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ARTICLE

Neonatal intensive care unit incubators reduce language and noise levels more than the womb

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Abstract

Objective To assess the sound reducing characteristics of modern incubators in the neonatal intensive care unit (NICU) and to better characterize auditory and language exposures for NICU infants.

Study design Sound frequency spectral analysis was conducted on language and noise audio acquired simultaneously inside and outside incubators located in the NICU.

Results Sound transmission into the incubators was nonuniform. Very low-frequency sounds (<100 Hz) were unattenuated or even slightly amplified inside the incubators. Maximal reduction was observed for low-to-mid frequencies (300–600 Hz) and high frequencies (>2000 Hz), which convey important language information.

Conclusions Sound reductions observed across NICU incubator walls are more severe than those reported for sound transmission into the intrauterine environment, particularly for midrange frequencies that are important for language. Although incubator walls may serve as a protection against noxious noise levels, these findings reveal a potentially detrimental effect on language exposure for infants inside a NICU incubator.

Introduction

Infants who are born premature often exhibit neurodevelopmental deficits later in life [1, 2], including auditory and language deficits [3–5]. The acoustic environment of the neonatal intensive care unit (NICU) may be a contributing factor [6, 7]. At a time when the auditory and language neural pathways are typically undergoing rapid development [8] nurtured by intrauterine sound stimulation, the preterm infant is largely deprived of intrauterine sounds, replaced with exposure to sounds and noises of the NICU. Because the human auditory system begins responding to sound as early as 23 weeks' gestation [9], this change in exposure has the potential to alter the auditory neurodevelopmental trajectory.

On one hand, *overstimulation* in the NICU has been a longstanding concern. The loud and potentially noxious noise levels of the NICU have been well documented, with long-term averaged sound levels (hourly, daily, or weekly L_{eq}) ranging between ~50 and 65 dBA across different NICU settings [10–17]. Short-term (5 sec) L_{eq} can reach 75–80 dBA [16] due to individual NICU alarms and other routine noises that can peak at 75–85 dBA [18]. The negative impact of NICU noise on infant physiology and behavior has also been established [18–24]. Infants have demonstrated elevated blood pressure, elevated heart rate, and disruption of sleep in response to routine NICU noise and alarms [18, 19, 23, 24]. The AAP and others have recommended an hourly noise exposure limit for NICUs of $L_{eq} < 45$ dBA [25, 26]. Efforts to mitigate NICU noise levels to comply with this guideline are on the rise [27–29].

On the other hand, *deprivation* (i.e., the lack of auditory exposures that might have occurred in utero) may play a role in auditory and language neurodevelopmental deficits [30–32]. For example, while preterm infants are exposed to some language in the NICU, this exposure is a relatively small percentage of the time [33, 34]. It has been suggested that longer duration of language exposure in the NICU could be beneficial later in life [35]. Reports of excessive silence in the NICU [33, 34]—which owing to the presence of mother's heartbeat, never occurs in utero [36]—indicate that general auditory deprivation might be a risk. Some

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Table 1 Sound level reductions by NICU incubators.

Incubator type	Sound	Location	External level (dBA)	Internal level (dBA)	Reduction (dB)
Omnibed	Speech	Left	73.1	55.1	18.0
		Front	75.3	58.3	16.9
		Right	72.4	56.9	15.5
	Noise	Left	73.7	60.7	13.0
		Front	73.5	54.3	19.2
		Right	74.4	57.5	16.8
Incubator	Speech	Left	74.9	54.7	20.2
		Front	75.6	58.6	17.0
		Right	73.9	56.6	17.3
	Noise	Left	76.4	59.5	16.9
		Front	74.1	53.3	20.8
		Right	75.0	58.1	17.0

evidence suggests that excessive silence in single-patient NICU rooms, for instance, may lead to neural abnormalities and language deficits [31].

A modern approach to optimizing NICU infants' auditory experience might focus on replicating some facets of the intrauterine environment by reducing exposure to noxious stimuli (e.g., loud noise levels), while enhancing exposure to beneficial stimuli (e.g., speech and language) [30]. However, if efforts to change the type and duration of NICU sounds to match those present in utero were successful, one stark difference would still remain: transmission of sounds into the intrauterine environment is vastly different than direct sound transmission through air. Measurements of sounds that pass through the abdominal wall and into the fluid-filled environment of the fetus reveal a nonuniform sound transmission, with low-frequency sounds (<500 Hz) transmitted relatively easily, and high-frequency sounds somewhat reduced in level, although not eliminated entirely [36–38]. Thus a NICU infant in an open crib will be exposed to high-frequency sounds at levels unlikely to occur in utero. NICU incubators, however, provide a barrier through which sounds must pass to reach the occupant's ear. How are language and other sounds modified when transmitted through the walls of the incubator?

While previous reports on older incubators indicate that overall sound levels are reduced when sounds are transmitted into the incubator [39, 40], such sound transmission is often nonuniform across frequency, and could potentially be similar to that of the intrauterine environment. It remains unclear to what extent the transmission of speech and language into modern NICU incubators in realistic settings is nonuniform, differentially affecting high vs. low frequencies. Here we aimed to assess sound transmission into NICU incubators, comparing our data directly to data previously reported for transmission into the intrauterine environment [37]. Thus we conducted frequency spectral analysis to assess the sound transmission characteristics of two modern widely-used incubators. Because talkers and other NICU sound sources can emit sound from different locations around an incubator, potentially affecting the sound transmission pathway, language and noise audio were presented from multiple locations around the incubators in a realistic NICU setting.

Materials and methods

This study was conducted at Carle Foundation Hospital in Urbana, Illinois. Data were collected in a NICU overflow room that was unoccupied by patients at the time of measurement. Two commonly used incubators were measured for this study: a Giraffe Omnibed (GE Healthcare, Ohmeda Medical, Laurel, MD) and a Giraffe Incubator (GE Healthcare, Ohmeda Medical, Laurel, MD). To avoid internally generated noise, the incubators were powered off during all measurements. Sound signals consisted of: (1) high-fidelity recordings of a male and female voice talking simultaneously [41], and (2) white noise. Sounds were presented external to the incubators using a KRK Rokit 8 G3 loudspeaker from three different locations (left side, front, right side) at a distance of 1 m from the incubator. High fidelity simultaneous audio recordings were acquired using two calibrated NTI M2211 microphones connected to a Zoom H5 two-channel audio recorder. One microphone was located external and adjacent to the incubator, four inches from the incubator wall, on the left, front, or right side, matching the side of the loudspeaker location. The other microphone was in a constant position located inside the incubator at the approximate location of an infant's head. Sound presentation levels were set such that the sound pressure levels at the external microphone were between 73 and 76 dBA.

We calculated overall sound level reduction in dB by calculating A-weighted sound pressure levels at each microphone for each sound and loudspeaker location. We

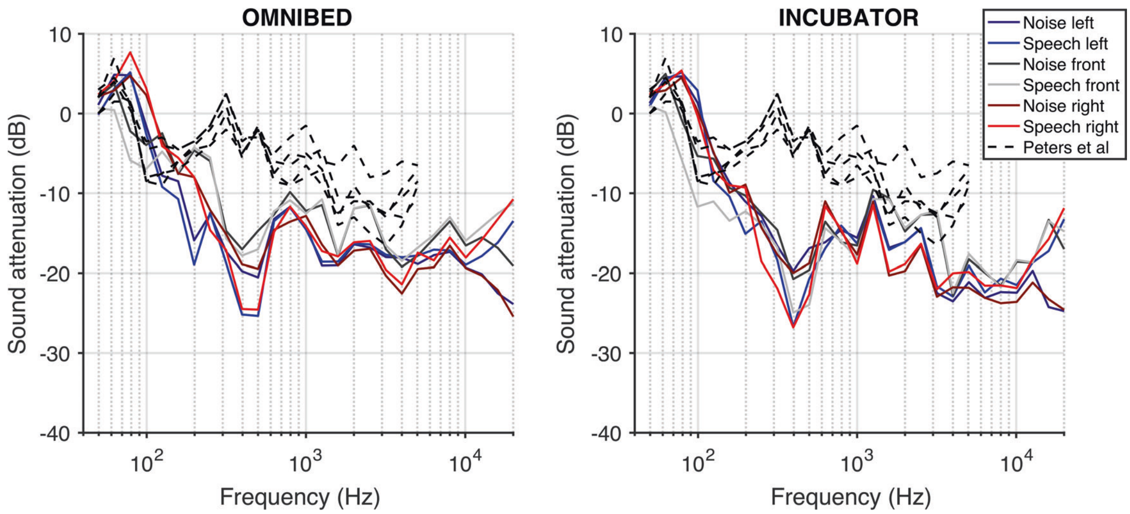

Fig. 1 Sound attenuation curves for NICU incubators. Each solid curve represents reduction for one sound type (noise or speech) presented from one location (right, front, or left) relative to the incubator. Dotted lines are attenuation curves measured at different locations within the intrauterine environment, adapted with permission from Peters et al. [37].

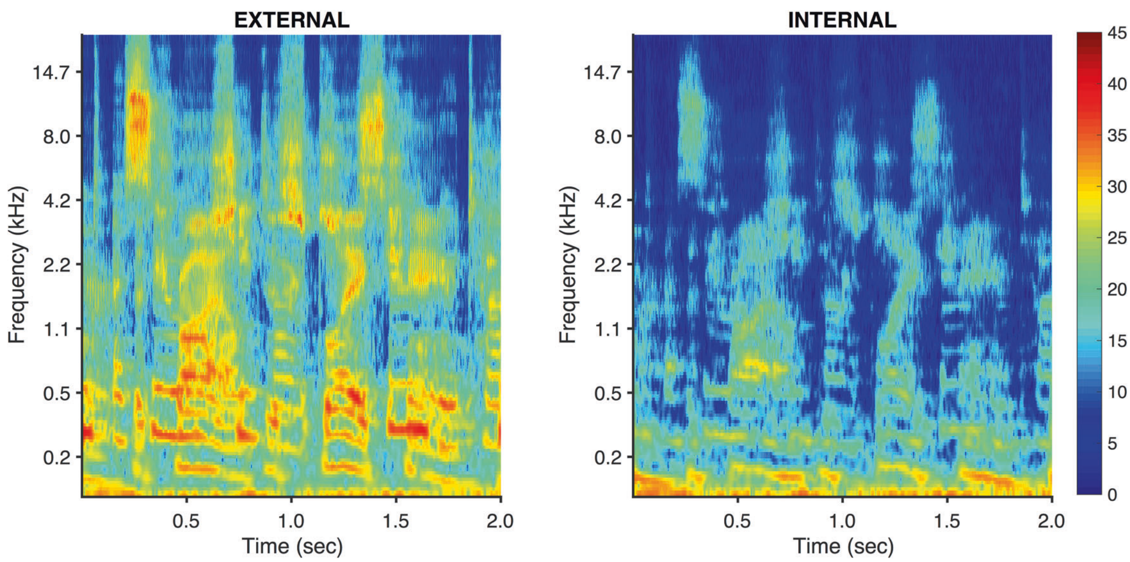

Fig. 2 Speech energy loss inside a NICU incubator. Each panel is a spectrogram (frequency vs. time; amplitude indicated with color) showing sound energy in speech, measured from the external (left) and internal (right) microphones. Substantial energy loss is apparent above 200 Hz.

conducted frequency spectral analysis in third-octave bands to determine the distribution of acoustical energy across frequencies (low to high) for each recording. We calculated the frequency-dependent sound reduction for each sound at each loudspeaker location by subtracting the third-octave sound levels obtained at the external microphone from the levels obtained at the internal microphone for each recording. We compared our measured sound reduction directly to data previously reported for reduction measured within the uterus of a pregnant sheep, which has been proposed previously as a model for sound transmission into the human uterus [37, 38]. All analyses were conducted using Matlab (Mathworks).

Results

Table 1 gives the overall sound reduction for each sound, each location, and each incubator. Sounds were reduced by 13–21 dB overall, with an average (±SD) reduction of 17.8 (±2.1) dB. Figure 1 shows the third-octave-band reductions for each sound, each location, and each incubator, revealing differential effects of the incubator on low- and high-frequency sounds. Reduction curves from different locations and different incubators have very similar trends across frequency. Previously published data on intrauterine attenuation [37] is also plotted for comparison. Similar to intrauterine transmission, sound at frequencies below

~100 Hz was typically unattenuated or increased in sound level when transmitted into the incubator. In stark contrast with intrauterine transmission, however, maximal reduction was observed for frequencies between ~300 and 600 Hz, reaching ~25 dB. Beyond 200 Hz, the incubators generally attenuated sound much more than the womb.

To visualize the nature of language information loss within the incubator, a spectrographic (frequency vs. time) representation of language recorded outside and inside an incubator is shown in Fig. 2. Midrange frequencies between 300 and 5000 Hz, which convey a substantial amount of phonetic and linguistic information, exhibited substantial energy loss when transmitted through the incubator walls.

Discussion

One of the most prominent sounds in the intrauterine environment is language, particularly that spoken by the pregnant mother [36]. Prenatal exposure to language is sufficient for full-term newborns to recognize their mother's voice [42] and even recognize passages regularly spoken by their mother during pregnancy [43]. Full-term newborns also display auditory memory for elements of their mother's native language [44, 45] suggesting that more complex speech and language information can be learned in utero. Such learning is likely fostered by additional exposure to nonmaternal language, to which fetuses have access [46], in spite of some reduction of high frequencies associated with sound transmission into the intrauterine environment [37, 38]. It is believed that preterm infants at similar post-menstrual ages and neurodevelopmental stages are also capable of learning from auditory exposures.

Our results reveal that modern NICU incubators, like the intrauterine environment, generally have greater sound reduction as frequency increases. However, incubators deviated from this trend with a peak reduction of nearly 25 dB at 400 Hz. Estimates for intrauterine reduction at this frequency are ~5 dB [37, 38]. Although attenuation curves were fairly consistent, the Omnibed front condition showed less attenuation overall for both speech and noise. This phenomenon is likely due to a small opening located in the front of the Omnibed, designed for tubing and wiring to pass through. This opening in front also allows more sound to pass through from that direction.

On the one hand, these data suggest that NICU incubators, somewhat like the womb, could protect maturing auditory systems from noxious noise levels. Such protection might alleviate concerns regarding overstimulation in the NICU, so long as the infant is inside an enclosed incubator. For example, the typical levels of 50–65 dBA reported across NICU settings would be substantially reduced within NICU incubators, and possibly in compliance with the 45 dBA AAP guideline. Individual alarms and noises would also be reduced, although the amount of reduction would depend on the frequency content of the individual alarm or noise source. The frequency content of individual sound sources and alarms in the NICU is not clear and warrants further investigation.

On the other hand, these data implicate the incubator as a potential contributor to auditory deprivation in the NICU, which is an increasing concern. The frequency range from 300 to 5000 Hz contains the majority of sound energy in language and conveys the majority of linguistic and phonetic information important for language processing (Fig. 2) [47]. For example, among the most robust linguistic cues in speech are the frequency locations of the first three spectral peaks, known as the first, second, and third speech "formants." The covariation in the loci of these three formants provides the auditory brain sufficient information to discriminate vowel categories, voiced consonants (e.g., "ba", "da", and "ga"), and liquid consonants (e.g., "la" and "ra") [48–51]. These spectral peaks all typically lay between 400 and 3400 Hz [48]. Because this frequency range is severely attenuated by incubator walls, preterm infants in enclosed incubators may receive *less* of this critical information from speech and language exposure than does the fetus in utero. Furthermore, peak energy in speech arises largely from the vowels and is typically centered around 300–500 Hz, corresponding the region of maximum attenuation for both incubators tested here. Large attenuations were also observed ≥2000 Hz, and it has been demonstrated that loss of this frequency range results in increased errors when identifying consonants [52].

Though the NICU environment merits concern about overstimulation, our data raise the possibility that preterm infants in incubators may need enhanced exposure to speech frequencies if the goal is to match that available to age-equivalent fetuses in utero. The intrauterine environment ought to be considered the biologically ideal acoustic environment for infants prior to full-term age, ergo we recommend that preterm infants be provided exposure to speech frequencies comparable to what is heard in utero while simultaneously protected from loud types of sounds that are unlikely to be heard in utero. This is a difficult balance to achieve, as factors including ambient noise and alarms from life-sustaining medical devices pose challenges to create womb-like auditory exposures for preterm infants.

Because NICU incubators are critical for providing life-saving medical care, one possible solution is to manufacture incubators that more closely mimic the sound reducing characteristics of the intrauterine environment, therefore ensuring that infants in incubators are receiving auditory input similar to what they would in utero. Another option involves the recording and digital processing of speech so as to match the frequency spectrum to that of speech in utero. Recent work has demonstrated that interventions using speech recordings [53–56] and live speech and singing [35, 57] might be beneficial to preterm infants. We recommend that, if such recordings are used, they should be digitally processed to match the intrauterine environment and then played inside of the incubator, thus allowing preterm infants proper language exposure while protecting them from unhealthy noise levels. Both of these potential solutions may result in an overall increase in sound level exposure for infants within the incubator. It is possible that this increase would result in exposure levels exceeding the AAP recommended exposure limit of 45 dBA.

Our data were collected in a realistic setting, representing accurate sound transmission for an incubator in the NICU. However, our data are limited to an otherwise silent NICU, without the interference of alarms, respiratory equipment, or other sources of noise, neither internal nor external to the incubator. The presence of these sounds and their frequency content may further reduce or degrade what language information is accessible to infants inside of an incubator. This possibility warrants further investigation. In addition, the sound levels used here (73–76 dBA) were louder than average levels for many NICU rooms. It is possible that the magnitude of measured reductions would change if external sound levels were quieter. We tested incubators from a single manufacturer. Because sound reductions at each frequency are dependent on enclosure materials and dimensions, attenuation curves will differ between manufacturers. For example, the large reductions we observed at 400 Hz are likely due to the materials and dimensions specific to incubators from this manufacturer. Finally, we have compared sound level reduction inside an incubator to that of the intrauterine environment, revealing what sounds are accessible (i.e., present in the environment). Several factors must be considered to understand what sounds a fetus or preterm infant actually hear. For example, the ear itself will change sound reception characteristics when the outer and middle ear spaces are filled with fluid (fetus) vs. air (preterm infant). Maturing auditory systems also display a developmental gradient of sensitivity to frequency, with low and midrange frequencies developing first, followed by high frequencies [9]. Our data should be interpreted with these considerations.

Conclusion

By analyzing the attenuation characteristics of NICU incubators, we show that noise and much of the important linguistic information in speech is severely reduced by incubator walls. We conclude based on our findings that, although noxious noise levels are reduced inside NICU incubators, language deprivation may also occur for infants within NICU incubators during crucial stages of brain development. If enhancing the acoustic environment of the NICU to more closely match that of the intrauterine environment is deemed beneficial for the development of infants born prematurely, the effects of NICU incubators must be considered.

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Author contributions BBM conceptualized and designed the study, collected the data, carried out the analysis, drafted the initial manuscript, and revised the manuscript. JR collected the data, drafted the initial manuscript, and revised the manuscript. MC collected the data and revised the manuscript. VS designed the study, coordinated data collection, and revised the manuscript. All authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest relevant to this article to disclose. The authors have no financial relationships relevant to this article to disclose. The authors declare that they have no conflict of interest.

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