in advance, contributing to better outcomes and cost containment.

We are now witnessing a transformation in healthcare reimbursement to a "pay for performance" model. Design and construction mandates related to acoustics can be expected to improve communication, speech privacy, and HIPAA compliance, lower staff stress levels, decrease medical errors, and limit patient sleep disruption. Together these should enhance clinical outcomes, reduce staff turnover rates, and provide advantages in the competitive marketplace, all of which have positive cost implications. The HCAHPS data described earlier lead us to conclude that patients will choose hospitals with quiet rooms when voluntary admissions are arranged. In "The Business Case for Building Better Hospitals Through Evidence-Based Design," Sadler, DuBose, and Zimring (2008) offer case studies, recommend ten critical steps to ensure an optimal cost-effective hospital environment, and provide a valuable ROI (return on investment) framework for organizational use directed toward evidence-based design. These can be implemented for acoustic interventions as well as for innovation in other areas.

6.3 Loneliness and Patient-Centered Care

Many of the solutions available for decreasing patient noise exposure such as closing room doors, single bed occupancy, and video monitoring/telemetry from nurses' stations, have the possible unintended consequence of isolating patients. With shortened stays and increased outpatient procedures, most hospitalized inpatients are sicker than in past decades and frequently not in the position to benefit from roommate support, even if that roommate is well enough to offer it. But some patients, when asked, do prefer to have their room doors open for stimulation and to feel more available to staff oversight. Face to face time with caregivers is very highly valued, so video monitoring, if undertaken, should not become a substitute for real patient contact. Design solutions here should address opportunities for patient choice, for example, by providing common rooms such as a unit solarium, where patients who are well enough might visit with each other, have meals together, or spend time with their guests and family members.

6.4 Changing Night Staff Behavior

Cambridge Health Alliance has undertaken a very successful parallel behavioral research effort, mentioned earlier on page 5, that has documented a statistically significant decrease in patient requests for sedative medication can be achieved by altering night care routines. The Somerville Protocol project under the direction of Melissa Bartick, MD, Hospitalist, took place on the same unit on which the acoustic event recordings were made for the acoustics research here reported. While changing staff behavior related to longstanding hospital protocols is known to be difficult, in this case the team was very committed to including the full staff in decision-making. The Somerville Protocol included altered medication routines along with sleep preserving implementation of evening "quiet time" triggers—lowering lights and playing music—which could be duplicated in other healthcare settings. The significant findings of this parallel study are available through the Journal of Hospital Medicine in March 2010 *(see Bibliography)*.

7. Continuing Efforts

Acoustical parameters available for additional study related to arousal probability thresholds include the following:

- Sound peak levels**:** peak (LCpk), Maximum (LAFmax), minimum (LAFmin), percentile (L10, L50, L90)
- Low Frequency (LF) content (difference between C- and A-weighted equivalent sound levels)
- Human voice content
- Spatial motion
- Dynamic range (Lmax-Lmin, L10-L90, Lmax-L90)
- Tonality
- Impulsiveness
- Intermittency

Our research team is now actively extending statistical efforts with mixed model analyses to further determine the acoustic, sleep stage, and individual factors contributing to the observed arousal probabilities.

8. Future Research Directions

8.1 Older Subjects

While sleep stage specific arousal probability curves for young and older individuals exposed to characteristic hospital sounds are hypothesized to be the same, there may nonetheless be differential effects from noise on the resulting sleep disruption for older and sick individuals. These could be related not only to the lesser amount of time spent in more protected NREM3 deep sleep (believed to be a natural consequence of aging), but to differences in lasting sleep fragmentation provoked by these sounds. For example, older or sicker individuals awakened by noise may not fall easily back to sleep the way healthy young people do. Greater "wake time after sleep onset" (WASO) indicates lower "sleep efficiency". Aging sleep architecture, together with the epidemiologically confirmed higher likelihood of sleep disorders with aging, support the hypothesis that the same number of noises at the same decibel levels would have a more lasting disruptive effect on the sleep of individuals typical of hospitalized patients. This disruption could be expected to be associated with alterations in physiology, greater risks to health outcomes, and decrements in cognitive performance.

The next steps in this research program to explore impacts on health outcomes should include, first confirming that baseline arousal probability thresholds found in the current study with young subjects are matched in older subjects at each of the sleep stages. Next, it should include analyzing the degree to which older subjects' sleep is differentially fragmented and less efficient with the same number and types of noise stimuli and amount of time in bed. Finally, this research should examine performance decrements in memory and learning, especially error analyses. The latter are of particular relevance in relation to informed consent elicited from hospitalized patients and to effective in-hospital patient learning, directed toward post-discharge requirements such as safe adherence to medication protocols. In addition it is well-known that clinical staff, especially doctors in training, may be sleep deprived. Analyses of cognitive performance under sleep deprived conditions might also lead to a better understanding of medical errors, particularly those made under high stress conditions.

8.2 Improved Hospital Equipment

While behavioral protocols related to improved response to alarm signals, timing of equipment use, or even its relocation can make an impact on noise, some standard-use equipment models such as electric towel dispensers and ice machines are not acoustically suitable, especially for night inpatient environments and should be re-engineered. Product testing or "jurying", with results listed by decibel levels and other relevant characteristics, should drive competition and innovation toward better engineered, quieter products.

8.3 Other Dedicated Hospital Environments

Earlier research explorations of the influence of acoustics on other areas in which patient care is delivered have produced valuable insights with regard to high intensity environments such as cardiac care units, neonatal intensive care, and operating rooms. Intake and registration areas, emergency departments, examination and laboratory areas might similarly benefit from improved acoustics especially in terms of communication, and cognitive load on staff. Evidence of typical and ideal sound levels would better inform future cycles of the construction Guidelines.

8.4 Anticipating the Future: Exterior Environments

Day/Night Average sound levels are most typically used to report acoustic characteristics of environments in preparation for siting hospitals. In order to provide building envelopes sufficiently protective of sleep, actual peak sound levels and patterns, including seasonal variations, such as those that occur with direct airplane over-flights, should be recorded and then applied in relation to preventing sleep disruption. This research could be used to inform policy decisions. Recently announced plans to provide financial incentives to move plane flights to overnight periods to allow for expanded operations in crowded airports (Logan Airport, in Boston) may be seriously misguided in respect to impact on hospitalized patients and the broader public health.

A newly reported concern for rural settings—where readings have typically shown very low ambient sound levels—is the installation of wind turbines. Some citizens, even those who had expressed support for turbine installations, have reported sleep-

lessness and other health and quality-of-life problems. Because the characteristic sounds include significant low frequency exposures, consideration may be needed in planning adequate hospital building envelopes in some rural settings. Future research should explore sleep disruption from these low frequency sounds especially as related to wind and turbine rotational speeds.

8.5 Beyond Remediation: Providing Positive Enhancements

Beyond eliminating or masking disruptive sounds, increased research attention should be given to active enhancement of the acoustic environment in healthcare settings. Offering patients a degree of choice and control over enhancements, such as familiar music, meditative or nature sounds, possibly combined with control of lighting and visual images, should be studied as part of the growing movement to implement healing attributes in healthcare environments. While providing needed distraction during brief out-patient procedures such as chemotherapy infusions, longer-lasting applications for inpatients may improve biomarkers, lower anxiety, relieve pain, and improve sleep.

The future of healthcare environments looks beyond preventing harm to actively supporting healing. To realize this vision, decision-making should be based on the best combined efforts of engineering, architecture, clinical expertise, and research at the juncture where evidence-based medicine meets evidence-based design.

9. Glossary

9.1 Acoustic Science

Please visit http://www.webref.org/acoustics/acoustics.htm for a full list of definitions.

9.2 Sleep Science

Please visit http://healthysleep.med.harvard.edu/glossary for a full list of definitions. *This is a resource from the Division of Sleep Medicine at Harvard Medical School in collaboration with WGBH Educational Foundation.*

10. Bibliography

10.1 Healthcare Quality and Policy

Asch, S., Kerr, E., Keesey, J., Adams, J., Setodji, C., Malik, S., & McGlynn, E. (2006). Who is at greatest risk for receiving poor-quality health care? *The New England Journal of Medicine, 354,* (11), 1147-1156.

Bartick, M., Thai, X., Schmidt, T., Altaye, A., & Solet, J. (2010). Decrease in as-needed sedative use by limiting nightime sleep disruptions from hospital staff. *Journal of Hospital Medicine, 5, (3), E20-E24.*

Blomkvist, V., Ericksen, C. A.,Theorell, T., Ulrich, R., & Rasmanis, G. (2005). Acoustics and psychosocial environment in intensive coronary care. *Occupational and Environmental Medicine*, *62*, 1-8.

Busch-Vishniac, I., West, J., Barhnill, C., Hunter, T., Orellana, D., & Chivukula, R. (2005). Noise Levels in Johns Hopkins Hospital. *The Journal of the Acoustical Society of America*, *118*, 3629-3645.

Chepesiuk, R. (2005), Decibel hell: The effects of living in a noisy world. *Environmental Health Perspectives*. *113*(1), A35-A41.

Hagerman, I., Rasmanis, G., Blomkvist, V., Ulrich, R., Ericksen, C. A., & Theorell T. (2005). Influence of intensive coronary care acoustics on the quality of care and physiological state of patients. *International Journal of Cardiology*, *98*, 267-270.

Jha, A., Orav, E., Zheng, J., & Epstein, A. M. (2008). Patients' perception of hospital care in the United States. *New England Journal of Medicine*, *359*, 1921-31.

Jones, H. (2009). FMI's construction outlook – third quarter 2009. Raleigh, NC: FMI.

Joseph, A., & Ulrich, R. (2007). *Sound control for improved outcomes in healthcare settings* (Issue Paper #4). Concord, CA: The Center for Health Design.

Kaldenberg, D. (2000). *Better or worse? Patient's perceptions of hospital services*. (Press Ganey Satisfaction Report Vol. 4). South Bend, IN: Press Ganey.

Lankford, M., Collins, S., Youngberg, L., Rooney, D.M., & Noskin, G.A. (2007). *Limiting the Spread of Infection in the Healthcare Environment; Assessment of materials commonly utilized in healthcare: Implications for bacterial survival and transmission*. (Report). Concord, CA: Center for Health Design with Coalition for Health Environments Research.

Lauderdale, D., Knutson, K. L., Lijing, L. Y., Rathouz, P. J., Hulley, S. B., Sidney, S., & Liu, K. (2006). Objectively measured sleep characteristics among early middle aged adults: The CARDIA study. *American Journal of Epidemiology, 164*(1), 5-16.

MacLeod, M., Dunn, J., Busch-Vishniac, I. J., & West, J.E. (2006, June). *Quieting Weinberg 5C: A case study in hospital noise control, Johns Hopkins University and Johns Hopkins Hospital*. Paper presented at conference of ASA/Providence, Manuscript submitted for publication.

Nanda, U., Pati, D., & McCurry. (2009) Neuroesthetics and healthcare design. *Health Environments Research and Design Journal. 2*(2),116-133.

Rubin, H., Owens, A., & Golden, G., Introduction by Weber, D. (1998). *Status Report (1998): An Investigation to Determine Whether the Built Environment Affects Patients' Medical Outcomes*. Concord, CA: The Center for Health Design.

Sadler, B., DuBose, J., & Zimring, C. (2008). The business case for building better hospitals through evidence-based design. *Health Environments Research and Design Journal, 1*(3), *22-39.*

Solet, J., Carballeira, A., Buxton, O., & Wyshak, G. (2008). Acoustics in the environment of care: An interdisciplinary Harvard Medical School Research Project [Abstract 2pAAc3]. *The Journal of the Acoustical Society of America, Acoustics, 123*(5), *319-3.*

Sykes, D., Rockstroh, R., Solet, J., & Buxton, O. (2006). Evidence-Based Design: The new AIA Guidelines on Noise and Privacy. *Healthcare Design Magazine*, *6*(5), 47-49.

Ulrich, R.S., Zimring, C., Quan, X., & Joseph, A. (2004). *The Role of the Physical Environment in the Hospital of the 21st Century: A once in a lifetime opportunity* (Report). Sponsored by The Center for Health Design and the Robert Wood Johnson Foundation. Available at http://www.healthdesign.org

Ulrich, R., S., Zimring, C., Zhu, X., DuBose, J., Seo, H., Choi, Y., Quan, X., & Joseph, A. (2008). A review of the scientific literature on evidence-based healthcare design. Healthcare Environments Research & Design Journal, 1(3), 61-125.

Guidelines and Reports

World Health Organization (December, 2005). *Quantifying burden of disease from environmental noise*: *Second technical meeting report*. Bern, Switzerland.

ANSI S12 Workgroup 44 and the Joint ASA/INCE/NCAC Subcommittee on Healthcare Acoustics and Privacy (August, 2006). *Draft Interim Sound and Vibration Design Guidelines for Health Care Facilities.* Cambridge, MA: WG44 Joint Subcommittee on Speech Privacy website: http://www.healthcareacoustics.com

The American Institute of Architects Academy of Architecture for Health, The Facility Guidelines Institute, with assistance from the U.S. Department of Health and Human Services (2006). *Guidelines for Design and Construction of Health care Facilities – 2006 Edition*. Washington, DC: The American Institute of Architects.

The American Society for Healthcare Engineering, The Facility Guidelines Institute. (2010). *Guidelines for Design and Construction of Health Care Facilities – 2010 Edition.* Chicago, IL: The American Hospital Association.

Berglund, B., Lindvall, T., & Schwela, D.(Eds.). (1999). *Guidelines for community noise. World Health Organization*.

Brown, R., Gormley,T., Pyskacek,D., O'Malley, P. W., & Pentecost, M. A. (2008, January). *Recommendation for the Guidelines for the Design and Construction of Healthcare Facilities* (Distributed to Members of HGRC).

Green Guide for Healthcare (January, 2007). *Acoustic Environment: Sound Isolation, v2.2* (EQ Credit 9.2). Available at http://www.gghc.org

Jones, H. (2008). FMI's construction outlook – third quarter 2008. Raleigh, NC: FMI Corporation.

10.2 Acoustics

Appropriate references for the Interim *Guidelines for the Design and Construction of Health Care Facilities* are contained in the body of the document. Please refer to the specific sections of the Guidelines for further references.

Miller III, R.E. (2002). ITU-R BS.775.1 Multi-channel stereophonic sound system with and without picture., Bethlehem, PA: Filmaker Studios

Gardner, W.G. (1995). Trans-aural 3D Audio. *MIT Media Lab Perceptual Computing Technical Report* (No. 342) Cambridge, MA: MIT Media Lab

McNeer, R. R., Bohorquez, J., Ozdamar, O., Varon, A. J., & Barach, P. (2007). A new paradigm for the design of audible alarms that convey urgency Information. *Journal of Clinical Monitoring and Computing. 21*(6), 353-63.

Montague, K. N., Blietz, C. M., Kachur, M. (2009). Ensuring quieter hospital environments. *American Journal of Nursing, 109*(9), 65-67.

Tsingos, N., Carlbom, I., Elko, G., Funkhouser, T., & Kubli, R. (July/August 2002). Validation of acoustical simulations in the "Bell Labs Box". *IEEE Computer Graphics & Applications, 22*(4), 28-37.

10.3 Additional Acoustics Resources

Funkhouser, T., Tsingos, N., Carlbom, I., Elko, G., Sondhi, M., West, J.E., …Ngan. A. A Beam Tracing Method for Interactive Architectural Acoustics. *Journal of the Acoustical Society of America, 115*(2), 739-756.

Funkhouser, T., Tsingos, N., Carlbom,I., Elko, G., Sondhi, M., & West, J. (2002, September). *Modeling Sound Reflection and Diffraction in Architectural Environments with Beam Tracing.* (invited paper) Forum Acusticum, Sevilla, Spain.

Funkhouser, T. A., Carlbom, I., Elko, G., Pingali, G., Sondhi, M., & West, J. (1999) *Interactive Acoustic Modeling of Complex Environments,* Proceedings of *The Joint Meeting of the 137th Regular Meeting of the Acoustical Society of America and the 2nd Convention of the European Acoustics Association: Forum Acusticum `99. Journal of the Acoustical Society of America, 105*(2).

Funkhouser, T. A., Pingali, G., Elko,G., Sondhi, M., West, J., Carlbom, I., & Gatlin, M. (1997, September). *Interactive Auralization of Virtual Environments. NetDays `97,* Holmdel, NJ.

10.4 Sleep and Health

Ayas, N. T., White, D.P., Al-Delaimy, W. K., Manson, J.E., Stampfer, M. J., Speizer, F.E., Hu, F.B. (2003). A prospective study of self-reported sleep duration and incipient diabetes in women. *Diabetes Care, 26*(2), 380-384.

Ayas, N. T., White, D. P., Manson, J.E., Stampfer, M. J., Speizer, F.E., Malhotra, A., & Hu, F. B. (2003). A prospective study of sleep duration and coronary heart disease in women. *Archives of Internal Medicine*, *163*(2), 205-209.

Belluck, P. (2009, November 20). Sounds during sleep aid memory, study finds. *The New York Times,* Retrieved from http://www.nytimes.com/2009/11/20/science/20sleep.html?_r=1&hpw

Berg, S. (2001). Impact of reduced reverberation time on sound induced arousals during sleep. *Sleep, 24*(3), 289-292.

Bruck, D., Ball, M., Thomas, I., & Rouillard, V. (2009). How does the pitch and pattern of a signal affect auditory arousal thresholds? *Journal of Sleep Research*, 18(2), 196-203.

Buxton, O. M., Speigel, K., & Van Cauter, E. (2002). Modulation of Endocrine Function and Metabolism by Sleep Loss. In: Lee-Chiong, T. L., Sateia, M. J., & Carskadon, M. A. (Eds.), *Sleep Medicine*, (pp 58-69). Philadelphia, PA: Hanley & Belfus.

Cmiel, C., Karr, D. M., Gasser, D. M., Oliphant, L. M., & Neveau, A. J. (2004). Noise control: A nursing team's approach to sleep promotion. *American Journal of Nursing,104*(2), 40-49.

Copinschi, G. (2005). Metabolic and endocrine effects of sleep deprivation. *Essentials of Psychopharmacology, 6*(6), 341-347.

Eriksson, C., Rosenlund, M., Pershagen G. R., Hilding, A., Ostenson, C-G., & Bluhm, G. (2007). Aircraft noise and incidence of hypertension. *Epidemiology*, *18*(6), 716-721.

Ellenbogen, J. M. (2005). Cognitive benefits of sleep and their loss due to sleep deprivation. *Neurology, 64*, E25-E27.

Ellenbogen, J. M., Hulbert, J. C., Jiang, Y., & Stickgold, R. (2009). The Sleeping Brain's Influence on Verbal Memory: Boosting Resistance to Interference. *PLoS ONE, 4*1): e4117.

Ellenbogen, J. M., Hu, P. T., Payne, J. D., Titone, D., & Walker, M. P. (2007). Human relational memory requires time and sleep. *Proceedings of the National Academy of Sciences of the United States of America (PNAS), 104*, 7723-7728.

Ellenbogen, J. M., Hulbert, J. C., Stickgold, R., Dinges, D. F., & Thompson-Schill, S. L. (2006). Interfering with theories of sleep and memory: sleep, declarative memory, and associative interference. *Current Biology*, *16*, 1290-1294.

Ellenbogen, J. M., Payne, J. D., & Stickgold, R. (2006). The role of sleep in declarative memory consolidation: passive, permissive, active or none? *Current Opinion in Neurobiology*, *16*(6), 716-722.

Freeman, W. J. (2003). Neurodynamic models of the brain. *Neuropsychopharmacology*, *28*,S1,54-63.

Friese, R. (2008). Sleep and recovery from critical illness and injury: A review of theory, current practice, and future directions. *Critical Care Medicine, 36*(3), 1-9.

Gottlieb, D. J., Punjabi, N. M., Newman, A.B., Resnick, H.E., Redline, S., Baldwin, C. M., & Nieto, F.J. (2005). Association of sleep time with diabetes mellitus and impaired glucose tolerance. *Archives of Internal Medicine*, *165*, 863-868.

Gupta, N. K., Mueller, W. H., Chan, W., & Meininger, J. C. (2002). Is obesity associated with poor sleep quality in adolescents? *American Journal of Human Biology, 14*, 762-768.
Hale, L. (2005). Who has time to sleep? *Journal of Public Health*, *27*(2), 205-211.
Haralabidi, A. S., Dimakopoulou, K., Vigna-Taglianti, F., Giampaolo, M., Borgini, A., Dudley, M., … Jarup, L. (for the HYENA Consortium) (2008). Acute effects of night-time noise exposure on blood pressure in populations living near airports. *European Heart Journal*, 29, 658–664.

Hasler, G., Buysse, D. J., Klaghofer, R., Gamma, A., Ajdacic, V., Elich, D.… Angst, J. (2004). The association between short sleep duration and obesity in young adults: A 13-year prospective study. *Sleep, 27*, 661-666.

Hobson, J. A. (2005). Sleep is of the brain, by the brain and for the brain. *Nature*, *437*,1254-1263.

Irwin, M., Wang, M., Ribeiro, D., Jin Cho, H., Olmstead, R., Breen, E., … Cole. S. (2008). Sleep loss activates cellular inflammatory signaling. *Biopsychiatry, 64*, 538–554.

Janszky, I. & Ljung, R. (2008). Shifts to and from daylight saving time and incidence of myocardial infarction. *New England Journal of Medicine*, *359*, 1966-1968.

Kim, H., & Young, T. (2005). Subjective daytime sleepiness: Dimensions and correlates in the general population. *Sleep*, *28*, 625-634.

Liu, S., & Sheth, R. (2009). Discrimination of behaviorally irrelevant auditory stimulu in stage II sleep. *NeuroReport*, *20*, 207-212.

Perrin, F., Garcia-Larrea, L., Mauguiere, F., & Bastuji, H. (1999). A differential brain response to the subject's own name persists during sleep. *Clinical Neurophysiology*, *110*, 2153-2164.

Perrin, F., Bastuji, H., & Garcia-Larrea, L. (2002). Detection of verbal discordances during sleep. *NeuroReport*, *13*, 1345-1349.

Nakagawa,Y. (1987). Sleep disturbance due to exposure to tone pulses throughout the night. *Sleep, 10*, 463-472.

Nilsson, P. M., Roost, M., Engstrom, G., Hedblad, B., & Berglund, G. (2004). Incidence of diabetes in middle-aged men is related to sleep disturbances. *Diabetes Care*, *27*, 2464-2469.

Roehrs, T., Hyde, M., Blaisdell, B., Greenwald, M., & Roth, T. (2006). Sleep loss and REM sleep loss are hyperalgesic. *Sleep, 29*(2),145-151.

Rudoy, J. D., Voss, J. L., Westerberg, C. E., & Paller, K. A. (2009). Strengthening individual memories by reactivating them during sleep. *Science, 326*, 1079.

Pavlova, M., Duffy, J., & Shea, S. (2008). Polysomnographic respiratory abnormalities in asymptomatic individuals. *Sleep*, *31*(2), 241-248.

Spiegel, K., Leproult, R., & Van Cauter, E. (1999). Impact of sleep debt on metabolic and endocrine function. *The Lancet, 354*, 1435-1439.

Speigel, K., Tasali, E., Penev, P., & Van Cauter, E. (2004). Brief Communication: Sleep curtailment in healthy young men is assciated with decreased leptin levels, elevated ghrelin levels, and increased hunger and appetite. *Annals of Internal Medicine*, *141*, 846-850.

Spiegel, K., Leproult, R., L'Hermite-Baleriaux, M., Copinschi, G., Penev, P. D., & Van Cauter, E. (2004). Leptin levels are dependent on sleep duration: Relationships with sympathovagal balance, carbohydrate regulation, cortisol, and thyrotropin. *The Journal of Clinical Endocrinology & Metabolism*, *89*, 5762-5771.

Stickgold, R. (2005). Sleep dependent memory consolidation. *Nature*, *437*, 1272-85.

Stone, K., Ensrud, K., & Ancoli-Israel, S. (2008). Sleep, insomnia, and falls in elderly patients. *Sleep Medicine, 9*, 18-22.

Taheri, S., Lin, L., Austin, D., Young, T., & Mignot, E. (2004). Short sleep duration is associated with reduced leptin, elevated ghrelin, and increased body mass index. *Public Library of Science Medicine*, *1*(3), 210-217.

Tasali, E., Leproult, R., Ehrmann, D. A., & Van Cauter, E. (2007). Slow-wave sleep and the risk of type 2 diabetes in humans. Proceedings of the National Academy of Sciences, *105*(3), 1044-1049. - .

Tassi, P., Saremi, M., Schimchowitsch, S., Eschenlauer, A., Rohmer, O., & Muzet, A. (2010). Cardiovascular responses to railway noise during sleep in young and middle-aged adults. *European Journal of Applied Physiology*,*108*(4) 671-80.

Topf, M. & Thompson, S. (2001). Interactive relationships between hospital patients' noise-induced stress and other stress with sleep. *Heart Lung, 30*(4), 237-243.

Tranmer, J., Minard, J., Fox, L. A., & Rebelo, L. (2003). The sleep experience of medical and surgical patients. *Clinical Nursing Research, 12*(2),159-173.

Van Cauter E. & Spiegel K. (1999). Sleep as a mediator of the relationship between socioeconomic status and health: A hypothesis. *Annals of the New York Academy of Sciences*, *896*, 254-261.

Velluti, R. A. (2008). *The Auditory System In Sleep*.. San Diego, CA: Academic Press.

Walker, M. P., & Stickgold, R. (2004). Sleep-dependent learning and memory consolidation. *Neuron, 44*(1),121-133.

Weigand, D., Michael, L., & Schulz, H. (2007). When sleep is perceived as wakefulness: an experimental study on state perception during physiological sleep. *Journal of Sleep Research, 16*(4), 346-353.

Weinhouse, G., & Schwab, R. J. (2006). Sleep in the critically ill patient. *Sleep, 29*, 707-716.

Wesensten, N., Balkin, T., & Belenky, G. (1999). Does sleep fragmentation impact recuperation? A review and reanalysis. European Sleep Research Society, *8*, 237-245.