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APPLICATION OF BEAMFORMING TECHNIQUES TO LOCALIZE AND REDUCE HOSPITAL NOISES WITHIN ACUTE CARE PATIENT ENVIRONMENT

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ABSTRACT

Hospitalized patients and clinical hospital staff identify noise as a major stressor. Environmental hospital noise raises ambient noise levels significantly above ideal levels. Options to reduce hospital noise include methods to modify noise, such as closing doors, adjusting hospital equipment, architectural and room acoustic design, hospital personnel behaviours and clinical alarms such as wireless communication devices for staff and future "smart" algorithms for patient-specific alarm thresholds.

This study utilizes the beamforming techniques to localize and reduce the noise source in hospital rooms and examines room acoustic characteristic through measurements and simulation of noise in an environment that effects the patient's audio perception; and collects evidence for impact of noise and its intensity on patient hearing within a real environment. The difference in applications of various architectural solutions to mitigate noise in hospitals within cardiovascular acute care units is estimated. The profiles of noise levels for their time and frequency domain as being reflected, absorbed or refracted within typical patient's room are determined

The findings will contribute to possible architectural acoustic design solution(s) to reduce acoustic disruption of sleep with adequate information and reproducible data to accelerate design decision-making process while providing more practical solutions as compared to theoretical offerings by the research community in this area.

1 INTRODUCTION

Sleep plays a critical role in maintaining human health and well-being; however, patients who are hospitalized are frequently exposed to noise that can disrupt their sleep. Efforts to attenuate hospital noise have been limited by: 1- Incomplete information on the interaction between sounds and sleep physiology; 2- Design guidelines for application of building materials acceptable for traditional infection control solutions which often work against a healthy acoustic environment. (e.g., surfaces covered with hard materials for easy cleaning generally reflect rather than absorb sound); 3 - Architectural design solutions for the architectural acoustic needs of the acute care unit spaces. Sounds during sleep influence both cortical brain activity and cardiovascular functions. Although a great deal of consideration regarding codes, standards, and guidelines has been given for the hospital and care facilities, very little design guidance or architectural solutions is available that provides for the requirements of the room acoustic within hospital.

This study systematically quantifies the reduction capacity of a range of hospital sounds in time and frequency domain as it influence the sleep while providing evidence that is essential to improving the architectural room acoustic within a given new design and or existing health care facilities to enable the provision of the highest quality of care by the health care system. The World Health Organization (WHO) recommends a decibel measurement (dBA) of 35 for average daytime noise levels in patient rooms and 30 for average night time levels in patient rooms. However, patient room doors are often kept open to allow supervision, providing an easy conduit for noise transmission in excess of the limit. Glass doors can provide a degree of acoustical privacy for patient rooms while allowing visual supervision. Television headphones, pillow speakers or headphones located within easy reach of the patient can reduce the level of television audio noise in the inpatient unit. If patient room doors located off active corridors must be left open at night, sound masking systems may be used to elevate the continuous room background sound levels to make intruding sounds less audible and startling. Personal bedside systems could provide acceptable low levels of background sound in each patient room while reducing the amount of sound added to the rest of the patient care environment. Appropriate background sound could include a steady sound-masking spectrum, nature sounds or music. Patients who may not benefit from elevated background sound are those at risk for hearing damage due to ototoxic medications. These patients should be placed in rooms with gasketed, heavy doors in high in absorptive, reduced mechanical noise and minimal noise interference from clinical alarms and medical pumps.

2 OBJECTIVES

The objectives of this study are to examine the:

1) Measurements and simulation of noise in an environment that affects the patient's auditory perception;
2) Collected evidence of noise and possible reduction of its intensity within real environment;
3) Architectural appearance of space and sound reflections as integrated within working or living environments as relates to recommended sound absorbing material and their spectral characteristics;
4) Difference in application of various architectural solutions to mitigate noise in hospitals;
5) Noise levels for their times of occurrence and frequency domain as being reflected, absorbed or refracted within cardiovascular acute care units; and
7) Architectural acoustic design solutions with adequate information and reproducible data to accelerate the design decision-making process while providing more practical solutions.

3 METHODOLOGIES

1- Time and frequency domain noise measurements through use of real space within a hospital nursing station and patient room, 2 - Computer simulation to examine possible architectural and room acoustic solutions.

3.1 Experimental set ups: **Design -** three-day sound level study. **Setting -** 7th floor of the UM - Hospital cardiovascular acute care units. **Participants -** Volunteer staff and all care givers within section C nursing station.

3.2 Intervention: Baseline night time hours followed by full weekend and weekday intervention within a) north side circulation area utilizing the architectural sonic absorptive panels and b) south side circulation area without any intervention. As a controlled strategy over the noise that is common in hospitals (e.g., voice, phone, outside traffic, and helicopter, staff talking, food cart, cleaning cart, bathroom flushing and intravenous alarm, doors opening and closing, chair moving over the wooden floor, hush curtain closings, etc.) a selected set of masking sound was used as background noise with known intensities while their spectrum were measured within a typical patient room given the industry standards for Preferred Noise Criteria.

3.3 Measurements: The sound exposures are measured within ranges of decibel levels 40 to 80 dBA during their regular working schedules of 24 hours at 1 second intervals. Limitations within this study include only one type of design solution and the participants are only the patients and staff on the 7th floor for that period of time. Results for these room acoustic studies may underestimate the effects of other possible noise attenuators or other possible design alternative using computer simulations.

3.4 Application of the Acoustic Camera: The Acoustic Camera was used to measure sound characteristic of the room. Specific measurements were made close to the side of the bed and close to patient head position. The system produces images of sound sources or “localizes” sound sources using the beamforming technique. Delay-and-sum beamforming is one of the oldest and simplest array signal processing algorithms…“as far back as 1880. The acoustic images consist of color contours indicating where the most significant noise sources are located. Detailed review of this technique is described in reference **[1].** The system consists of a microphone array with camera, data recorder, and Noise Image software running on a laptop PC. **Figure 2** shows the typical system components used by the Acoustics Camera and the actual setting for measurements within the hospital room. Despite its extreme simplicity, the delay-and-sum method in the time domain is quite robust and powerful and has shown its practical usability in an extraordinary wide range of acoustic localization and troubleshooting applications for years now **[2].**

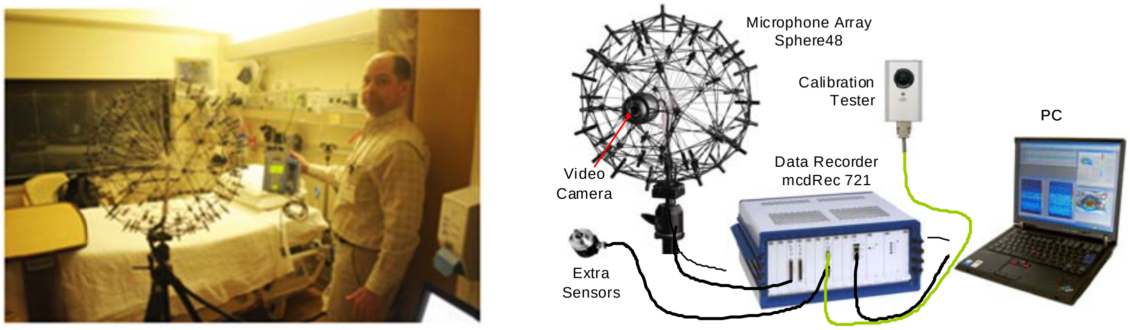


Figure 1: Actual experimental set up for measurements within the hospital room.

The net result from the system is a sound image superimposed onto a 3-D CAD model for specific application. Data can be analyzed for specific time periods and frequency ranges allowing results to be correlated with standard architectural acoustic measures. The measured results were used to simulate the sound source in other computer programs. An acoustic program EASE was used for detail calculation and parametric studies. The 120 small microphones recorded the impulse noise from a large balloon burst and the generated signal from sound masking systems with a steady sound-masking spectrum as well as nature sounds and live noise by nursing staff in making noise simultaneously at a given times of the day. The software allows the user to pinpoint exactly how much sound individual people and sources make within the patient’s room. Other factors such as the duration of the sounds from cardiovascular monitoring instrument by the bed or masking sounds, or the length of time it takes the balloon burst or the masking sound signals to reach "full loudness", or the point at which the sound intensity level remains steady had to be evaluated for peak measurements and their spectral characteristics.

3.5 Computer simulation: The computer models were based on the condition of having patient-room doors opened or closed, a scenario often required to support intensive care and emergency access by the nursing station staff. To provide speech privacy as one solution in double bedrooms, the adjustable hanging curtain became the critical element for sound isolation. Applying more absorption in the patient room increased the speech intelligibility, but with the drawback of decreasing speech privacy in double bedrooms during the visiting hours. In hospital room acoustic design, one has to change or eliminate the source of noise or shield the receiver from the source or alter the path of noise to reduce its impact on patient’s auditory comfort.

4 RESULTS & DISCUSSIONS

The attempt to contain the source of sound energy within cardiovascular acute care units only, was shown to be one design option. Further design alternatives, such as locating specially designed absorptive panels at the critical reflection point, were identified based on measurements using acoustic beamforming techniques. Data processing of the impulse responses was used for objective evaluation of the room acoustics quality due to the design variations. The change in auditory perception was observed by analyzing the output signals produced from Energy Time Curve (ETC) data, room’s mode, sound envelope and auralization based on the simulated impulse responses. The simulated results observed based on these parametric studies, particularly to isolate this sound field from other parts of the open-space layout as shown further in the results section of the paper, are selfevidence. The art of acoustic design for existing spaces is in optimizing the acoustic isolation, diffusion, the treatment of surfaces given the room's geometry and volume. Enhancing techniques in sound mixing rely heavily on new audio products along with options offered by audio design engineering firms. A simple web search will give you over 20 well-known companies, nationally and internationally, offering more than one way of treating architectural surfaces for diffusion. "Quadratic Residue Diffusers" or "Reflection Phase Grating" panels have been largely the solutions to approximate the listening room characteristic to the unique acoustic "fingerprint" of concert halls.

A new set of sonic panels have been designed, developed and physically built to meet the noise reduction criteria within hospitals. They have matte colour-studded hollow surfaces with an ordered array of half - and full-sized cones, which jut from every wall surface and or the ceiling. The panels have shown positive results of delay or decay of the mid and high frequencies within the space. The main concept of designing an efficacious diffuser is to provide a surface with no highlights for a given frequency, amplitude, or angle of incidence or reflection. Hence, an effective surface is created only for a small percentage of the total sound energy impinging on it. The measured results conducted at the UM hospital are validated through computer simulation, a certified laboratory and the on-site evaluation (before and after) as part of these case studies. The results show the data collected over the week days and weekends with and without the room acoustic design intervention using sets of sonic diffusers panels located at various reflective points strategically, did reduce the ambient noise by approximately 3dBA. See **Figure 2 and 3.** A patient's room in a hospital becomes their home away from home for the duration of their stay. For a child and or elderly people, it is especially important that they truly feel at home and at peace, in their space.

Figure 2. Installation of sonic panels within typical hospital rooms and circulation area.

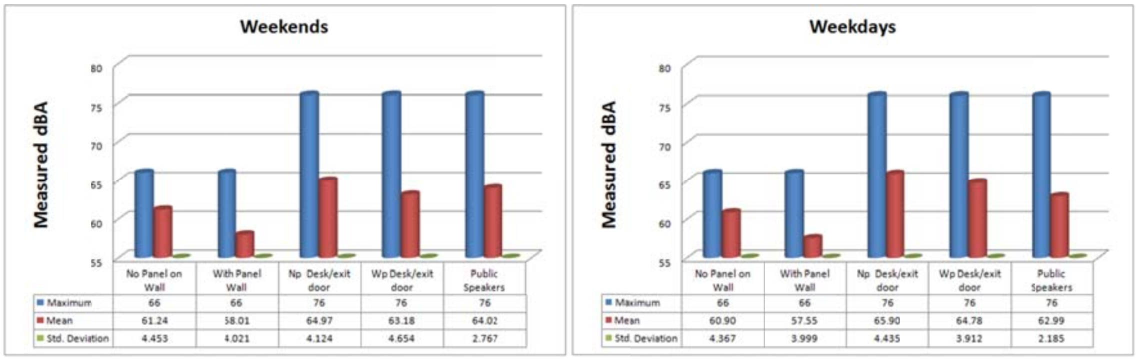


Figure 3. The summary results of noise monitoring within two circulation areas with (Wp) and without (Np) diffuser sonic panels. Wall = hallways, Desk /Exit door = Nursing station.

Options to reduce hospital noise include methods to modify noise, such as sound masking systems to elevate the continuous room background sound levels to make intruding sounds less audible and startling. The measured data shows it is possible to reduce the sound through use of this method; however, the original source needs to be much lower or the masking sound itself will be a new source of noise. **See Figure 4.**

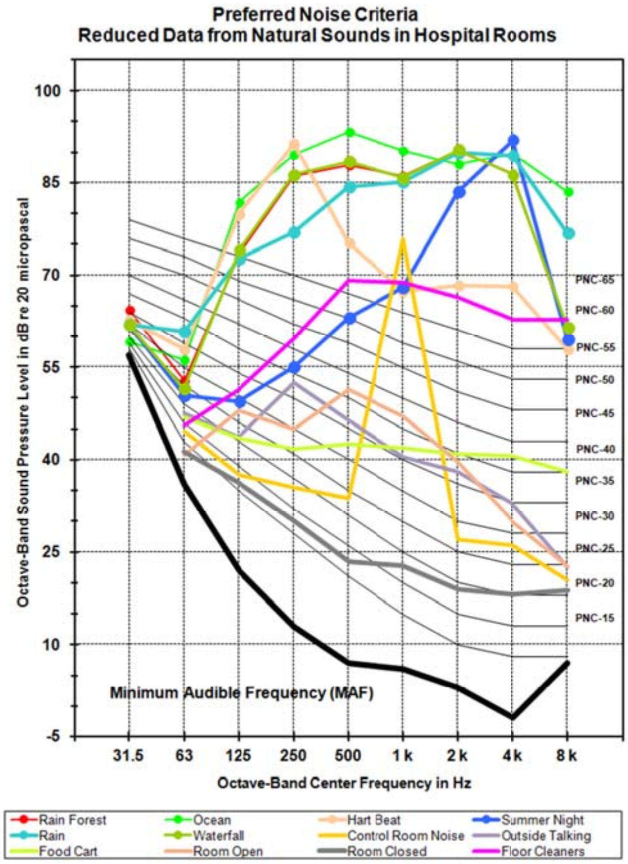


Figure 4. Measured noise level in patient room from sound masking (e.g., rain, heartbeat, summer night, water fall etc.) systems with a steady spectrum, nature sounds and live noise by nursing staff in making noise simultaneously at a given time of the day. Control room noise = Heart monitoring equipment noise signals coming from ICU station.

Patients listen to conversation, TV, bathroom flushing, door opening and closing, food cart passing by or other noise within or from outside circulation area in a hospital while sitting or laying flat on the bed, more often listening at a distance, where the sound pressure level of the reflected sounds is greater than that of the direct sound. Real time measurements show that frequency response measured at the patient position above 250Hz dominates the spectral characteristic of most sound energy returned to the patient from surfaces with high reflectance in the room such as doors, floor, glass windows, head board and foot boards by the bed. Below 250Hz, within a typical hospital room, room modes become the dominant factor in what patients hear. It is critical to localize the source and determine the frequency of the off-axis response of noise at the patient's ears. The acoustic characteristics of the main surfaces within the field of view of a patient with high reflection do impact the spectral frequency response at the listening position. Schroeder Frequency (SF) expresses a cross-over value of frequency for a rectangular room so that above the SF the modal density dictates statistical behaviour of the enclosed sound filed [3]. Studies have shown that the (SF) is a good predictor of empty rooms' modal behaviour only [4]. The following summarize the SF expressions.

$$RT = 0.161\frac{V}{\alpha A}, \qquad f_s = 2000\sqrt{\frac{T}{V}}, \qquad f_s = c\sqrt{\frac{6}{A}}, \qquad \lambda_s = c\sqrt{\frac{A}{6}}$$

Where T_{60}= Reverberation (s), V=Room Volume (m^3), α = absorption coefficient and A = total surface area (m^2), λ_s = Wave length and C= speed of sound in (m/s). These expressions will make the frequency range for design and treatment of these types of small to moderate size rooms under considerations into four zones from low to high frequency. The room acoustic characteristic can be viewed and analysed based on its frequency region. **Figure 5** shows the frequency response of a typical patient room based on an impulse measurement by bursting a large size balloon. The various zones namely, pressure zone, Eigen mode zone, Schroeder Frequency, 4 times the Schroeder Frequency and Specular Zones are identified on the plotted chart. These frequency subdivisions or regions allow one to select particular techniques to control the steady state of the room response since statistical models are applied at high frequency only. Based on studies on discrete modes in a small room by Blaszak for selecting optimum geometric proportions of rooms [5], the range of the acceptable dimension ratios decreases with decreasing α and for mean absorption coefficient lower or equal 0.3 based on Sabin's equation. This approach is only good for room with absorption less than about 0.3 or the results becomes not so useful and there are only a few of the ratios for which a uniform distribution of Eigen mode is obtained.

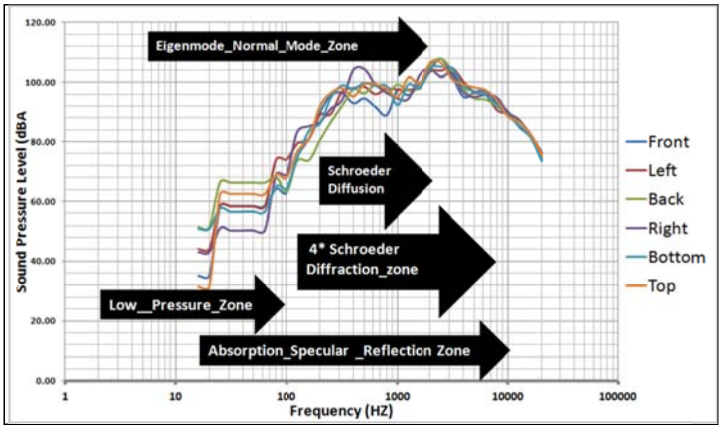


Figure 5. The measured frequency response of a typical hospital room at patient's head position

Since most absorptive materials response to particle velocity; placement of the high absorption materials within the Eigen mode zone and their selection should be based on frequency and location of the large particle velocity. Just as a scenario toward application of a possible solution, if permitted by hospital administration to use 1-inch thick, high absorptive surface at a reflection point within the room, then that surface will be absorbing most of the sound above 1000Hz; therefore the frequency below this level will not be impacted by the noise and the overall sound will be distorted by the ear. To determine the exact frequency to make this change of sound characteristic for a given room depends on the size and volume of the room. At this point, the reflected sound has also different spectral characteristics as well.

The interaction between reflection and localization has an impact on the perception of where in the space a noise comes from. This phenomenon, so called "Precedence Effect", has been investigated by many researchers. Precedence effect or "law of the first wave front" states that if the same sound arrives at the ear from two different directions at two different times (e.g. one arriving from the left and another one from the right 10 ms later) then the perceived location of the sound corresponds to the direction of arrival of the first sound. This 'law' holds true up to about 40 ms. Haas shown that humans localize sound sources in the direction of the first arriving sound regardless of the presence of a single reflection from a different direction. A reflection arriving later than 1 ms after the direct sound, increases the perceived level and spaciousness **[6]**. A single reflection arriving within 5 to 30 ms can be up to 10 dB louder than the direct sound without being perceived as a secondary auditory event with a time varying in reflection level. If the direct sound is coming from the same direction the listener is facing, the reflection's direction has no significant effect on the perceived sound **[7].** The precedence effect appears if the subsequent wave fronts arrive between 2 ms and about 50 ms later than the first wave front. This range is signal dependent. For speech the precedence effect disappears for delays above 50 ms, but for music the precedence effect can also appear for delays of some 100 ms **[8].**

ETC (Energy Time Curve) is the most commonly used acoustic measurement used to examine reflections. ETC simply looks at amplitude over time, but it gives no additional information into the spectrum of that energy. Frequency response, as shown by the Fast Fourier Transform (FFT) of an impulse response (IR), adds up all incident sound within the IR and creates a plot of amplitude vs. frequency. ETC by itself is not a good indicator to show the performance of a room. These room acoustic criteria should be considered in conjunction with the other stated indicators to show the left / right ear frequency response. A large balloon was used as a source to measure the room impulse using the AC and Noise image software. The results show the sound pressure level at different frequencies of the spectrum. Noise image allows presenting this data with frequency axis smoothing (e.g. 1/3rd octave), this makes it much easier to view the room frequencies conditions. See **Figure 5**.

Patient ability to localize sound helps them to sort out individual sounds among many other sources of noise within their environment. Physical, physiological, and psychological studies have shown the head shadows or affects the sound that is reaching the human left ear if the sound is arriving first at the right ear **[7].** The standard comparison between intensities in the left and right ears is known as the inter-aural level difference (ILD). ILD is a good indicator to show high correlation between frequencies over much of the audible spectrum (20-20KHz). Psycho-acoustical experiments show that the central nervous system is equally sensitive to all frequencies. The smallest detectable ILD is approximately 0.5 dB, regardless of the frequency **[8].** If ILD is used, it would be very difficult to localize a sound with a frequency below 500 Hz. However, Rayleigh discovered that a steady-state low-frequency pure tone such as 256 or 128 Hz could easily be localized. He concluded in 1907 that the ear must be able to detect the difference in wave form phases between the two ears **[7, 9].**

A patient's head and its surroundings include a variety of secondary scattering that can be expected to lead the higher-frequency dependence of the ILD. Conceivably, this could help to provide a solution for additional possibilities to impact the sound localization while in bed. The combined use of measured data with AC and Noise Image software and Mat Lab utilizing the Multiple Signal Classification (MUSIC) algorithm developed by Forooze **[10]** provides the opportunity to see and examine this phenomenon. The MUSIC is a standard method to localize acoustic sounds using sequential projections to properly identify local maxima of the gain function as origins of true sources. The localization results for Delay and Sum (DAS) beamformer as part of this exploration are shown in **Figure 6.** The local maxima of the source of reflections while listening to masking sound located on the side table by the bed are identified within the surface of the pillow and its surroundings clearly. Similar attempts are made to demonstrate the impact of various sound reflections that are equal to the source itself shown in **Figure 7.** The use of High Definition algorithm available within Noise Image software allows the user to see multiple reflections within roof surfaces including the sum of all peak reflection within the room. The frequency plot option provides the ability to see the frequency domain impact on the room acoustic characteristic. The **Figures 8 a, b, c, and d** show the frequency domain impact of a pressure zone, Eigen mode zone, Schroeder Frequency, 4 times the Schroeder Frequency and Specular Zones within the hospital room. It is possible to see the surfaces that are impacted by the contribution of each frequency zone.

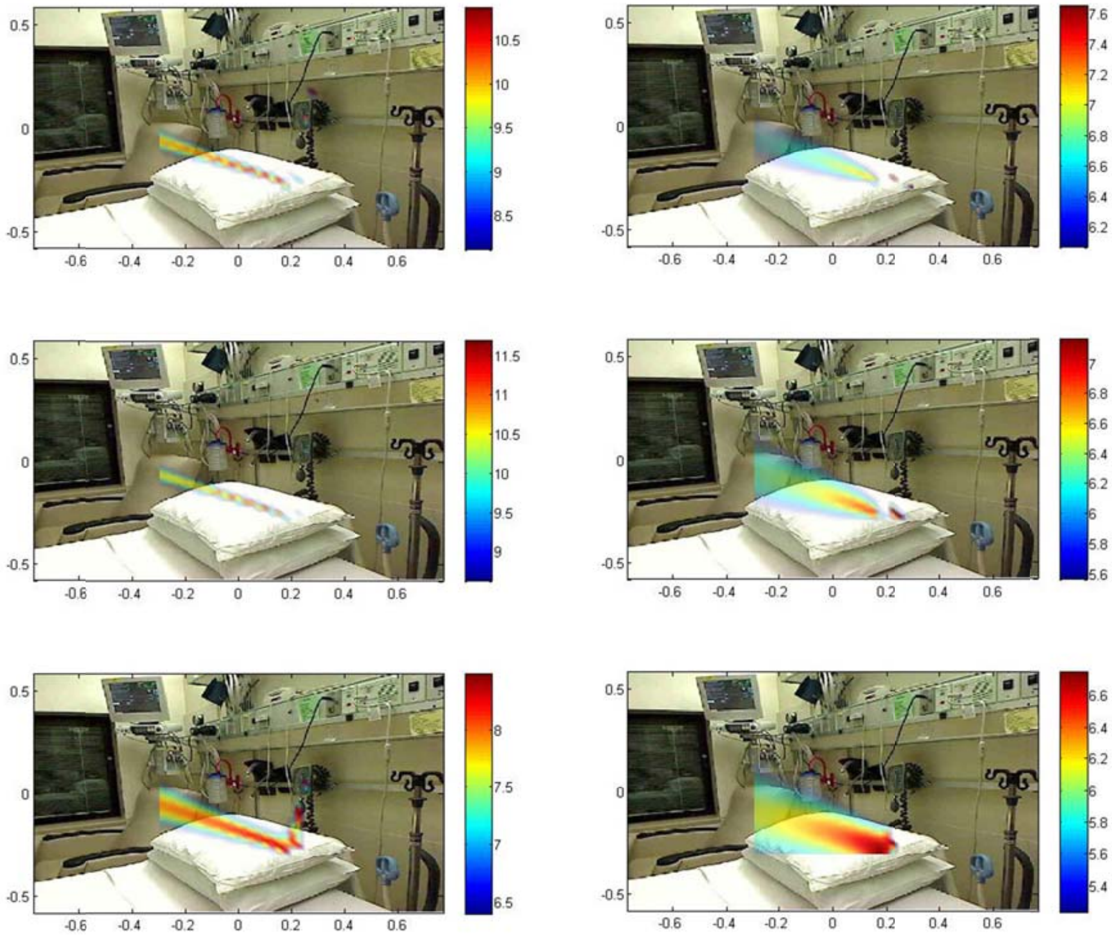
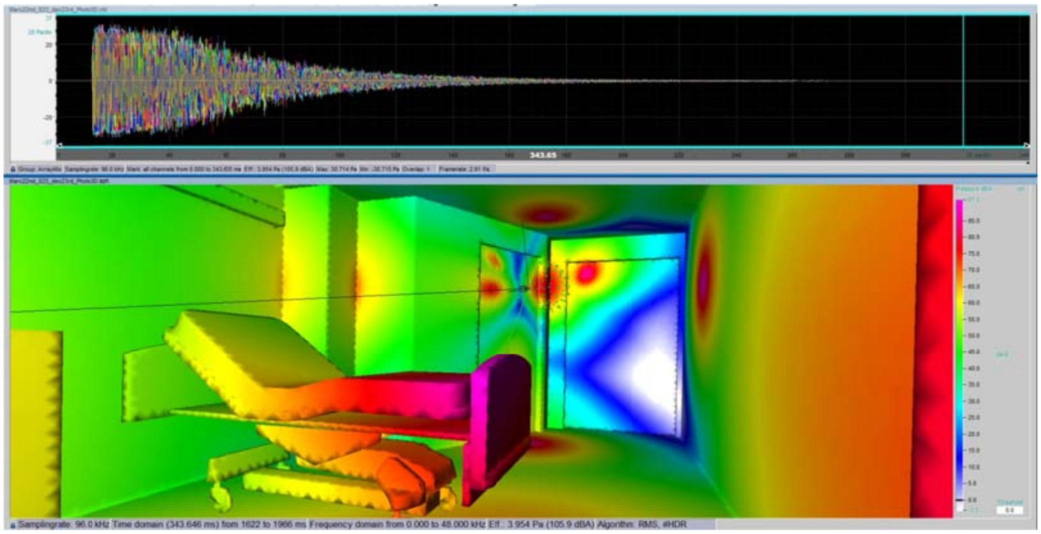
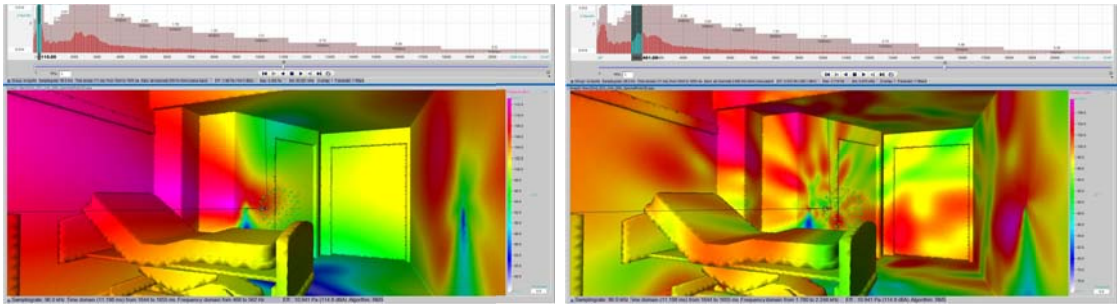


Figure 6. The local maxima of the source and number of reflections in patient room.

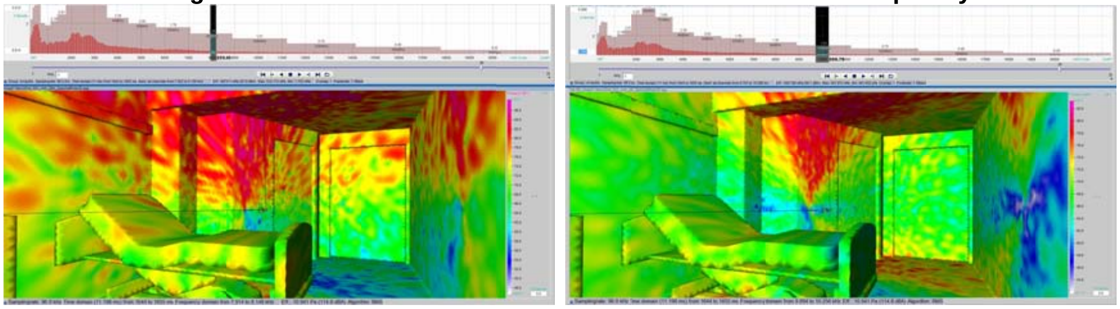


Samplingrate: 96.0 kHz Time domain (343.646 ms) from 1622 to 1966 ms Frequency domain from 0.000 to 48.000 kHz Eff.: 3.954 Pa (105.9 dBA) Algorithm: RMS, #HDR

Figure 7. Measured sound intensity reflection equal or close to the source in patient's room.



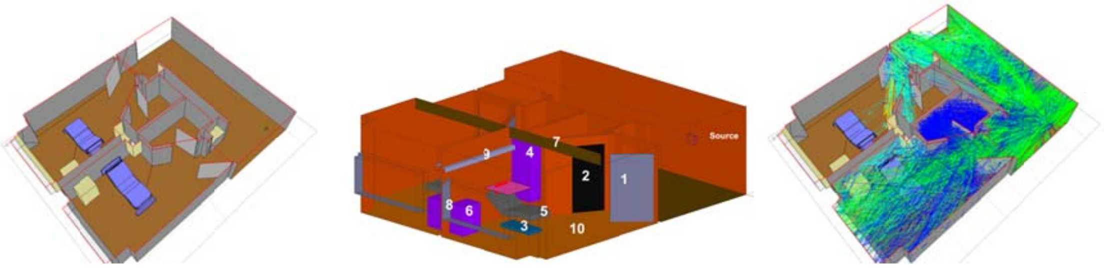
Eigen mode zone **Schroeder Frequency**



4 times the Schroeder Frequency **Specular Zones**

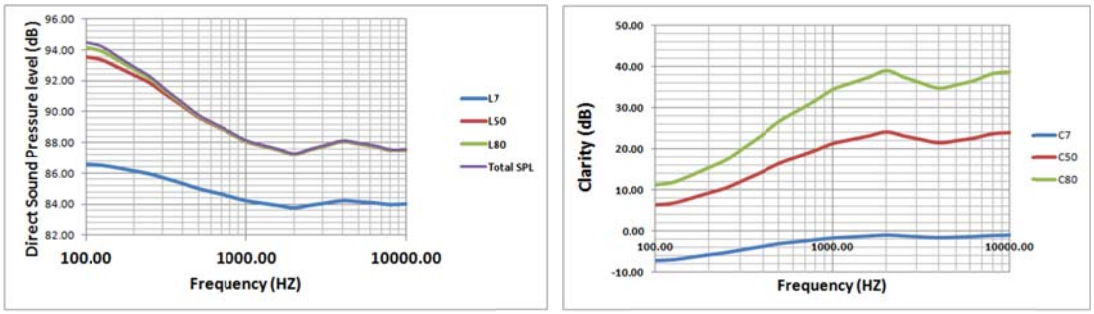
Figures 8 a, b, c, and d. Frequency domain impact within pressure zone, Eigen mode zone, Schroeder Frequency, 4 times the Schroeder Frequency and Specular Zones in a hospital room.

Sound travels approximately a foot every millisecond. In an untreated room, there will be clearly defined energy spikes over time as the sound reflects off various surfaces and arrives at the listening positions. Placing a diffuser in the reflection path will scatter the sound energy across a wide angle and therefore it will not reach the ear. Diffusion takes away from the listening-room layer in many ways. It affects the arrival time, eliminates the echoes that often exit in domestic listening environments due to the parallel room surfaces and reduces the impact of frequencies. Use of any sound system in an architectural space, is an acknowledgment of the lack of provision of an architectural solutions for the architectural acoustic needs of the space by the design team. In general, with adequate diffusion and appropriate reflection, you can theoretically get a small listening room to sound rather like a very good concert hall because, psycho acoustically, all the same basic ingredients will be there including smoothly decaying reverberation that permeates the whole room. The hospital room was modelled within EASE program and the surfaces with peak reflection points were change to high absorptive surfaces. The results show that it is possible to use selected surfaces to eliminate acoustic hot spots for a better hearing for the patients.

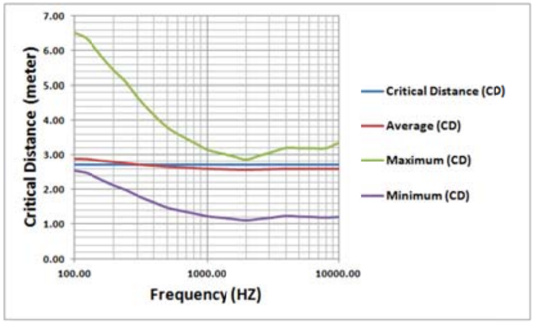


Figures 9 a, b, and c. Computer model of hospital rooms and noise reflections within circulation space.

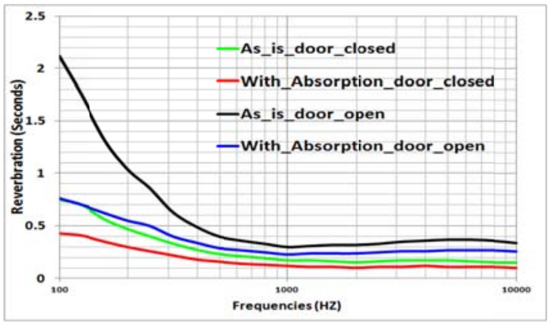
The computer model allows the design team to explore all possible options to solve the noise problem without use of electrical sound cancelling system or masking. Specific surfaces are identified in terms of their sound absorption and their contribution to the total noise reduction of the room. Sound Pressure Levels as L7, 50 and 80 are the sum of the direct and reverberant energy, in dBSPL, within the first 7, 50 and 80 milliseconds of the first arrival. **Figure 10** shows the calculated results of room total sound pressure level and L at 7, 50 and 80 milliseconds. The data shows the contribution of reflected components. The difference in L7 and L80 at low frequency shows in small rooms, the direct sound intensity has major influence on the reverberation time given room surface reflectivity. Clarity (C) is the ratio of energy before and after 7, 50 and 80 milliseconds in decibels. This index shows the strength of direct sound of sources. Any value above –15 dB allows a good localization of the sound source. The closer the value is to 0 the better the localization. Similar calculation on calculated clarity at 7, 50 and 80 milliseconds shown in **Figure 10b** are supportive exhibits as data for contribution of high frequency to noise levels given their density as was shown in **Figure5.** Critical Distance is a distance from the source where the direct sound equals the reverberant sound. See Max and Min critical distance in **Figure 10c.**



Figures 10 a, b, Total sound pressure level and, clarity at 7, 50 and 80 milliseconds in a hospital room.



Figures 10 c. Estimated critical distance.



Figures 11 Estimated reverberation reduction.

The simulation results shown in **Figure 11** indicate it is possible to use absorptive panels located strategically at the identified location (acoustic hot spots) within a patient room as show in **Figure 9b** providing the noticeable reduction of noise within the hospital room. The discussion and performance analysis of design and development of these absorptive panels are beyond the scope of work for this paper, however, **Figure 12** shows the detail and the proposed locations for these sound absorbers or silencers to be within the door cavity.

Figure 12. Design detail and the proposed location of sound absorber or silencers within the door cavity.

5 POSSIBLE OUTCOMES

The question is how do the medical staffs negotiate the use of a working and care giving environment and what kinds of codes, standards, and guidelines exist for designers of new construction and renovations to help them to achieve their goals. It is hoped that the application of these architectural solutions brings the benefit from medical audio and architectural engineering research to room acoustic design. There is a need to increase the availability of research results and related information to case studies in hospitals with high noise problems. Given the current technology and methods; it is possible to reduce the noise for patients within cardiovascular acute care units, and verify the benefit of enhanced architectural environment and or room acoustic environment that deviate from noisy sources. It is essential to integrate the room acoustic designs and architectural solutions with space operation that do not require electronic and accessibility requirements of persons for its operation and control into current design practices.

6 CONCLUSIONS

As sounds during sleep influence both cortical brain activity and cardiovascular function. This study has shown systematic quantification and the reduction capacity of a range of hospital sounds in time and frequency domain. Application of sonic panels and door silencers provides evidence that is possible to improve the architectural room acoustic within a given new design and or existing health care facilities without use of electronic controls while providing highest quality of care by the health care system.

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