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Noise Control for Neonatal ICU for Demolition and Construction Within Hospital Facilities

Jack B. Evans [1]
JEAcoustics
1705 West Koenig Lane
Austin, TX 78756

ABSTRACT
Hospital facilities are frequently expanded, modified or renovated while nearby spaces are occupied. Noise, vibration and impacts from demolition and construction within the building cause audible and perceptible vibration disturbances in patient, nursing, procedure, laboratory and physician spaces. This case study presents the results of a vibration and noise measurement evaluation of simulated construction tool use in a hospital, near the Neonatal Intensive Care Unit (NICU). Based on the results, various temporary noise and vibration control measures were developed in consultation with the architect, hospital and construction, including scheduling, staging and physical isolation and attenuation of construction events at the source, along the transmission path and within the NICU receiver space. Existing and expansion plans and photos of the hospital NICU are shown along with types of simulated tool uses. Measurement results are shown on spectrum analysis charts (level versus frequency) compared with criteria and in statistical (Ln) spectrum charts contrasting continuous ambient versus typical operational transient noise. Difficulties encountered in implementation are presented along with indications of success of the construction project (which is still in progress).

1. INTRODUCTION
A substantial expansion and renovation of the neonatal intensive care unit (NICU) was proposed at the Phoenix Children's Hospital. The project phases would include demolition of facilities adjacent to the existing NICU for renovation and reconstruction of additional NICU space. Throughout the demolition and construction, existing and new NICU spaces, as they were completed, would remain occupied and fully in use. The NICU occupancy of distressed newborn infants, mothers and medical staff is very sensitive to intrusive noise, vibration and other disturbances. For that reason, the hospital was very interested in minimizing demolition noise and vibration within the NICU. It requested the expansion architect and construction manager to find ways of reducing the disturbances.

The architect retained the acoustical consultant to review the master plan phasing and proposed renovations and expansions with regard to vibration and noise, and to develop concepts for noise control. Investigation of demolition and construction power tool use effects by simulation and measurement was proposed. Findings could potentially indicate feasible methods of vibration and noise isolation, attenuation, damping or even masking. Subsequent to hospital and architect approval of the proposed procedure, the consultant and the construction manager identified construction tools that would be in common use and locations to simulate tool use for

[1] Email address: Evans<at>JEAcoustics.com

measurement of transmitted structure borne vibration and/or airborne noise in the NICU. Results comparison with ambient conditions in the NICU could be used to determine severities of disturbances and establish priority of solution development and implementation.

Recommendations for mitigation measures are presented below, following description of tool use simulation, measurement procedures and results. Objective evaluations of the success have not been undertaken, because the multi-year project is still in process, but subjective indications are positive.

2. NOISE AND VIBRATION CRITERIA

A. NICU Standards

The Committee to Establish Recommended Standards for Newborn ICU Design reviews and refines many criteria, parameters and standards annually, including acoustics [1]. The Committee's published work is also adopted and incorporated in the American Institute of Architects' *Guidelines for Design and Construction of Hospital and Health Care Facilities.* The objectives of acoustical standards include (a) freedom from intrusive noise, (b) protection of infant and adult sleep, (c) safeguard adult speech intelligibility and speech sounds for infants, (d) reduce error in speech communication and distraction, (e) reduce annoyance, discomfort and physical symptoms due to noise, and (f) to provide acoustical privacy for patient families and medical staff. [2] Over time, the acoustical standards have trended toward quieter background noise, in part through design parameters for architecture and hospital mechanical systems.

The 1999 Report of the Fourth Consensus Conference "Recommended Standards for Newborn ICU Design, Standard 23: Noise Control," states that, "the combination of continuous background sound and transient sound in any bed space or patient care area shall not exceed an hourly L_{eq} of 50 dB and an hourly L_{eq} of 55 dB, both A-weighted slow response. The L_{max} (transient sounds) shall not exceed 70 dB, A-weighted slow response." [3] Recognition is implicit that continuous background noise from building systems is added to by occupant speech and activity in addition to intrusive noise from outside the NICU. With no exemption for long-duration temporary conditions, demolition and construction disturbances are expected to comply. Since this project began, NICU acoustical standards have continued to evolve. The 6th edition of Recommended NICU Standards lowered permissible noise levels 5 dB. [4]

B. Background Noise

Permissible continuous background noise levels in hospitals due to building systems, such as mechanical and HVAC systems, lighting, electrical, plumbing/piping and elevators are recommended by ASHRAE [5] not to exceed NC/RC 30 in private rooms and NC/RC 35 in wards. ICU noise criteria are not specified. Building systems noise should be limited to the level that would permit compliance with the NICU operational noise criteria above, when hospital installed equipment noise and occupant activity noise contributions are added to the background building noise. Assuming NICU equipment and activity noise to be dominant, therefore, building systems noise ideally would be 10 dB below the hourly L_{eq} 50 dBA criterion (re: Decibel addition of two source levels separated by 10 dB would sum to no louder than the dominant source. [6]). On this premise, continuous background building system noise levels in Nursery and Isolation/NICU spaces are recommended RC 25-35 (equiv. 37-47 dBA) and RC 30-35 (equiv. 42-47 dBA), respectively. Similarly, the Nurses' Station, which may be permitted some relaxation over the levels near infant cribs, should not exceed RC 35-40 (equiv. 42-47 dBA). [7] In conjunction with building systems noise control design, NICU demising assembly design should consider flanking and intrusive noise penetrations for ducts, pipes, conduits and other building elements.

C. Intrusive Demolition and Construction Noise

The project criteria for intrusive disturbances were developed based on relative increase of transient sound or vibration above overall continuous ambient level. Based on judgment and past experience, the acoustical consultant considered transient disturbances to be audible at 2-3 dB increase, annoying at 5-7 dB increase and unacceptable at 10 or more dB greater than ambient. The NICU operational criteria allow 70 dBA transient maximum levels, but since the demolition and construction would continue for two years or more, it is preferable to limit intrusive demolition and construction transients to no more than 10 dB above the ambient.[8]

D. Intrusive Demolition and Construction Vibration

Surface vibration on walls, ceiling and other large areas that is at least 60 dB below 1 g RMS acceleration produces radiated sound less than NC-35 (equiv. 45 dBA). It varies with frequency, but acceleration (on the floor) ranging from approximately 60 dB below 1 **g** at very low frequencies up to approximately 35 dB below 1**g** at 250 Hz is close to "feelable" perception.[9] Demolition and construction source levels of acceleration on floors and walls, therefore, at amplitudes greater than 60 dB below 1 **g** RMS, should be considered perceptible, and potentially contributing to or reinforcing intrusive transient airborne noise.[10] Note: Generic floor vibration criteria in 1/3 octave RMS velocity, relative to human perception or vibration sensitive installations are commonly used for facility design. For this project, surface vibration as radiated noise was judged to be more significant than feelable vibration as a perceptible disturbance. Therefore, only the acceleration criterion was employed. Shock and impacts were recognized for potential startle, sleep disturbance or annoyance effects, but not given specific allowable limits.

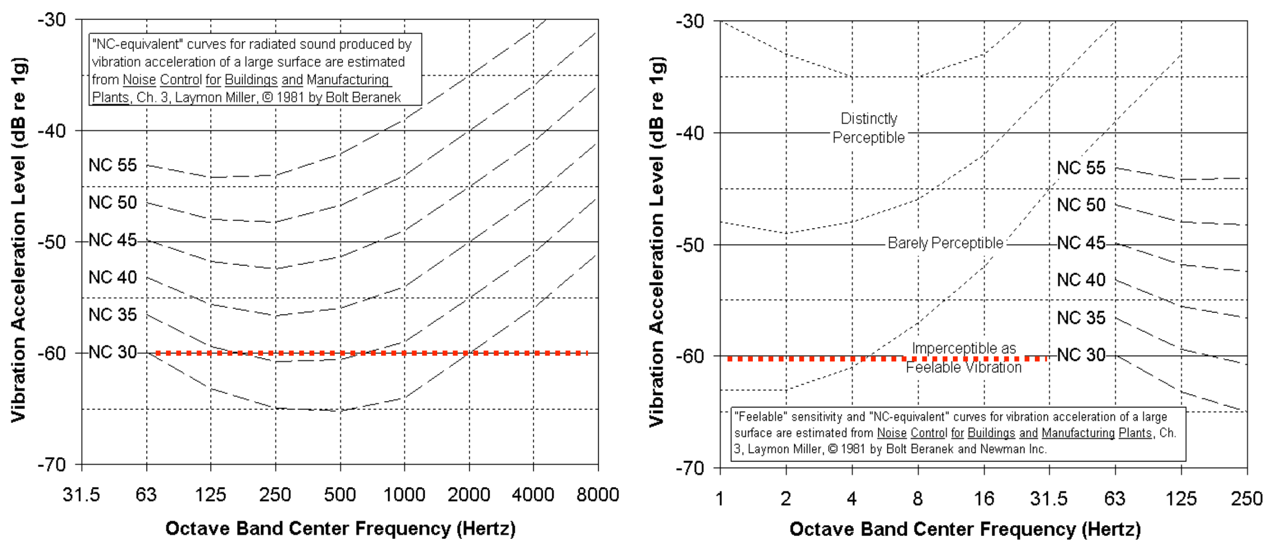

Figure 1: Surface Vibration Amplitudes and Related Radiated Sound Levels (Octaves)

3. EXISTING AND PROPOSED NICU PLANS

A. Existing NICU

The existing NICU incorporated an office and nurses' work area, ancillary support spaces, a large open ICU and a smaller ICU. The area to the north was an existing roof over Emergency Department and parking. The east was an exterior wall. An air handler mechanical equipment room (MER) was immediately west. A corridor separated C-Section operating rooms and recovery to the south. The floor below the NICUs has occupied hospital spaces. The NICU area is on the highest floor of this wing, so only a roof is above the demolition/construction spaces.

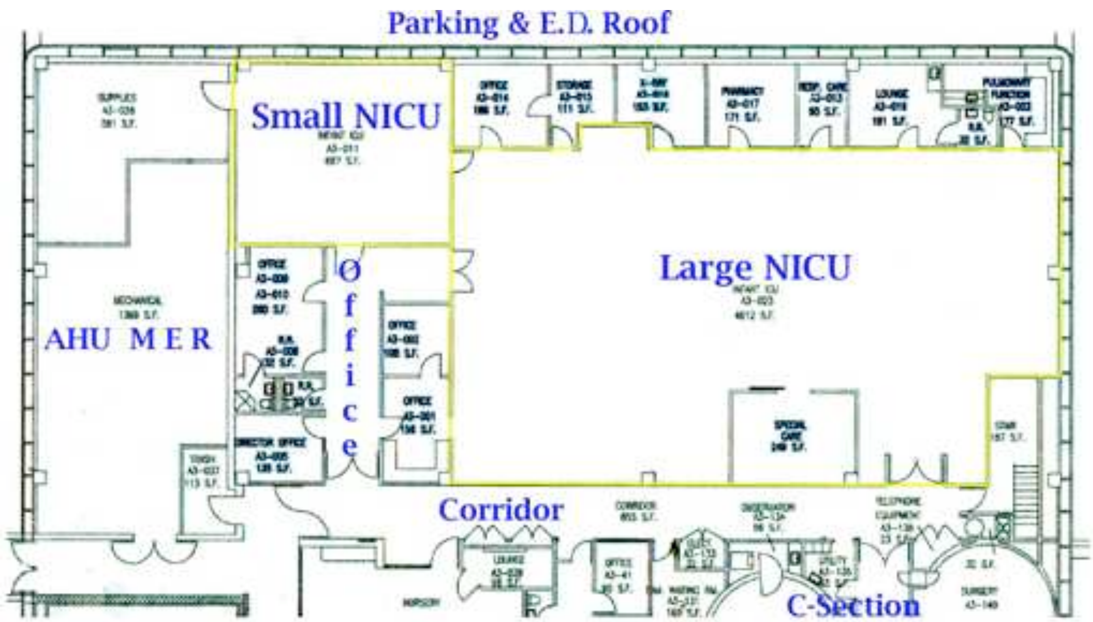

Figure 2: Floor Plan: Existing Large and Small NICU Facilities.

B. Proposed Master Plan

The Master Plan called for Phase 2 demolition of the C-Section and LDR departments south of the existing NICUs, and construction of new NICU space. In Phase 3, new NICU space would be constructed on the existing Emergency Department roof. The existing NICU would remain occupied and operational during the demolition and construction in surrounding areas.

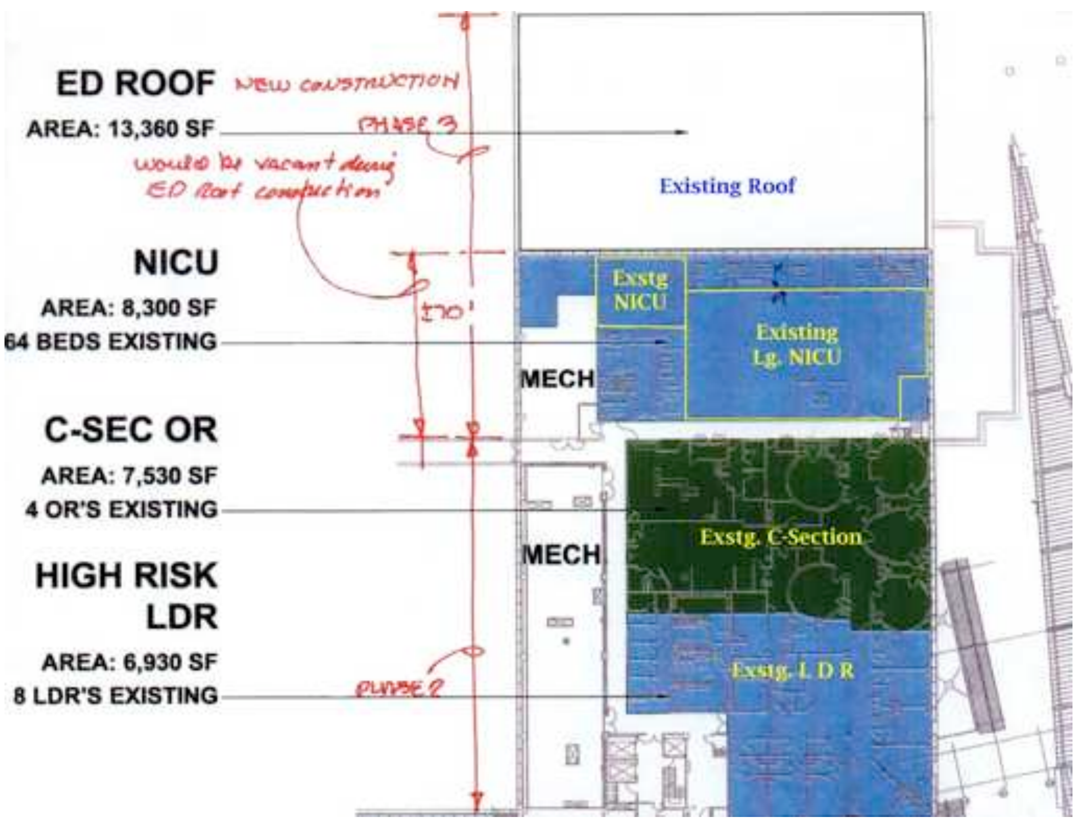

Figure 3: Master Plan: Demolition and Construction Phasing

4. AMBIENT NOISE IN NICU

Statistical (Ln) measurements conducted in the large and small NICUs showed a variable noise spectrum, with numerous transient events, some of which exceed background level by 15 dBA or more. Observations indicated the transients included family and medical staff speech, monitoring alarms, movement of linen carts, mobile X-ray units and other activity. When reviewing the statistical spectra (Fig. 4 and 5, below), more continuous or prominent tonal sources are indicated by percentile spectra that are close together at a given frequency. At frequencies where smaller and larger percentiles converge, continuous noise is dominant, but where they diverge, transients are prominent. Lower frequency background levels are greater in the smaller NICU, which is close to an air handler mechanical equipment room. The higher frequency background level however, is somewhat lower in the small NICU, compared with the large NICU. Maximum transient peak levels, mainly due to monitor alarms and staff speech are similar in both NICUs.

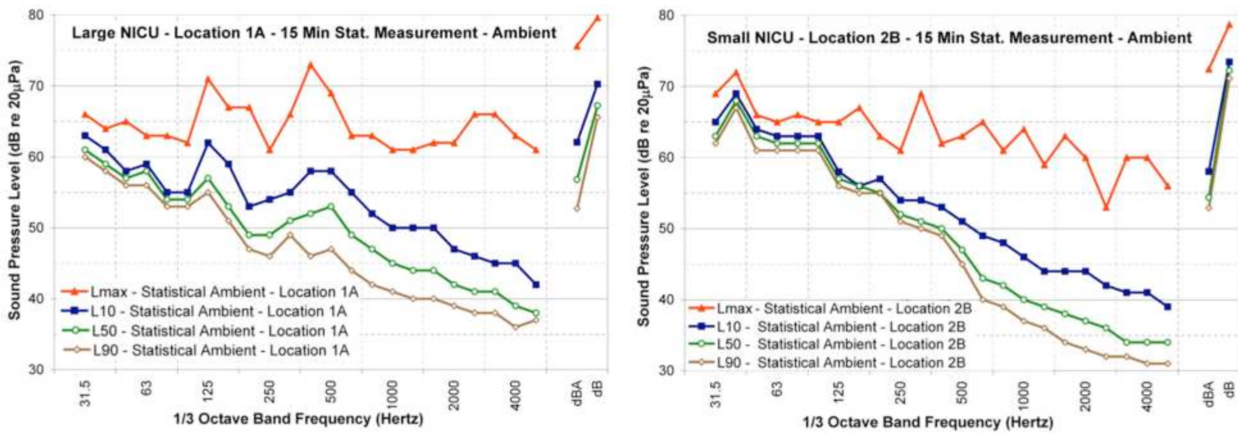

Figure 4: Statistical (Ln) Ambient Noise Measurement Results in Large (left) and Small (right) NICUs.

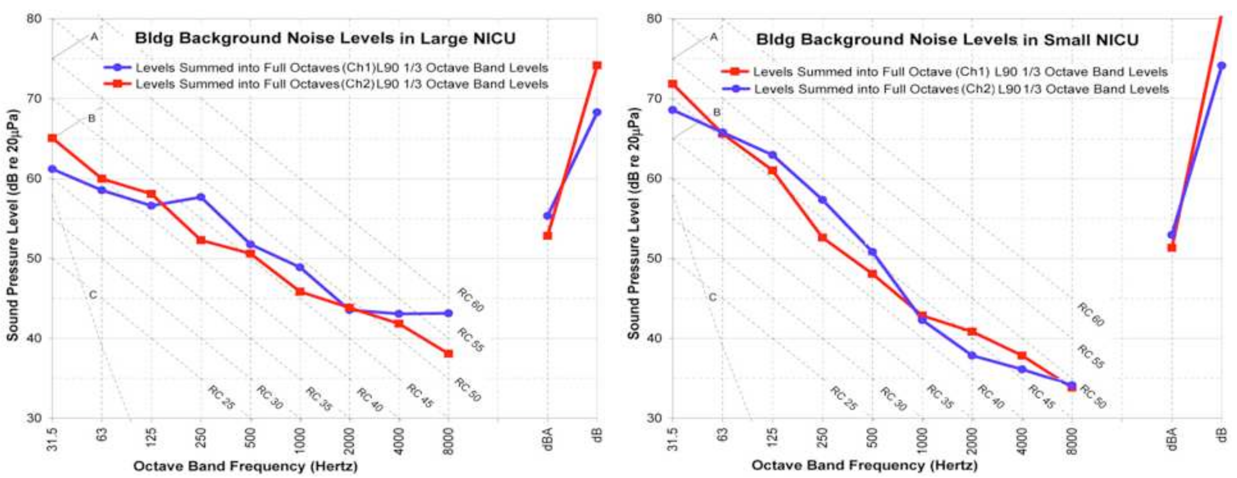

Figure 5: L90 Representing HVAC Background vs. Room Criteria (RC) in Large (left) and Small (right) NICUs.

Figure 5 shows the L90 background levels at both measurement locations in each NICU, as a proxy for continuous background noise, which is assumed to be predominantly HVAC and continuously operating user-installed medical equipment. The spectra in both NICUs are relatively smooth and lay close to Room Criteria (RC) lines. The large NICU has somewhat less rumbly low frequency, but more hissy high frequency noise. The small NICU low frequency sound is great enough to induce vibration into lightweight structures (Region B of the RC chart).

In both NICUs, speech frequency (500-2000 Hz) background noise is relatively quiet, allowing adequate speech communication between families and medical staff. The increased L50 and L90 levels in frequencies close to 50 Hz indicate greater incidence of raised voices in the large NICU.

5. CONSTRUCTION TOOLS AND SIMULATED USE MEASUREMENT

A. Manual and Power Hand Tools

The construction manager identified tools that would be used in the demolition. To reduce major impacts and vibration from large equipment, only hand tools would be used. Tools were selected to simulate, based on a review of a general work scope and sequence plan for demolition and construction on the outer bay of the existing garage concrete roof deck and plaster wall façade. They included power tools; (a) concrete saw, (b) chipping (rotary) hammer, (c) slag hammer, (d) sawsall and manual tools; (e) sledge hammer and (f) claw hammer. Expectation of remodeling disturbances in the C-section area near the NICU resulted in simulation use of (g) powder-actuated fastening device (no photo) on the concrete (partition floor plate anchor-pin setter).

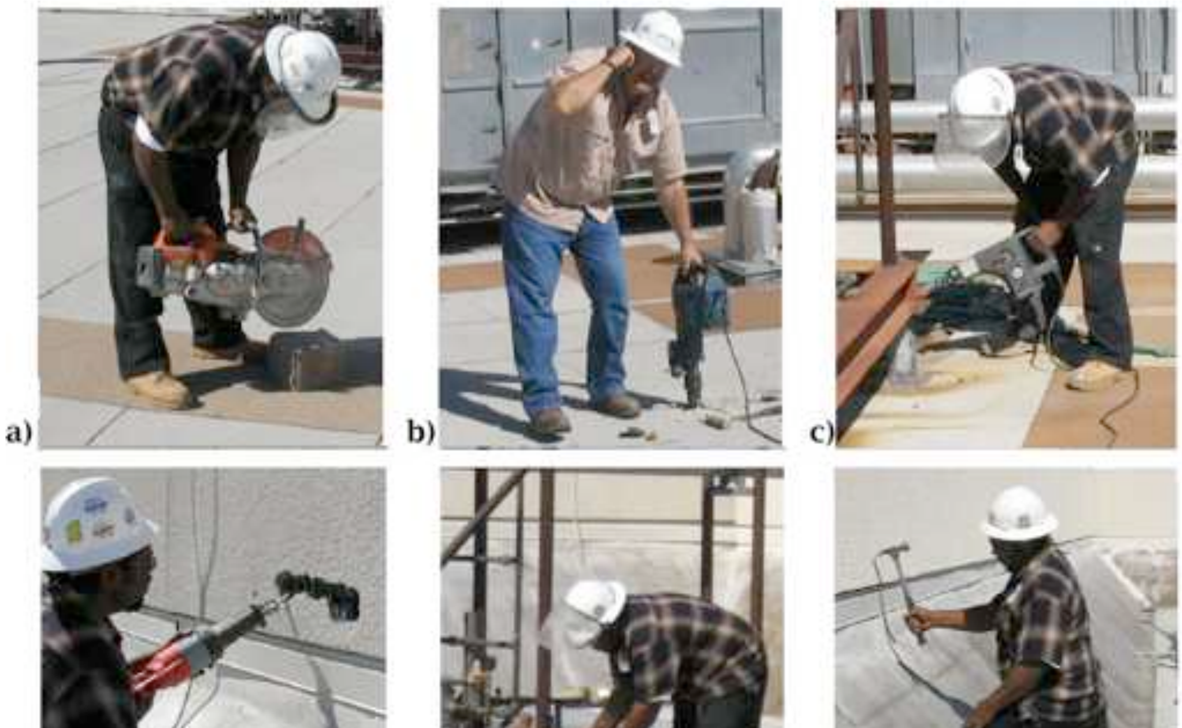

Figure 6: Tool Simulations: (a) concrete saw, (b) chipping (rotary) hammer, (c) slag hammer, (d) sawsall (reciprocating saw) and manual tools; (e) sledge hammer and (f) claw hammer. (g - fastening device not pictured)

The intent was to manually demolish roof mounted equipment base structures and interior partitions, ceilings and fixtures. To prevent large impacts and transient noises, disassembled fabrications, materials and rubble would be moved on wheels to locations where they could be lifted off by cranes, to prevent throwing or dropping off the roof, or sliding down a trough to a dumpster container. The tools were used one at a time on representative surfaces while measurements of transmitted vibration and noise were measured in the occupied NICU.

B. Measurement Procedures

Statistical (Ln) measurements of ambient noise levels were conducted for 10-15 minutes to capture a wide range of continuous and transient noise sources at two locations each near infant bed spaces within the large and small NICUs. Tool simulation measurements were conducted for 15-30 seconds each to capture the transient source of interest. Sources included (a) hammer impacts on an equipment base structure on the roof, on a building column below the NICU and on the bare concrete floor slab in the adjacent MER, (b) power tool sawing, chipping, etc. on exterior areas and (c) powder-actuated anchor setting in the corridor south of the NICU. Measurements conducted included (*i*) airborne sound near wall surfaces, using ½" Precision (ANSI Type I) microphone (*ii*) horizontal acceleration on wall surfaces with Wilcoxon 726 100 mV/g accelerometer attached to wall with bees wax, and (*iii*) vertical acceleration on (non-carpeted) floor using Wilcoxon 731A 10 V/g seismic accelerometer. A Larson-Davis 2900 two-channel real-time analyzer was used to simultaneously capture combinations of airborne sound and wall vibration or wall and floor vibration in narrow band and 1/3 octave bandwidths.

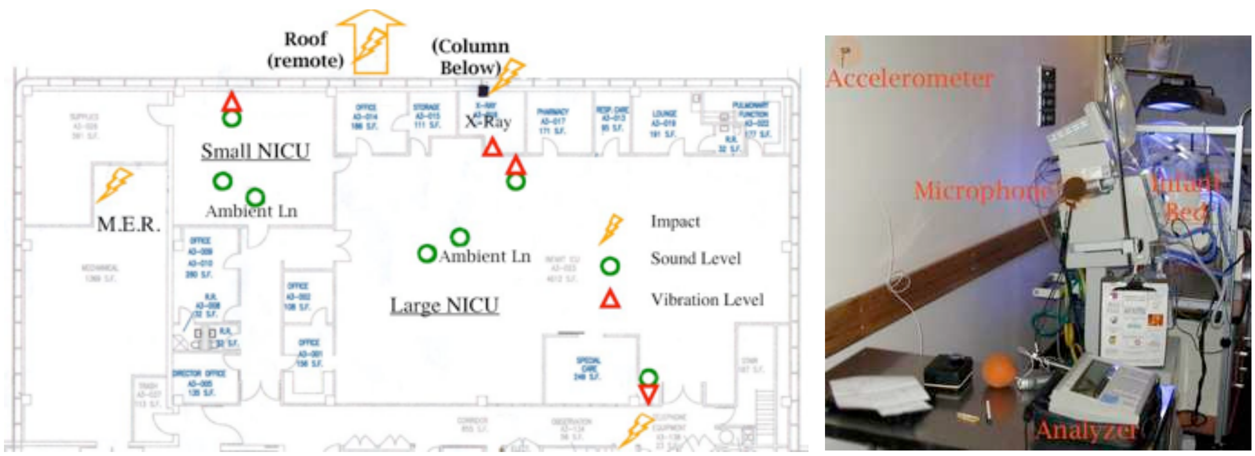

Figure 7: Tool Simulation, NICU Measurement Locations and Typical Arrangement.

C. Simulated Tool Use Measurement Results

Individual tool use outside of the NICU demonstrated audible noise and feelable vibration in the NICU. On a subjective basis, however, with the normal amount of daytime activity and noise in the NICU, the transient disturbances were not particularly noticeable. Multiple simultaneous tools in use would undoubtedly increase the levels of transient noise and vibration. The consultant judged that perception sensitivity to intrusive noise was likely to increase over time.

The measurement charts below, for short-term, 15-30 second transient peak spectra (Lmax) compared with ambient (Leq) spectra for various floor and wall vibration and airborne sound near the wall, assisted with determination of transient level increase. The seismic transducer used for floor measurements has resonance in the 500 Hz 1/3 octave, but results are charted across a wide span of audible frequencies. Floor vibration peaks between 400-800 Hz should be ignored. Wall (partition) measurements, however, are not affected by transducer resonance.

Other charts show vibration levels over "NC-equivalents," indicating potential radiated sound level from transients and also over perception curves, indicating feelable vibration. Numerous measurements were conducted. Only representative charts are displayed below to show that transmitted structure borne vibration was measurable above the background and produced enough surface vibration on partitions to cause audible radiated sound in the NICUs.[11]

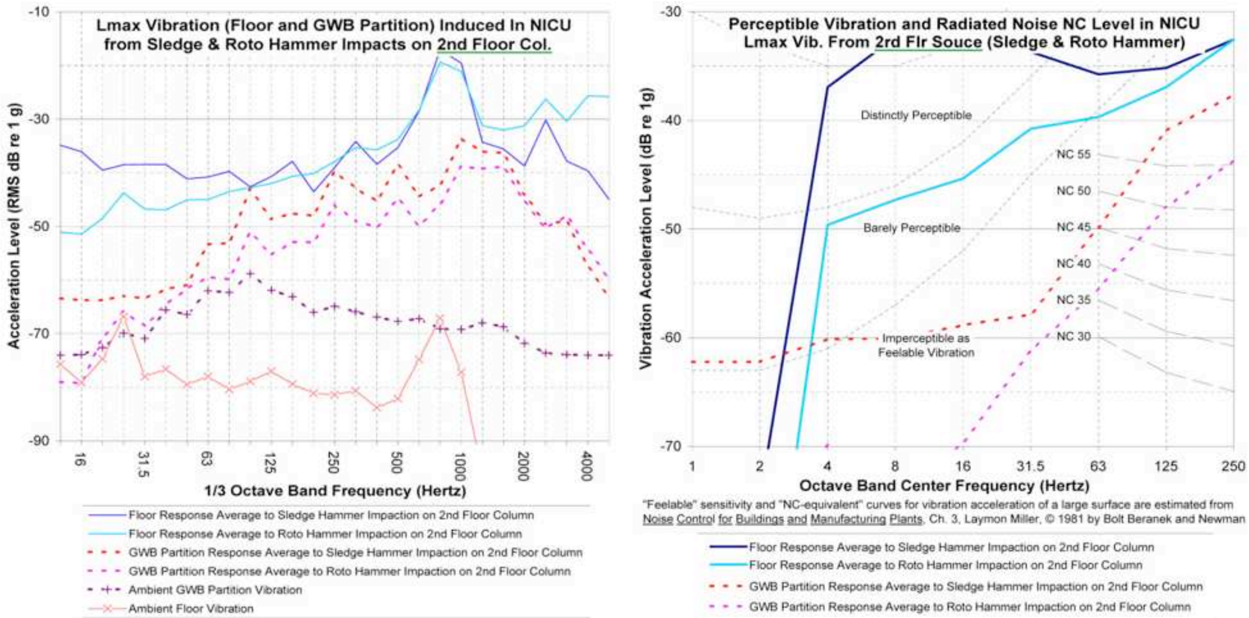

Figure 8: Floor and Partition Surface Vibration Reactions to Impacts on Remote Building Column.

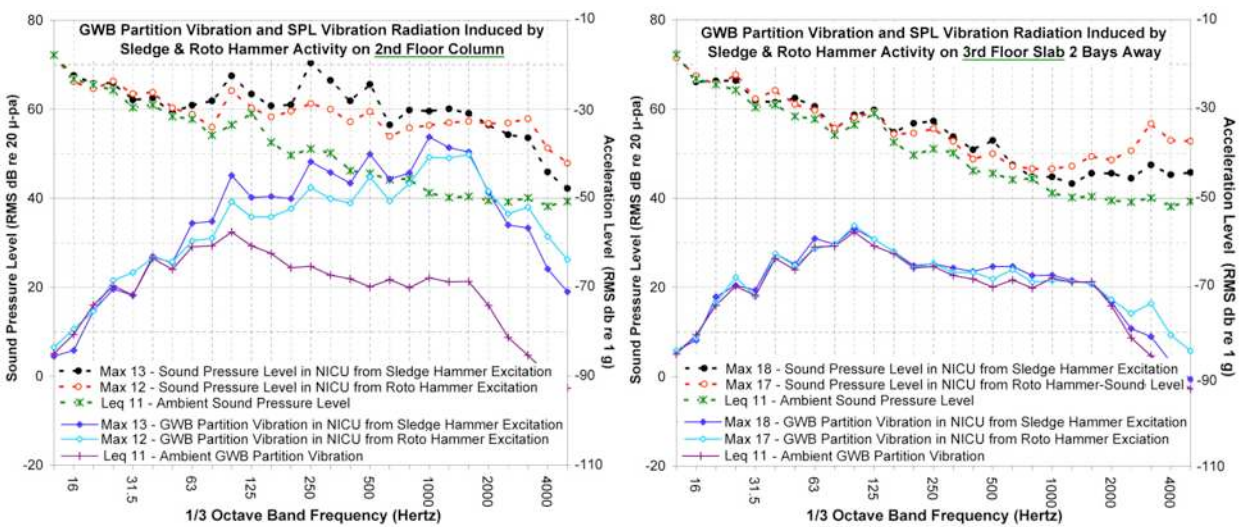

Figure 9: Airborne Sound and Partition Surface Vibration From Impacts at Different Locations and Distances

Comparison of similar sources at different distances from receiver locations showed that the amplitudes of transmitted vibration from two to three structural bays away were reduced substantially from those occurring on the adjacent structural bay (see Table 1, below).

Table 1: Summary of Feelable Vibration and Audible Radiated Sound From Simulated Tool Uses

Tool Use Simulated	Adjacent Bay Vibration / Sound		MER (2 Bays West) Vibration / Sound		Roof (1 & 2 Bays North) Vibration / Sound	
Sledge Hammer (Impact)	Distinctly	Distinctly	Barely	Moderately	Imperceptible	Barely
Rotary Hammer (Power)	Moderately	Distinctly	Barely	Moderately	- - -	- - -
Anchor Setting (Impact)	Distinctly	Distinctly	- - -	- - -	- - -	- - -

6. FINDINGS AND CONCLUSIONS

A. Ambient Conditions

There is a lot of activity in the NICU, especially during daytime hours. Nursing staff, families with newborns and doctors making rounds are present at all hours. The continuous ambient background noise level is somewhat greater than recommended. Monitoring alarms and voice communications are increased to be heard over background. The background noise masks some sound events, but sound levels are variable, demonstrating prominence of many transient sounds.

B. Vibration Transmission and Radiated Noise

Vibration travels via the continuous structure. Airborne sound intrusion from outside the NICU is insignificant, but radiated sound due to structure borne tool impacts and vibration is audible.

C. Conclusions

Structural discontinuities are needed to isolate or attenuate structure borne vibration transmission. Other methods of reducing radiated sound from partition and ceiling surfaces are needed, such as sound barriers or surface vibration damping. Some impact sources may not be attenuated enough to prevent NICU disturbances. In those cases, scheduling or procedures need to be created to minimize undesirable effects, such as planning identified significant impacts during busiest parts of the day, when the additional noise intrusion would be less noticeable in comparison to internal activity and occupant generated noise.

7. VIBRATION AND NOISE CONTROL RECOMMENDATIONS

Conceptual recommendations were developed by the acoustical consultant for implementation by the architect and engineers (design), by the hospital (operational), and by the construction manager (demolition and construction). [12]

A. Hospital Operational Strategies

1. Scheduling: The normal activity and noise within the NICU should be studied to determine hours of greatest and least ambient noise. The construction managers and NICU staff should coordinate activities so that demolition and construction procedures that cause greatest perceptible vibration and noise in the NICU can be scheduled to occur only when other noise within the ICU is elevated. Since noise is additive, it might seem that construction noise added to NICU occupant generated noise would be increasing the already greatest levels. Most of the loudest construction procedures, however, are impacts with instantaneous sound increase, but very short duration. Masking those sounds with other variable activity noise reduces the "startle" effect of sudden disturbance.

2. NICU Rearrangement: Many hospitals operate at near capacity conditions for long durations. This facility is no different. There are few viable options for sensitive occupants to relocate to other areas that are less subject to construction noise. Within the NICU, however, partitions closer to the demolition and construction can radiate louder noise due to the structure borne vibration (re: vibration reduction rate over distance). Therefore, utility, work and storage spaces within the NICU should be rearranged to be closer to the construction, while infant beds, nurse stations, and family consultation/procedure spaces should be moved away from demising partitions and construction zones to benefit from the relatively quieter conditions.

B. Architectural & Engineering Design Modifications

1. Structural Isolation / Path Discontinuities: Identify existing building structural discontinuities, such as building expansion joints or change in slab type (example: concrete beam-slab transition to concrete on metal deck and joists). Use those structural discontinuities to attenuate structure borne vibration along the propagation path. Establish demolition and construction zones that are separated from NICU spaces by the existing joints, such as material movements (pallet jacks, etc.), impacts, disassembly of fabrications, and operation of compressors or other equipment from NICU spaces.

Locate pipes, conduits and other building elements that can transfer vibration from demolition or construction zones to occupied hospital space. Insert flexible pipe and conduit segments or flexible connections where feasible, or retrofit vibration isolator hangers or stanchion supports, either in the demo zone where vibration can enter or in the occupied space where pipes and conduits can transfer vibration.

2. Existing Demising Partitions and Temporary Noise Barriers: Review existing demising partitions around the NICUs and around the demolition areas. Determine weak spots that permit airborne sound transmission, such as doors, windows, penetrations and partitions that do not extend to the deck above. Apply effective acoustical seals to door heads, jamb, thresholds and double door meeting stile astragals. Retrofit interior windows (usually single layer glass) with thick laminated noise control glass, Plexiglas, mass-loaded vinyl sheet (clear or opaque), plywood, sheet metal or drywall to increase sound transmission loss. Extend short partitions from ceiling levels to deck above. Duct attenuators should be placed in return air transfer openings, or the return air path should be re-routed around demising partition between work area and occupied NICU. Locate partition penetrations and seal them airtight with acoustical sealant, soft-pliable fire caulking or caulking putty.

Partitions subject to radiation noise from structure borne vibration should be modified or covered to reduce or contain noise. Consider removing drywall from studs and reinstalling on resilient drywall mountings. Alternately, hang temporary sound barriers over wall surfaces, such as noise quilts with septum barriers, mass-loaded vinyl sheet, etc. to contain radiate noise.

C. Demolition and Construction Practices

1. Non-Impact Demolition Procedures: Where feasible, substitute torch-cutting, sawing, unbolting and other non-impact procedures to demolish existing building components, in lieu of sledge hammer, power rotary hammer, etc. Also, where possible, use rotary saw or band saw in lieu of reciprocating saw. Note that sawing can create some significant airborne transient sounds, which also should be dealt with, but reduction of structure borne vibration takes a higher priority since it is feelable and can cause radiated audible noise within remote enclosed spaces.

2. Construction Equipment Condition and Maintenance: Assure that construction air compressors, engine generators and other ancillary equipment are in good operating condition. Retrofit standard compressor inlet and exhaust and engine exhaust mufflers with higher performance mufflers with greater attenuation. Plan equipment staging to locate compressors and generators outside the building, if possible, because loud low frequency noise from the equipment may induce structure borne vibration into lighter weight partitions and ceilings in the building. Alternately, mount ancillary equipment on vibration isolator supports and place noise enclosures around the noise-producing equipment.

3. Demolition/Construction Zone Floors: Place a resilient surface on the floor prior to demolition, such as interlocking tiles of rubberized flooring (commonly used in work areas where employees stand on their feet for long durations), to reduce impact of falling and dropping items, or of tool impacts and abrasion on building elements under demolition.

4. Demolition/Construction Zone Isolation: Erect temporary partitions around demolition/construction zone to reduce airborne sound transmission into occupied areas of the hospital, including NICU. Insert duct attenuators in HVAC supply, return and exhaust ducts that pass through work zone to attenuate break-in noise. Reduce or prohibit doors or passages between work zone and occupied hospital spaces. Assign elevators, stairs and corridors for exclusive demolition/construction material movement and personnel.

5. Fabrication and Assembly Shops: Segregate high-noise tools and procedures. Set-up shops outside the hospital building and transport fabrications to the work area by segregated traffic paths C.3. above). For items that need to be fabricated on-site or near the installation location, create de-coupled work floors for construction phase fabrication, assembly and other impact procedures. Use vibration isolation pads under thick plywood or 2x4 wood joists for platforms. Erect temporary partitions or noise control curtains around these fabrication and assembly shops to contain equipment and procedure noise. Partially assembled fabrications can then be moved into place and installed with less localized impact and machine noise.

8. DIFFICULTIES ENCOUNTERED

Some recommendations were not considered feasible or practical in the occupied hospital. Structural modifications, such as installing supplemental beams or joists and cutting slabs to create structural isolation breaks between impact sources and sensitive receivers, could not be undertaken without significant dislocation and disturbance to existing occupants. The expense and difficulty were also considered excessive for the limited benefit. Modification of finished partitions within the NICU to reduce radiation of noise from structure borne vibration, such as stripping existing drywall from studs and reinstalling on resilient mountings, was considered too intrusive in the NICU. It would create dust, noise and other intolerable conditions. As previously noted, even short-term temporary relocations of NICU occupants for remodeling is not practical. Similarly, inserting resilient hangers or vibration isolators in existing ceiling suspensions would be excessively intrusive in the occupied NICU space. Therefore, with the exception of suspending acoustical blanket or mass-loaded vinyl curtains over wall surfaces, all noise control measures needed to be executed outside of the occupied NICU spaces.

9. SUMMARY CONCLUSIONS

Demolition and construction noise produces significant structure borne impacts, vibration and airborne noise, which can disturb sensitive distressed newborns, mothers and hospital staff. While it is not practically feasible to eliminate or attenuate impacts on the structure, it may be possible to isolate or attenuate structure borne vibration along the path or near the receivers. Scheduling and rearrangement of the NICU and demolition/construction procedures can coordinate more noisy activities at certain predictable times. Other measures can be put in place by construction management to move noisier or higher impact procedures away from the NICU or to segregate those activities and equipment within segregated and vibration isolated enclosures in the construction zone. Cooperation, site monitoring and thoughtful pro-active noise control policies by the hospital and construction managers, with the helpful direction of architect can permit facility renovation and expansion with only minimal intrusive disturbance to the NICU.

Reports of subjective evaluations indicate demolition and construction have been relatively quiet and create few disturbances in the NICU. To date the Architect is pleased with results.

ACKNOWLEDGEMENTS

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