REGULAR ARTICLE

Questionable sound exposure outside of the womb: frequency analysis of environmental noise in the neonatal intensive care unit

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Keywords
Environment, Frequency, NICU, Noise, Preterm infants

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Received
4 April 2014; revised 5 September 2014; accepted 23 September 2014.

DOI:10.1111/apa.12816

ABSTRACT

Aim: Recent research raises concerns about the adverse effects of noise exposure on the developing preterm infant. However, current guidelines for NICU noise remain focused on loudness levels, leaving the problem of exposure to potentially harmful sound frequencies largely overlooked. This study examined the frequency spectra present in a level-II NICU.
Methods: Noise measurements were taken in two level-II open-bay nurseries. Measurements were taken over 5 days for a period of 24 h each. Spectral analysis was focused on comparing sound frequencies in the range of human speech during daytime (7 AM–7 PM) vs. night-time (7 PM–7 AM).
Results: On average, daytime noise levels (L_{eq} = 60.05 dBA) were higher than night-time (L_{eq} = 58.67 dBA). Spectral analysis of frequency bands (>50 dB) revealed that infants were exposed to frequencies <500 Hz 100% of the time and to frequencies >500 Hz 57% of the time. During daytime, infants were exposed to nearly 20% more sounds within the speech frequency range compared with night-time ($p = 0.018$).
Conclusion: Measuring the frequency spectra of NICU sounds is necessary to attain a thorough understanding of both the noise levels and the type of sounds that preterm infants are exposed to throughout their hospital stay. The risk of high-frequency noise exposure in the preterm population is still unclear and warrants further investigation.

INTRODUCTION

Preterm infants in the neonatal intensive care unit (NICU) are exposed to a large variety of environmental noise. According to the recommended standards set by the American Academy of Pediatrics (AAP), the combination of continuous background sound and operational sound shall not exceed an hourly equivalent continuous noise level (L_{eq}) of 45 dB and an hourly L10 of 50 dB, while transient peak levels (Lmax) shall not exceed 65 dB, A-weighted slow response (1). However, research has shown that, in reality, NICU noise level typically exceeds the AAP standards, often more than 70% of the time (2). Noise levels within the NICU yielded an overall average L_{eq} of 60.44 dBA and Lmax of 78.39 dBA (3), with peaks impulse over 100 dBA (4), especially in infants receiving continuous positive airways pressure (CPAP) support (5). Whereas majority of studies have focused on measuring loudness levels, the frequency content of NICU noise has not been well studied. In addition, the 2013 guidelines and regulations set by the AAP (1) remain solely focused on loudness levels, leaving the problem of excessive exposure to potentially suboptimal frequencies largely overlooked.

The acoustic environment in the NICU is quite different from that of the womb. In the womb, the foetus begins its auditory experience with a precise mixture of low-frequency sounds (e.g. mother's voice and heartbeat) and background noises (e.g. breathing and bowel movement) that are transmitted by the conduction of sounds through the bones of the skull (6,7). However, the untimely exit from the intrauterine environment exposes preterm newborns to direct exposure of airborne sounds across the entire frequency range when their auditory system is likely to still be accustomed to bone conduction mode. While the exact frequency spectrum the human foetus is exposed to in the womb remains ambiguous, it is clear that maternal tissues

Key notes

- This study demonstrates the significant presence of high-frequency sounds (>500 Hz) in a multibed, open-bay, level-II NICU.
- High-frequency noise in the NICU environment deviates from the sound exposure of a normally developing newborn, which may potentially result in abnormal auditory development.
- There is a reason to theorise that overexposure to high-frequency noise during critical periods may be a contributing factor to the language and attention deficits often seen in the preterm population.

and fluids within the intrauterine cavity achieve high-frequency sound attenuation (8) – with frequencies > 500 Hz more attenuated than frequencies < 500 Hz. Therefore, the intrauterine environment protects the foetus by allowing for the gradual tuning of hair cells within the cochlea. However, the optimal environment present in the womb is abruptly terminated when the premature infant enters the suboptimal acoustic environment of the NICU. The altered acoustic environment imposed by the NICU may be harmful to the infant. Some studies have shown that high-frequency noise exposure can alter blood pressure, decrease respiratory rate and disrupt sleep patterns [reviewed in (9)]. Transitioning from the protected environment of the womb to the exposed environment of the NICU during this critical period undoubtedly changes the typical patterns of auditory development, including altering how frequency information is represented. However, the effects of high-frequency noise exposure in the NICU on preterm infants' long-term development are yet to be determined.

In addition to internal sounds in the intrauterine environment such as the mother's voice and heartbeat, the foetus is also exposed (although to a much lesser degree) to external sounds outside of the womb. Hepper and Shahidullah (10) have examined the responsiveness of the human foetus to external auditory stimuli (pure tones) presented by a loudspeaker placed on the maternal abdomen at different frequencies (100 Hz, 250 Hz, 500 Hz, 1000 Hz and 3000 Hz). Recording of foetal movements via ultrasound revealed the preferential sensitivity of the foetus to external sounds in low-frequency range (<500 Hz) as early as 19 weeks of gestation. At 27 weeks of gestational age, the vast majority of foetuses responded to sounds < 500 Hz but none responded to sounds at 1000 Hz and 3000 Hz. Responsiveness to sounds > 1000 Hz was not observed until 33 weeks' gestation. For all frequencies presented, there was a significant decrease in the intensity required to elicit a response with increased gestational age, likely due to the maturation of the auditory system and the thinning of the intrauterine walls in the last trimester of the pregnancy. Although the above study by Hepper and Shahidullah clearly demonstrated that foetuses can respond to high-frequency sounds, it does not rule out the possibility that this particular exposure was harmful.

In considering the presence of different sound frequencies within the NICU environment, it is important to highlight that frequency is a quantitative characteristic of the human voice. The frequency variation of speech stems from resonances in the air-filled cavities of the vocal tract (11). These acoustical resonances (defined as peaks in the spectral envelope of speech sounds) and their corresponding spectral prominences are commonly referred to as formants (12). Formants are particularly important for speech perception because they convey real-time articulatory information about vocal tract shape and its change over time (13). The first (F1) and second (F2) formants frequencies (approximately 350–2500 Hz) are known to include much of the cues necessary for speech intelligibility and vowel discrimination (14). Although the acoustical energy of the human voice beyond 5000 Hz may contain potentially important information (15), for this particular study, the frequency range of human speech was considered between 501 and 3150 Hz, largely overlapping with the first two and most critical speech formants (F1 and F2).

Does the acoustic environment of the womb contain high-frequency sounds? This question is difficult to answer largely because majority of studies examining the acoustic characteristics of the intrauterine environment are based on nonhuman models. For example, Gerhardt and colleague surgically implanted a hydrophone in pregnant ewes to determine the internal sound pressure under three conditions: sound field exposure, broadband octave noise and quiet (16). For low frequencies (<250 Hz), they found that sound pressures were 2–5 dB greater inside the ewe compared with outside. For frequencies >250 Hz, sound attenuation increased 6 dB per octave, and for 4000 Hz, sound attenuation averaged 20 dB, suggesting that sound transmission *in utero* occurs nonlinearly. In addition, Lecanuet and colleague (17) presented sweeping pure tones to an artificial model of a womb made with a plain rubber sphere filled with water and an embedded hydrophone. The authors found that in low-to-mid-frequencies (100 and 1000 Hz), the intensity of the inside signal remained stable and that with higher frequencies, the inside pressure fell gradually, reflecting attenuation of the external signal. At the highest frequency range, a series of rapid peaks and drops in the frequency pressure occurred indicating the presence of a resonance system. Data from this artificial model were compared to an ewe model, which further validated the nonlinearity aspects of the acoustic environment of the womb (17). These groundbreaking studies have provided important insights regarding the acoustic properties of the intrauterine environment; however, the various methodologies and models used make it difficult to generalise the findings to human preterm neonates, especially given the complex environment of the NICU.

Previous studies examining sound frequency in the NICU were completed in level-III nurseries. These studies demonstrated the presence of high-frequency noise ranging from 1000 up to 8000 Hz within the NICU environment (18,19). However, because majority of infants in a level-III unit are placed in an incubator, they are protected, at least to some extent, from high-frequency noise exposure owing to the acoustic attenuation of the incubator walls. Thus, previous measurement of sound frequencies taken outside the incubator (18, 19) do not truly reflect the frequency spectra an infant is exposed to inside the incubator. To provide representative measures of exposure, spectral measurements should be taken in a level-II unit, wherein majority of infants are placed in open cribs with essentially little to no protection against environmental noise. To our knowledge, no previous study has specifically examined the sound frequency in an open-bay, level-II NICU. The current study aimed to address this gap in knowledge, with a particular interest in comparing the sound frequencies in the human speech range during daytime vs. night-time. We hypothesised that the spectral content of NICU noise during daytime will contain more frequencies in the speech range compared with night-time.

METHODS

Experimental settings

Noise measurements were taken in two level-II nurseries within the NICU at Brigham and Women's Hospital. Five 24-h measurements (totalling 120 h of data) were taken on five consecutive weekdays to capture a wide variety of hospital routines, including parental visitations, physician rounds and medical exams. Measurements were taken both during daytime (7 AM–7 PM) and night-time (7 PM–7 AM), in accordance with the nursing shift schedule in our NICU. The vast majority of infants (N = 57) admitted to the level-II nurseries during the noise measurement period were in an open crib. Measurements were taken in two NICU pods; each pod contained 10–12 bed spaces with a nurse-to-patient ratio of 1:3. Staffing did not differ across the 5-day measurement period. There were no restrictions on parental visiting hours.

Sounds measurements

Noise measurements were attained using a Bruel & Kjaer hand-held SPL meter (type 2250-L) omni-directional microphone (type 4950), sound calibrator (type 4231) and an external power source. Calibration of the meter was attained prior to the NICU measurements by placing the tip of the microphone into the calibrator, which generated a pure tone of 1000 Hz at 94 dBA. The SPL meter was positioned at a central location within the NICU pod to optimally capture noise levels in the immediate surrounding the infants' bedside; the specific location of the meter was determined based on pilot testing performed prior to this study.

Data analysis

Because decibels are measured on a logarithmic scale, the mean L_{eq} was calculated by first converting the A-weighted decibels for each 24-h measurement period into intensity, then taking the daily average and converting it back to dBA. A *t*-test was used to compare the L_{eq} levels during daytime vs. night-time. Spectral analyses were completed by converting the Z-weighted decibels for each 24-h measurement period into intensity and then summing across the frequencies. Z-weighting means that the measurements were taken with no filters over the full frequency bandwidth, excluding the electrical output of the SPL microphone (which is not weighted). This method is particularly useful where measurements of particularly low or high frequencies are desired (20). Next, we looked for energy >50 dB within the following frequency bands: 20–500, Hz 501–3150 Hz, 3150–6300 Hz and 6301–16 000 Hz (these particular frequency bands were preset by the SPL meter). For analysis, a 50 dB cut-off was chosen based on both the AAP guidelines (1) as well as Graven's recommendations (21) for noise criteria in the NICU to not exceed an hourly L_{eq} of 45–50 dBA. A *t*-test was used to compare the frequency in the human speech range during daytime vs. night-time.

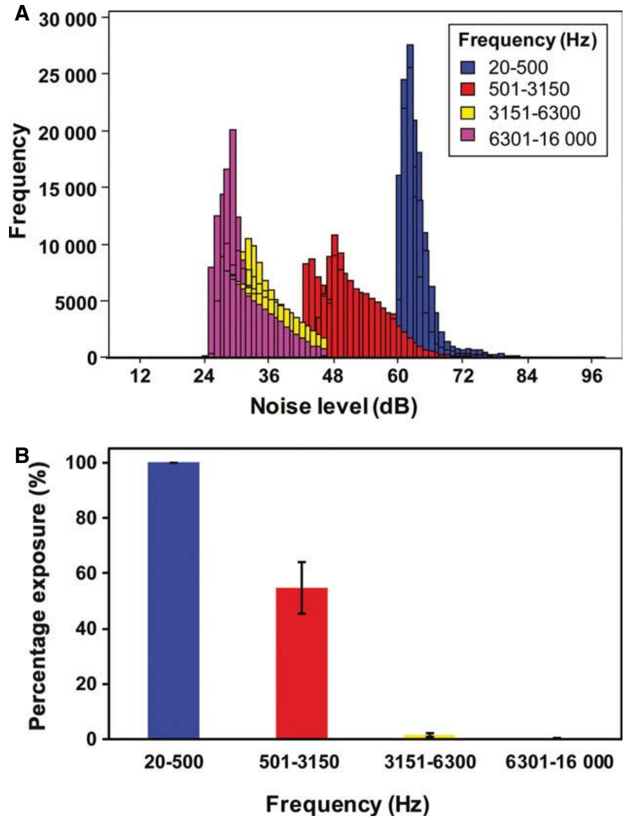

Figure 1 (A) Spectral histograms over the 5-day measurement are shown for the following frequency bands: 20–500 Hz (blue), 501–3150 Hz (red), 3151–6300 Hz (yellow) and 6301–16 000 Hz (magenta). (B) The mean percent daily exposure to noise intensity >50 dB is shown for each of the above bands. The mean percent exposure across 5 days reveals that ~100% of the time infants were exposed to 20–500 Hz, ~55% of the time to 500–3150 Hz, ~1.6% of the time to 3151–6300 Hz and <1% of the time to 6301–16 000 Hz.

RESULTS

The histogram shown in Figure 1A illustrates the noise levels across the 5-day measurement period for the following frequency bands: 20–500 Hz, 501–3150 Hz, 3151–6300 Hz and 6301–16 000 Hz. The mean percent daily exposure to noise intensity >50 dB is shown for each of the above bands (Fig. 1B). Results reveal that 100% of the time infants were exposed to 20–500 Hz, 55% of the time to 500–3150 Hz, 1.6% of the time to 3151–6300 Hz and <1% of the time to 6301–16 000 Hz.

A subsequent analysis was completed examining the loudness level and frequency spectra during daytime (7 AM–7 PM) vs. night-time (7 PM–7 AM) throughout the 5-day measurement period (Fig. 2). The mean L_{eq} over the study period was higher during the day (L_{eq} = 60.05 dBA) compared with during the night (L_{eq} = 58.67 dBA; Fig. 2A), but this difference was not statistically significant (p = 0.356). In addition, infants were exposed to significantly more sound frequencies within the human speech range (501–3150 Hz) during daytime vs. night-time (p = 0.018) (Fig. 2B).

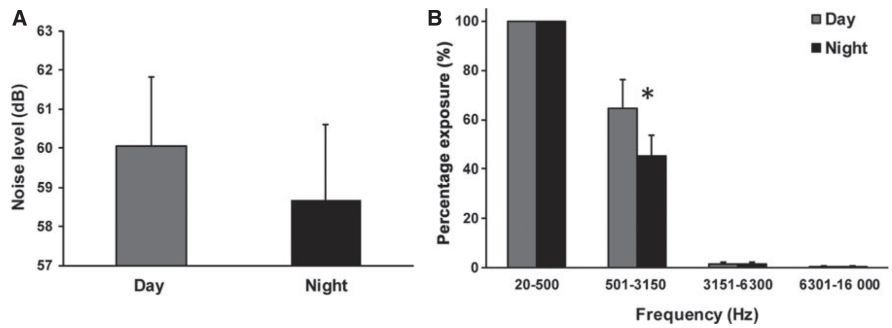

Figure 2 (A) Average loudness measures of the daily L_{eq} (grey) and nightly L_{eq} (black shade). (B) Frequency spectra analysis of daytime (7 AM–7 PM; grey) vs. night-time (7 PM–7 AM; black) is shown for the 5-day measurement period. Infants were exposed to significantly more sound frequencies in the human speech range (501–3150 Hz) during daytime vs. night-time ($p = 0.018$).

DISCUSSION

The results of the present study are based on a 5-day analysis of the frequency spectra in a multibed, open-bay, level-II NICU. Although the vast majority of the time infants were exposed to low frequencies similar to those present in the womb, our results show that they were additionally exposed to frequencies up to ~6300 Hz that are presumably attenuated *in utero*. The risk of such high-frequency noise exposure in the preterm population is still unclear and warrants further research.

There are justifiable reasons for the concern that the sound frequencies present in the NICU do not comply with the audible frequencies present in the womb. The womb setting is optimal for hearing development because the frequencies available *in utero* parallel the tonotopic development of the cochlea [reviewed in (21)]. The exact hierarchical emergence of the frequency development in the cochlea remains unclear; however, previous studies have indicated that human foetuses hear predominately low-frequency sounds owing to the attenuation properties of the maternal tissue and fluids (6). This gradual, fine-tuning process of sound frequencies, from low to high, promotes the optimal development necessary for auditory recognition and discrimination abilities that are present soon after birth (22). Animal models have shown that auditory impoverishment during critical periods of development, in the form of acoustic noise, impairs the tonotopic organisation of the auditory brain system and results in atypical assembly of cortical neural circuits [reviewed in (23)]. These animal studies raise valued concerns regarding the auditory environment available for preterm infants in the NICU. It is therefore possible that prolonged exposure to high frequency noise that the cochlea is not yet mature enough to process may compromise the initial wiring of the auditory brain system and hinder subsequent language development [reviewed in (24)]. Until further evidence is obtained, the optimal frequency and sound exposure for intensive care neonates remain a matter of speculation, and more research efforts are needed to determine whether the frequencies present in the NICU should parallel the frequencies present in the womb.

Notably, previous studies have shown that preterm infants have atypical neural pathways when processing, discriminating, and memorising auditory information (25,26), likely due to altered auditory development. Similarly, studies using brainstem auditory evoked potentials suggest that preterm infants have a delayed myelination of the central auditory pathway (27), which can lead to a variety of auditory processing disorders. Whether or not the high prevalence of auditory and language deficits seen in NICU graduates is attributed to the premature presentation of high-frequency noise in the NICU is still undetermined. Until further evidence is available, efforts should be made to ensure that preterm infants receive developmentally appropriate exposure to sound frequencies, which may change accordingly with postnatal age in an effort to best support their growth and development.

The present study aimed to examine the frequency spectra present in the NICU, with a particular focus on frequencies in the human speech range. We specifically looked at frequencies between 501 and 3150 Hz as this range was preset by our SPL meter. Generally, the fundamental frequency (F0) of human speech is <500 Hz, ranging from ~130 Hz for males and ~200 Hz for female (with the exception of some children and female speaking with extreme high-pitched voice) (14). The narrow-based spectra of 501–3150 Hz range used in the present study, does however, contain the first (F1) and second (F2) formants frequencies, which include the much needed cues necessary for speech perception and vowel discrimination (28), consistent with the frequency voice band used in current landlines and mobile phones (300–3400 Hz).

The analysis of the frequency spectra as a function of the time of the day revealed significantly more sound exposure in the human speech range (500–3150 Hz) during daytime compared with night-time. These findings are not surprising considering that there was likely more presence of medical staff and visitors in the NICU during the day (and thereby more language exposure) than during the night. However, the present study cannot rule out the possibility that some of the frequencies measured within the 501–3150 Hz range originated, in fact, from other, non-speech sources of noise (e.g. monitor alarms), whose frequencies fall within or partially overlap with the frequency of human speech. Future studies may consider the use of more in-depth measurements tools, such as the Language Environment Analysis (LENA) technology (29), to determine with greater certainty whether the source of these frequencies in the 'speech range' was indeed speech related.

Interestingly, we found that only 0.34% of the sound energy present in our NICU was in the highest frequency range (6301–16 000 Hz). These results (shown in Fig. 1B) were anticipated given that majority of infants in our study did not require intensive oxygen support. It is likely that the presence of extremely high-frequency noise would have been significantly more evident had the infants been assisted by a CPAP machine, a potentially major source of high-frequency noise (30). It is reasonable to assume that the absence of such respiratory systems in our level-II NICU explains the negligible presence of extremely high-frequency sounds energy.

CONCLUSIONS

This study provides evidence for high-frequency sound exposure experienced by preterm infants in a level-II NICU. The adverse effects of high-frequency noise exposure in NICU infants are still unclear and cannot be determined by the present study. Protocols for measuring NICU noise should not rely on loudness measurements alone, but also include a spectral analysis of the sound frequency. More data and knowledge regarding the frequency content in the NICU may be particularly vital for longitudinal studies to determine the potential effects of high-frequency noise exposure on auditory and language outcomes. Further research and quality improvement initiatives are needed to establish evidence-based guidelines regarding the optimal sound frequency in intensive care nurseries.

ACKNOWLEDGEMENTS

We thank Emily Zimmerman for assisting with the execution of the study and the preparation of this manuscript. We thank Brian Arnold for helping with data collection. This work was supported in part by the Charles H. Hood Foundation, Peter and Elizabeth C. Tower Foundation, Gerber Foundation, Little Giraffe Foundation and Nexxspan Healthcare.

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