The Fetus

Fetal Exposures to Sound and Vibroacoustic Stimulation

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Sounds in the environment of a pregnant woman penetrate the tissues and fluids surrounding the fetal head and stimulate the inner ear through a bone conduction route. The sounds available to the fetus are dominated by low-frequency energy, whereas energy above 0.5 kHz is attenuated by 40 to 50 dB. The fetus easily detects vowels, whereas consonants, which are higher in frequency and less intense than vowels, are largely unavailable. Rhythmic patterns of music are probably detected, but overtones are missing. A newborn human shows preference for his/her mother's voice and to musical pieces to which he/she was previously exposed, indicating a capacity to learn while in utero. Intense, sustained noises or impulses produce changes in the hearing of the fetus and damage inner and outer hair cells within the cochlea. The damage occurs in the region of the inner ear that is stimulated by low-frequency sound energy.
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INTRODUCTION

Whereas it has been long known by expectant mothers that fetuses often move in response to a loud sound, the quantification of the stimulus capable of evoking fetal movements and the characterization of the fetal response have, until recently, received little attention in the scientific literature. Curiously, early reports described the fetal environmental sound level as insufficient for fetal hearing. Now, evidence from carefully controlled human and animal studies confirms the subjective experiences of women of fetal movements and additionally shows simultaneous changes in fetal heart rate and fetal sleep state.

This relatively new information raises many questions. What sounds actually reach the fetal head? At what gestational age is the fetus capable of detecting sound? What stimulus levels and frequencies can the fetus hear? Are experiences to speech and music beneficial? Do these experiences facilitate subsequent speech and language development? Is there any evidence that the fetus retains memories of prenatal experiences of speech and/or music? Do intense noise exposures of pregnant women have any adverse consequences on the hearing of their fetuses?

Reviewed below is a body of experimental evidence gathered from humans and pregnant sheep that delineate the acoustic nature of the intrauterine environment and the peripheral response of the fetus to sounds generated from outside the uterus. Sheep are good models for human fetal studies because sound attenuation characteristics of the abdominal contents of sheep are similar to those of humans.[1–4] Also like humans, sheep have precocial hearing and their hearing is only slightly poorer than that of humans for frequencies below about 8.0 kHz.[5]

SOUND TRANSMISSION TO THE FETAL HEAD

Specifications of the amplitudes and frequency distributions of sounds reaching the fetal head have implications for our understanding of fetal responses. The fetal sound environment is composed of a variety of internally generated noises, as well as many sounds originating from the environment of its mother.[6] The stimulus used to produce a fetal response is altered as it passes through the abdominal wall and uterus and into the amniotic fluid. For reviews of these topics, see Gerhardt[7] and Busnel et al.[8] and the chapter by Abrams and Gerhardt in this journal.

There are many factors that determine how well a fetus will hear sounds from outside its mother. These factors include: the frequency content and level of the internal noise floor; the attenuation of external signals provided by the tissues and fluids surrounding the fetal head; sound transmission into the fetal inner ear; and the sensitivity of the hearing mechanism at the time of sound stimulation.

The acoustic characteristics of external sounds that penetrate the uterus have been described in humans.[2,4,9] An underwater microphone — referred to as a hydrophone — positioned inside the cervix or inside the uterine body after amniotomy has been used by many scientists to measure the sound pressure levels produced by a loudspeaker located near the abdomen. Recorded levels are then compared to levels detected with a standard microphone positioned between the loudspeaker and abdomen. Intrauterine levels in humans[2,4,10] are very similar to those recorded in pregnant sheep via a chronically implanted hydrophone on the fetal head inside the intact uterus.[3,11,12]

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Sounds generated inside the mother and present in the uterus are associated with maternal respiratory, cardiovascular, and intestinal activity and with body movements.[1–3] These sounds provide a background or "noise floor" above which maternal vocalizations and externally generated sounds emerge. Internal sounds of sheep are predominately of low frequency (<0.1 kHz) and reach 90 dB SPL.[3] Spectral levels decrease as frequency increases and are as low as 40 dB for higher frequencies.[13] Gagnon et al. positioned a hydrophone in a pocket of fluid by the human fetal neck and measured sound pressure levels of 60 dB for 0.1 kHz and less than 40 dB for 0.2 kHz and above. Thus, for both humans and sheep, the noise floor tends to be dominated by low-frequency energy less than 0.1 kHz and can reach levels as high as 90 dB.

Exogenous low-frequency sounds, less than 0.2 kHz, penetrate the uterus with very little reduction in sound pressure (<5 dB). Some enhancement of low-frequency sound pressures has been reported in both humans[14] and sheep.[3,11,12] In other words, sound pressures can be greater inside the abdomen than they are outside the abdomen. Higher frequencies up to 4.0 kHz are attenuated by approximately 20 dB. These general findings have been refined and extended by Peters et al.,[15] who evaluated the transfer of airborne sounds across the abdominal wall of sheep as a function of frequency and intra-abdominal location.

Over the frequency range from 0.125 to 2.0 kHz, the abdomen can be characterized as a low-pass filter with high-frequency energy rejected at a rate of approximately 6 dB/octave.[3] Simply put, the fetus would be stimulated by music with the "bass" register turned up and the "treble" register turned down. Thus, external stimuli are shaped by the tissues and fluids of pregnancy before reaching the fetal head.

DEVELOPMENT OF FETAL HEARING

Human fetal auditory responsiveness begins about the 24th week of gestation.[16,17] During the next 15 weeks, exogenous sounds may have an effect on fetal behavior and central nervous system development. It is during the latter stages of fetal development — when the hearing mechanism is intact — that the human fetus may be most influenced by the sound environment inside and outside its mother.[18]

The auditory system of the fetus does not just begin to function uniformly across frequencies. Its development follows a consistent pattern. Whereas the adult range of audibility is from 0.02 to 20.0 kHz, with greatest sensitivity in the 0.3 to 3.0 kHz range, the fetus hears a much more limited range. Hepper and Shahidullah[19] examined the range of frequencies and intensity levels required to elicit human fetal movements as assessed with ultrasonography. Of 450 fetuses involved in the study, only one demonstrated a response to a 0.5-kHz tone at 19 weeks' gestation. By 27 weeks, 96% of the fetuses was responding to tones at 0.25 and 0.5 kHz, whereas no response was recorded from any of the fetuses for 1.0 and 3.0 kHz. It was not until weeks 29 and 31 that the fetuses responded to tones at 1.0 and 3.0 kHz, respectively. Between 33 and 35 weeks' gestation, the fetuses were responding 100% of the time to presentations of 1.0 and 3.0 kHz. As gestation progresses from 19 to 37 weeks, the fetus exhibits responsiveness to frequencies over a progressively wider range. During this period, there was a significant decrease in the intensity level of stimulus required to elicit a response for all frequencies. This finding suggests that fetal hearing to pure tones becomes more sensitive as gestation proceeds.

FETAL SOUND ISOLATION

Our understanding of the influences of sounds during prenatal life, as well as the possible adverse effects of intense sound exposures, is incomplete. We have a fair idea about how much sound pressure is present at the fetal head and now have information about how much sound actually reaches the fetal inner ear.[20] Gerhardt et al. reported a procedure used to evaluate the extent to which exogenous sounds of different frequencies stimulate fetal hearing in utero. Inferences regarding sound transmission to the inner ear were made from cochlear microphonic (CM) input–output functions to stimuli with different frequency contents. The CM — an alternating current generated by the hair cells of the inner ear — mimics the input signal in frequency and amplitude over a fairly wide range. CMs recorded from the round window are sensitive indices of transmission characteristics of the middle ear. Thus, changes in the condition of the middle ear influence the amplitude of the CM. Comparisons of CM recorded from fetuses in utero in response to sound field stimulation and CM recorded from young lambs after birth in the same sound field provide estimates of fetal sound isolation.

Assessment of fetal sound isolation involved surgically removing the fetal head from the ewe, implanting an electrode on the round

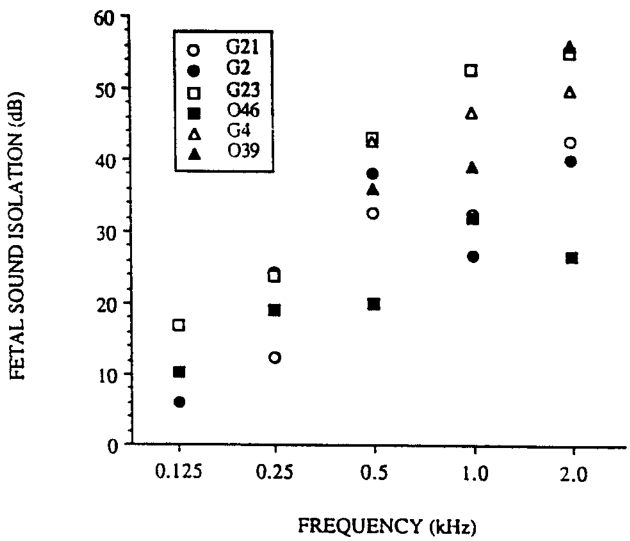

Figure 1. Fetal sound isolation. The average differences between the SPLs in decibels necessary to produce equal CM function for each frequency recorded from the fetus and the newborn (ex utero CM minus in utero CM). Reprinted with permission.[20]

window of the fetus, and returning it to the uterus. A few days after surgery, CM responses to different noise bands delivered through a loudspeaker were recorded from the fetus. Next, the fetus was delivered by cesarean section. After a few hours or days, the lamb was positioned in front of the same loudspeaker and CM input–output functions produced by the same stimuli were repeated. The difference between the SPL necessary to generate pre-determined CM amplitudes from the fetus in utero and the SPL necessary to produce the same CM amplitudes from the lamb after delivery served as an index of fetal sound isolation.

The magnitude of fetal sound isolation was dependent on stimulus frequency as shown in Figure 1. For low-frequency sounds (<0.5 kHz), the fetus detected much of the sounds that occurred in its mother's sound environment. These sounds were reduced by only 10 to 15 dB. However, very little high-frequency energy (>0.5 kHz) reached the fetal inner ear (40 to 50 dB reduction).

At least two factors influence the stimuli that evoke responses from the fetus. First, the amount of attenuation for different frequencies that is provided by the tissues and fluids surrounding the fetal head determines the spectral shaping of the signal. Second, further reduction in the stimulus occurs due to the transmission of sound pressure from the fluid at the fetal head into the inner ear.

ROUTE OF SOUND TRANSMISSION INTO THE FETAL INNER EAR

The mode of transmission of external sounds that reach the inner ear of the fetus is not clearly understood. The route of sound transmission postnatally is through the outer and middle ear system. However, in the fetus, this route is likely to be rendered less efficient because the mechanical aspects of the ear are highly dampened due to the presence of fluids that fill the external canal and middle ear cavity.

Two hypotheses, which describe the route that exogenous sounds take to reach the fetal cochlea, have been advanced. It has been suggested that acoustic stimuli in the fetal environment pass easily through the fluid-filled external auditory canal and middle ear system to the inner ear. The impedance of inner ear fluids is similar to that of amniotic fluid; thus, little acoustic energy is lost due to an impedance mismatch.[21]

Hearing via bone conduction is a second alternative. Researchers have shown that the contribution of the external auditory meatus to auditory sensitivity in underwater divers is negligible.[22] By comparing the ability of a diver to hear under different conditions while in water, bone conduction has been shown to be much more effective in transmitting underwater sound energy. Similarly, fetal hearing occurs in a fluid environment and sound transmission may be through bone conduction as well.

Gerhardt et al.[23] designed a study to compare the effectiveness of the two routes of sound transmission (outer and middle ear versus bone conduction). CM amplitudes from fetus sheep in utero in response to airborne sounds were recorded during three different conditions that included covering the entire head with a 1/4-in. neoprene hood. It was determined that sounds reach the inner ear through a bone conduction route rather than through the outer and middle ear. As is known from other experiments, bone conduction is the principal route that sounds take to stimulate human hearing underwater.[22]

Vibratory energy delivered to the human head postnatally through a bone oscillator results in an impression by the subject that the signal is equally loud at the two ears. This assumes that the conditions of the outer and middle ears are the same.[24] From this impression, it has been concluded that bone conduction stimulation produces a symmetrical input to the central auditory system. However, detecting airborne sounds postnatally through the regular route, outer and middle ear, results in asymmetrical input to the central auditory system and gives rise to a perception of signal location. Two factors contribute to sound localization — stimulus amplitude and time of arrival. Depending on stimulus frequency, the ear toward the sound source will receive the acoustic signal first and at greater amplitude than the ear farther from the sound source.

The opportunity to localize sounds is probably not available to the fetus. Even though the acoustic signal is greater near one ear of a fetus in utero than at the other,[15,25] both cochleae are equally stimulated; thus, only one auditory image will likely be formed. This finding has implications for researchers interested in speculating about the importance of fetal hearing for early development of speech and language[26] and cerebral lateralization.[27]

MODEL OF FETAL HEARING

It is intriguing to consider what sounds are present in the environment of the fetus and the extent the fetus can detect them. The data presented in the preceding sections have been integrated into a model of fetal sound transmission and displayed in Figure 2. The model includes information regarding sound transmission through the tissues and fluids associated with pregnancy and sound transmission through the fetal skull into the inner ear.

The ambient sound level in utero or noise floor is indicated in Figure 2 by a dashed line. For detection by the fetus to occur, extrinsic sounds have to exceed these levels. The internal noise floor of the mother is dominated by low-frequency energy produced by respiration, intestinal function, cardiovascular system, and maternal movements. Presumably, the ability of the fetus to detect exogenous sounds will be dependent, in part, on the spectrum level of the noise floor because of masking. The thin solid line on top of the figure represents a broadband noise in air. For the sake of illustration, a spectral level of 90 dB was considered. The dotted line represents the sound pressure that this noise level would produce in the uterus. As expected, high-frequency sound pressures would be reduced by about 20 dB. The attenuation of low-frequency sounds by the abdominal

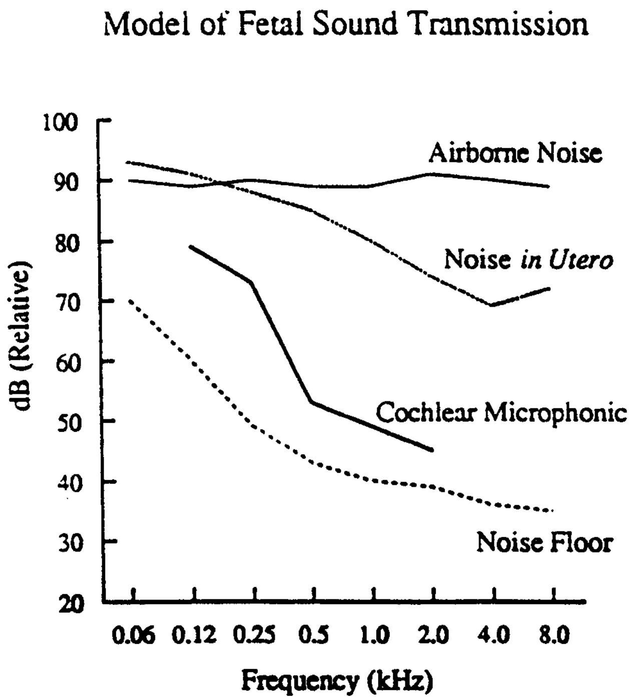

Figure 2. A model of sound transmission into the fetal inner ear. The noise floor is produced by internally generated sounds from digestion, maternal movements, and perhaps cardiovascular system. Sound levels (y-axis on the left) in the uterus are produced by airborne white noise. The parameter labeled CM (y-axis on the right) comes from data described as fetal sound isolation. The CM parameter describes the level of the exogenous noise that would stimulate the fetal cochlea. A 90-dB noise in the sound field surrounding the mother would result in fetal stimulation at levels in excess of the internal noise floor from 0.125 to 2.0 kHz.

wall, uterus, and fluids surrounding the fetal head is quite small and, in some cases, enhancement of sound pressure of about 5 dB has been noted. Between 0.25 and 4.0 kHz, sound pressure levels drop at a rate of 6 dB/octave.

Sound pressures at the fetal head create compressional forces through bone conduction that result in displacements of the basilar membrane, thereby producing a CM. As explained above, by evaluating the CM (bold, solid line), it is possible to determine the extent to which the fetus is isolated from the external milieu. For 0.125 and 0.25 kHz, a 90-dB airborne signal would be reduced by 10 to 20 dB in its passage to the fetal inner ear over what would be expected to reach the inner ear of the organism in air. For 0.5 to 2.0 kHz, a 90-dB signal would be reduced by 40 to 45 dB. For frequencies in this range, the fetus is buffered from sounds in the environment surrounding its mother probably because of limited function of the ossicular chain. However, for low-frequency sounds, the fetus is not well isolated. It is interesting to note that low-frequency stimuli that reach the inner ear coincide with the development of the inner ear that begins first for low-frequency sounds.

The fetus in utero will detect speech, but probably only the low-frequency components (below 0.5 kHz) and only when the airborne signal exceeds about 60 dB. If it is less than that, the signal could be masked by internal noises. It is predicted that the human fetus could detect speech at conversational levels, but only the low-frequency components.

Likewise, if music were played to the mother at comfortable listening levels, the fetus could sense rhythms, but the high-frequency overtones would not be of sufficient amplitude to be detected.[28] How this information relates to in utero development of speech and language, to musical preferences, and to subsequent cognitive development is the topic of considerable speculation.

INTELLIGIBILITY OF SPEECH SOUNDS RECORDED AT THE HEAD OF THE FETUS

Fetal identification of its mother's voice and its ability to form memories of early exposure to speech are, in part, dependent on the intelligibility of the speech message. In a study conducted by Griffiths et al.,[29] a panel of over 100 untrained individuals judged the intelligibility of speech recorded in utero from a pregnant ewe. Intelligibility was influenced by three factors: transducer site (maternal flank or in utero); gender of the talker (male versus female); and intensity level (65, 75, or 85 dB). For recordings made at the maternal flank, there was no significant difference between male and female talkers. Intelligibility scores increased with increased stimulus level for talkers and at both recording sites. However, intelligibility scores were significantly lower for females than for males when the recordings were made in utero (Figure 3).

An analysis of the feature information from recordings inside and outside the uterus showed that voicing information is better transmitted in utero than place or manner information. "Voicing" refers to the presence or absence of vocal fold vibrations (e.g., s versus z); "place" of articulation refers to the location of the major airflow constriction during production (e.g., bilabial versus alveolar); and "manner" refers to the way the speech sound is

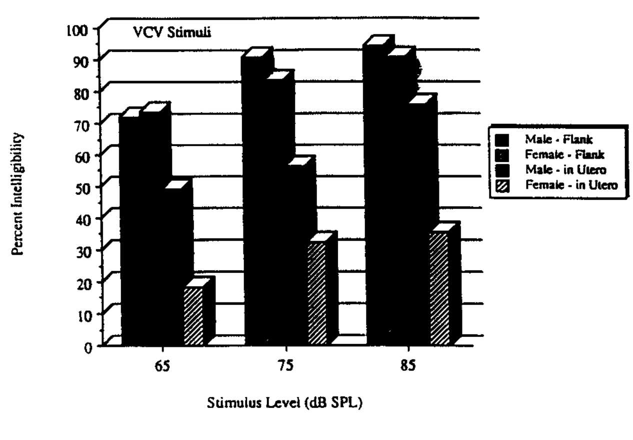

Figure 3. Mean percent intelligibility of VCV syllables spoken by a male and a female talker recorded at the flank and within the uterus of a sheep at three airborne stimulus levels. Reprinted with permission.[29]

produced (e.g., plosive versus glide). These findings are consistent with filtered speech tests that showed the importance of high-frequency information for the recognition of manner and place.[30]

Voicing information from the male talker, which is carried by low-frequency energy, was largely preserved in utero. The judges evaluated the male talker's voice equally well regardless of transducer site. Speech of the female talker carried less well into the uterus. The fundamental frequency of the female talker was higher than that of the male talker. Thus, it is understandable that voicing information from the male would carry better into the uterus than that from the female.

The maternal voice is a prominent stimulus in that it is present during a crucial part of fetal development — a time in which several biological systems, including the auditory system, are developing. The immediate effects of exposure to the voice on the fetus may provide a way of tracking auditory system development, as well as measuring fetal ability to process sensory information.[31] Fetal auditory discrimination has also led to the hypothesis that prenatal experience with auditory stimulation is the precursor to postnatal linguistic development.

FETAL AUDITORY DISCRIMINATION

The fetal auditory system is functional by the start of the third trimester.[17] Although quantification of fetal hearing cannot be made using standard audiometric equipment, researchers have found methods to measure fetal responsiveness to exogenous stimuli. The most common approaches used to measure responsiveness to sound include the monitoring of fetal pulse rate,[32] activity or inactivity,[33] and reflexive behavior such as the auropalpebral reflex.[17] Fetal movements in response to sound and/or vibroacoustic stimuli relate closely to the development of fetal audition.[34]

In 1983, Birnholz and Benacerraf[17] measured fetal responsiveness to an electronic artificial larynx applied to the maternal abdomen. An ultrasonic imager monitored the auropalpebral reflex of the 236 fetuses used in the study. Blink responses were observed for these fetuses from 16 to 32 weeks' gestational age. Reflexive eye movements increased in frequency after the 26th week of gestation. Between weeks 28 and 36, eight of the fetuses demonstrated no observable response to electronic artificial larynx stimulation, two of which were diagnosed later with severe sensorineural hearing loss and the other six suffered from a range of non-auditory anomalies. The level of the stimulus and the placement of the electronic artificial larynx in relation to the fetal head are significant variables when judging the responsiveness of the fetus.

Because the fetus has the capability to respond to tonal stimuli of varying frequencies from as early as 19 weeks, experimenters wondered whether or not it is capable of discriminating among them. In a study conducted by Shahidullah and Hepper,[33] the habituation/dishabituation of 48 fetuses to tonal stimulus was measured. Ultrasound imaging was used to monitor fetal response to 0.25 and 0.5 kHz tones. Habituation was defined as a decrement in response to repeated presentation of the same stimulus. Other properties of the fetus may result in reduced responsiveness including adaptation of the sensory system, receptor fatigue, or motor fatigue. In order to distinguish among these possibilities, a dishabituation procedure was used. After presentation of the original stimulus and observation of a decrement in responsiveness, a new stimulus was introduced. If the response decrement was due to habituation, then the introduction of a novel stimulus should reinstate the response. If the reduction in responsiveness was due to motor fatigue or sensory adaptation, then no response would be observed even to a novel stimulus. Whereas dishabituation is used to determine whether or not true habitation occurred, it can be used also to test if the organism is capable of making a discriminative response between two stimuli. Shahidullah and Hepper[33] found that 35-week-old fetuses were capable of distinguishing between the two pure tones of 0.25 and 0.5 kHz. However, fetuses at 27 weeks' gestation were not as likely to demonstrate these same discriminations.

The confirmation of discriminative abilities of newborn humans comes from Eisenberg.[35] She found that signals below 4.0 kHz evoke two to three times as many responses as do signals above 4.0 kHz. Moreover, low-frequency sounds tend to elicit gross motor activity in infants (stress-inhibiting), whereas high-frequency signals elicit ''freezing-like'' responses from the neonate (stress-eliciting).

Shahidullah and Hepper[33] not only analyzed the discriminatory abilities of 36 fetuses to tonal stimuli, but also evaluated their ability to differentiate between speech sounds. Fetuses at 27 and 35 weeks' gestation were exposed to a pair of pre-recorded syllables at 110 dB through an earphone placed on the maternal abdomen. Half of the fetuses received ''baba'' as their habituating stimuli and ''bibi'' as their dishabituating stimulus and vice versa. Although all fetuses habituated, fewer stimuli were required for the 35-week-old than the 27-week-old fetuses, and a greater number of the 35 week-old fetuses (17 of 18) demonstrated dishabituation compared to the younger ones. Thus, fetuses at 35 weeks' gestation possess the ability to discriminate among different phonemes.

POSTNATAL IMPLICATIONS OF IN UTERO EXPERIENCES

The ability to discriminate speech stimuli in utero may provide the means for language acquisition to begin prenatally. A child's ability to establish certain fundamentals of their native language during fetal life was reported by Ruben.[36]

Carefully controlled studies of newborns using a non-nutritive sucking choice procedure demonstrated that the language that their mothers used while pregnant with them was preferable to a foreign language even when spoken by the same woman.[37,38] Not only do newborns prefer the language that they heard during life in utero, but they also showed preferences for their mother's voice.[39] DeCasper and Prescott[40] found that 2-day-old babies did not prefer their father's voice to that of another male's voice even after 4 to 10 hours of postnatal contact with their father. This postnatal contact was determined to be insufficient to develop in the newborn a preference for his/her father's voice.

MUSIC AND THE FETUS

Tones, noise, and speech are not the only externally generated forms of stimuli that may have a behavioral effect on the developing fetus. Male and female singing voices have the ability to penetrate the uterus, as indicated by recordings of fetal movements.[41] Fetal movements have also been shown to become livelier during exposure to music.[42] The reaction of the fetus, which is typically an alteration in fetal heart rate, depends on how loudly the music is played, how suddenly the music crescendos, which frequencies are incorporated in the musical selection, and the state of the fetus during presentation.[42]

Some questions have arisen concerning whether or not fetal responsiveness is directly related to the presentation of music or if it is a secondary reaction to the mother's response. Music presented directly to the mother through earphones did not elicit fetal movements.[43] Similarly, if one type of music is played softly to the mother under headphones and another for the fetus, an increase of fetal heart rate is seen within 5 seconds.[42]

Not only has it been hypothesized that fetuses can perceive music, but that they can differentiate among different types of music and demonstrate a musical preference. In a study conducted by Olds,[43] the responses of twin fetuses were found to be different depending on the type of music to which they were exposed. Whereas these results have not been replicated, they do raise the possibility that fetuses can discriminate between different musical scores. Along these same lines, Hicks[44] suggested that if the same music that was played during the last few months of gestation were played during childbirth, then the child would perceive its new environment as being familiar. Whereas these anecdotal reports are interesting, it has not been confirmed with any certainty whether or not prenatal exposure to music has any short- or long-term benefits to the newborn child.

ADVERSE AFFECTS OF NOISE

The deleterious effects of exposures to noise on human hearing have been known for at least 150 years. According to a 1990 U.S. Public Health Document, overexposure to noise is responsible for the hearing loss suffered by about half of the over 21 million Americans affected by this disorder. More than 20 million American workers are exposed, on a routine basis, to noise levels that are capable of induced permanent hearing loss.[45]

Increased participation rates of women in the labor force have led to concern regarding whether or not guidelines are needed for pregnant women. In 1994, approximately 75% of women in the prime childbearing years of 24 to 35 was in the work force.[46] Whereas hearing loss is documented in persons overexposed to intense noise, the effects of these exposures on the hearing of unborn children are not known.

Important questions regarding noise effects on the fetus remain to be answered. Is noise exposure of a pregnant woman capable of producing damage to the hearing of her fetus? If so, are there reasonable limits of safety that will protect the fetus? These issues were raised in a report prepared by a committee of scientists sponsored by the National Research Council.[47]

The mechanisms through which intense sound may act on the unborn are the direct effects of noise on the developing fetus and on the mother, with indirect neuroendocrine effects on the fetus. If the effect of noise is direct, then protecting the hearing of the mother does little for the hearing of the fetus. However, if it is indirect, ear protection for the mother may protect the fetus as well by altering the function in some unspecified manner of the mother's neuroendocrine system.[47]

HEARING LOSS PRODUCED DURING FETAL LIFE IN HUMANS

Two studies document an increased risk of hearing loss in children whose mothers were noise-exposed during pregnancy. Lalande et al.[48] reported that noise exposures to 65 to 95 dB(A) for 8 hours per day increased the risk of having a child with a hearing loss by a factor of 3. The hearing of 131 4- to 7-year-old children was tested. The children whose mothers worked during pregnancy in noise levels over 85 dB(A) suffered greater hearing loss as compared to children whose mothers worked in conditions from 65 to 85 dB(A). In an earlier report, Daniel and Laciak[49] reported hearing loss in 35 of 75 children, ages 10 to 14, whose mothers worked in weaving industries where noise exposures were up to 100 dB. Whereas the studies suggested an increased likelihood of hearing loss as a consequence of noise exposures in utero, both reports have been criticized because of methodological problems including a lack of adequate control groups.[50]

NOISE EXPOSURES TO FETAL SHEEP

Recent studies using pregnant sheep provide evidence that noise exposures of the ewe can induce changes in hearing sensitivity of the fetus as assessed with auditory brainstem response (ABR) and can produce morphologic changes of the fetal inner ear as determined using scanning electron microscopy. Moreover, these studies clarify some issues regarding sound transmission to the fetal inner ear.[51–53] In all studies, extreme noise exposures to 120 dB for 16 hours, repeated in some instances, were used. Pregnant women do not normally experience these noise conditions.

In this series of studies, pregnant ewes were anesthesized and the fetus was exteriorized through a cesarean section, instrumented with ABR electrodes and a bone oscillator, and returned to the uterus. The uterus and abdomen were closed and the electrodes and wires were tunneled under the maternal skin to a point on the flank where they exited and were stored in a pouch sutured to the ewe. After recovery from surgery, ABR thresholds were recorded from the fetus before and after continuous noise exposures. Thresholds for the ABR were defined as the lowest stimulus level that evoked a consistent response from the fetus.

In order to understand more about the sensitivity of fetal sheep, Pierson et al.[54] studied non–noise-exposed fetuses from 111 to 136 days' gestational age (dGA, term is 145 days) (Figure 4). They found that ABR thresholds rapidly decreased (indicating improved sensitivity) from 111 to 123 dGA, approximately 3.2 dB/day. From 123 to 136 dGA, the rate at which sensitivity improved was considerably slower, approximately 0.15 dB/day. These data were used to establish times to deliver noise exposures to other groups of fetuses.

When a noise exposure was delivered during the time when ABR thresholds were just beginning to emerge (113 dGA), no immediate affects on ABR thresholds were apparent. However, ABR thresholds recorded later in gestation (130 to 136 days) were significantly less sensitive than thresholds from age*matched, control fetuses.[53] When the noise exposure was delivered at about 130 dGA, ABR thresholds were poorer immediately post-exposure. Thresholds recovered to pre-exposure levels 24 to 72 hours later. Thus, there appeared to be a marked difference between the ways in which the auditory system of the immature fetus responded to a noise exposure when compared to that of a more mature fetus. This finding relates to the issue of a period of increased susceptibility to noise damage in the immature ear — a finding that has been reported by others.[55]

Numerous studies have shown that exposure of young mammals to noises at levels that would not produce damage in adult animals can cause severe high-frequency hearing loss and histologic damage

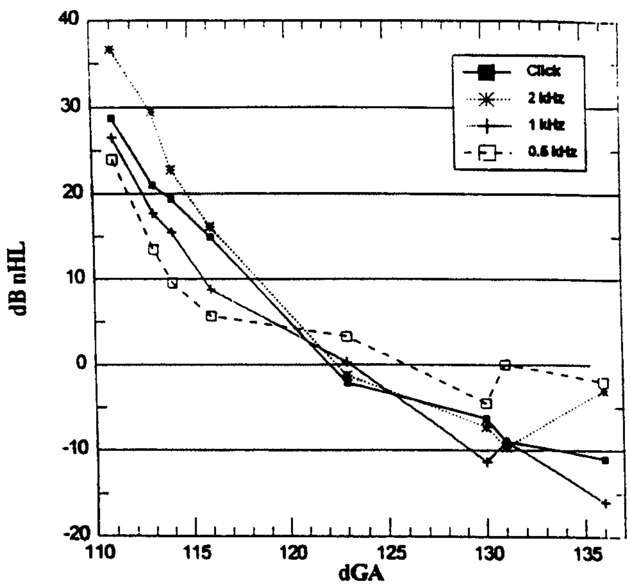

Figure 4. Mean ABR thresholds to clicks, 2.0, 1.0, and 0.5 kHz tone bursts recorded in utero from sheep fetuses of increasing gestational ages. Reprinted with permission.[54]

of the cochlea. The period of increased susceptibility corresponds to the final stages of morphologic and functional development of the cochlea. It has not been determined if and when this period of susceptibility occurs in human fetuses and neonates. Much work is still needed to answer these questions.

It is known that exogenous sounds are reduced in amplitude as the sound pressures pass through the abdomen and uterus and reach the inner ear. High-frequency energy is reduced more so than is low-frequency energy. Given these facts, the question arises as to what areas of the cochlea are affected by noise exposures? This question has been addressed in two different ways. Huang et al.[52] exposed pregnant ewes to both low-pass (<1.0 kHz) and high-pass noise (>1.0 kHz) at 120 dB SPL for 16 hours. ABR latencies and thresholds to click and tone bursts were determined before and after these exposures. Both thresholds and latencies increased significantly for 0.5 kHz tone bursts following the low-pass exposure. No significant effects on the ABR were found for 2.0 kHz tone bursts or clicks. The high-pass exposure produced significant shifts in thresholds and latencies only for the 1.0-kHz tone bursts. The authors concluded that the lower-frequency energy in the high-pass noise reached the fetus and induced threshold shifts at 1.0 kHz. In addition, the low-frequency exposure created its greatest affect on ABR thresholds elicited with the lower-frequency tone bursts.

The study by Gerhardt et al.[53] supports the arguments that low-frequency energy reaches the fetal inner ear and, if sufficiently intense, can evoke changes in hearing. These investigators evaluated the integrity of cochlear hair cells using scanning electron microscopy in non-exposed and noise-exposed fetal sheep. Four 16-hour broadband exposures were delivered to fetal sheep from 111 to 114 dGA and cochleae were removed for evaluation 3 weeks later.

Hair cells from noise-exposed fetuses appeared different in a number of respects. Following exposure, hair cell damage of both inner and outer hair cells was noted primarily in the apical and middle turns of the cochlear. Abnormalities of hair cells included distorted and/or missing stereocilia, giant stereocilia, and phalangeal scarring. The extent and location of damage were plotted as cochleograms and displayed in Figure 5. The cochleograms are averages of the hair cells from eight controls and eight noise-exposed fetuses. Note that most damages found in the noise-exposed animals were confined to the middle and apical turns — regions of the inner ear that respond to middle- and low-frequency sounds. On average, the inner hair cells were more severely affected than the outer hair cells and the damage was primarily confined to the region 5% to 20% of the total distance from the apex.

A few important points need to be emphasized. First, it is highly unlikely that a pregnant woman would experience the magnitudes of exposures used in the above-reported studies. Moreover, the difference in susceptibility to noise between humans and sheep has not been determined. Thus, whereas findings of these reports are of potential interest to the understanding of human fetal noise exposures, these results may be specific to fetal sheep and should not be applied to humans.

Secondly, the long-term consequences of damage to hair cells that code low-frequency sound are not understood. In fact, most screening tools used to assess hearing in human infants and children fail to evaluate the apical region of the inner ear. However, behavioral studies of hearing sensitivity to pure tones conducted in monkeys, guinea pigs, and chinchillas suggest that marked damage to apical hair cells does not result in appreciable hearing loss for low-frequency tones.[56] The same degree of damage in the basal region resulted in quite severe hearing loss in all species. The authors concluded that a redundancy of encoding mechanisms exist for low-frequency stimuli, at least for threshold responses. Suprathreshold responses were not evaluated. Whether or not the findings from the study of Prosen et al.[56] apply to humans is not known.

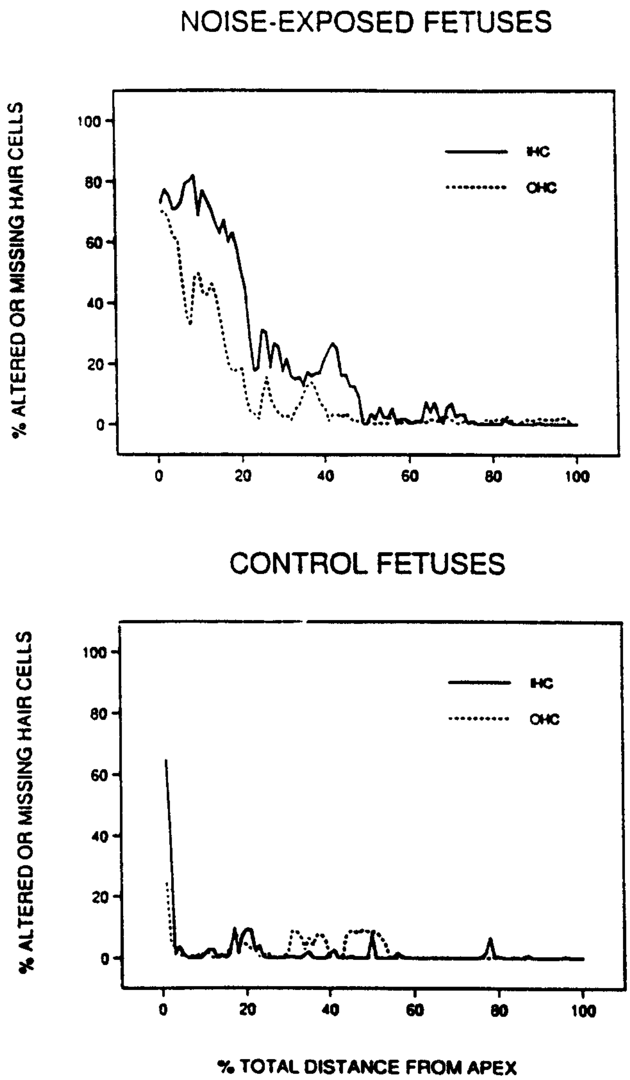

Figure 5. Average cochleograms from eight control fetuses and eight noise-exposed fetuses. Noise exposures occurred near the time when the ABR from the fetus was first observed (111 to 114 dGA) and temporal bones were harvested from the fetuses at 137 dGA.

PATTERNS OF HEARING LOSS

The effects of noise exposure on the hearing of most terrestrial mammals follow the same general pattern. Broadband noise produces inner ear damage that is typically confined to the high-frequency region of hearing. After years of exposure, hearing loss becomes progressively more severe and affects lower frequencies. The pattern of cellular damage that is found in fetal sheep is quite different. It is the low-frequency regions of the inner ear that are damaged, not the high-frequency regions.

With regard to hearing, the fetus is really more like an aquatic mammal than a terrestrial one. Its ears are immersed in amniotic fluid that also fills its middle ear cavity. In the adult, the middle ear amplifies sound energy as it passes from an air medium into the fluids of the inner ear. In situations where fluid accumulates in the middle ear, the flow of acoustic energy is impeded. This scenario appears to be the case with the fetus. Whereas the function of the fetal middle ear is not adult-like, the fetus is still able to detect low-frequency sounds through bone conduction. Low-frequency energy seems to produce some affect in the apical (low frequency) region rather than the basal (high frequency) region of the inner ear as is the case in the adult ear. Thus, the patterns of noise-induced hearing loss are quite different between the fetus and the adult.

CONSEQUENCES OF MINIMAL HEARING LOSS IN CHILDREN

Hearing loss in adults is usually the consequence of years of repetitive noise exposures. Most hearing losses occur from 3.0 to 6.0 kHz and are present before hearing loss develops for low frequencies. An average hearing level (HL) of less than 25 dB for frequencies from 0.5 to 2.0 kHz is considered normal in adults. Thus, individuals who have suffered from many years of noise exposure may lose considerable high-frequency sensitivity, yet their hearing may still be normal from 0.5 to 2.0 kHz. The likelihood that a human fetus will develop a significant hearing loss from noise exposure of its mother is very small. However, slight hearing loss in the child after it is born will have far greater consequences that the same amount of hearing loss in an adult.

The use of a 25-dB HL criterion for defining normal hearing in children is inappropriate because the development of communication and behavioral skills that affect educational experiences and relationships with other people is greatly influenced by a child's ability to hear. A more appropriate level for defining normal hearing in children is 15 dB HL.[57]

There is a growing body of research that demonstrates that minimal hearing loss (15 to 40 dB HL) in children results in dramatic negative consequences on academic progress.[58] A recent analysis indicated that 14.9% of U.S. children (>14 million) has hearing loss of at least 16 dB HL in one or both ears.[59] Most hearing losses were unilateral and slight in severity (16 to 25 dB).

In a sample of 1218 children, 1 in 20 school age children exhibited minimal sensorineural hearing loss. A shocking 37% of children with minimal sensorineural hearing loss failed at least one grade in the educational system (K-12).[58] Furthermore, even mild hearing loss was associated with increased social and emotional dysfunction among school age children. Thus, the prevention of hearing loss in neonate, young child, and even the unborn, regardless of cause, is a critical issue. Care must be taken to avoid exposing the immature ear of fetuses and neonates to noise levels, sustained or impulsive, which may produce hearing loss. Whereas a specific noise level and duration has not been agreed on as minimal exposure, a conservative approach, when at all practicable, is recommended.

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