What Sounds Reach Fetuses: Biological and Nonbiological Modeling of the Transmission of Pure Tones

ABSTRACT: In utero transmission of external and maternal sounds has been studied in pregnant women and in an animal model of human species, the sheep. These works, especially the most recent ones, suggest that local and environmental factors interfere in such a way that signals are attenuated in a complex manner as frequency increases. The present work investigated whether a plain rubber sphere which was filled with water could be considered as a reliable nonbiological model in a study describing the characteristics of sound transmission. A sweeping pure tone, presented externally, was measured inside the rubber sphere using a high signal-to-noise ratio experimental hydrophone. A paradigmatic three components curve...
INTRODUCTION

Transmission of acoustical signals to the fetus has been directly measured in humans using rubber-wrapped microphones or hydrophones inserted: (a) in the vagina or in the cervix of pregnant or nonpregnant women (Bench, 1968; Murooka, Koi & Suda, 1976; Walker, Grimwade & Wood, 1971); and (b) in utero after the rupture of membranes, during or after labor (Benzaquen, Gagnon, Hunse, & Foreman, 1990; Gagnon, Benzaquen, & Hunse, 1992; Henshall, 1972; Johansson, Wedenberg, & Westin, 1964; Murooka et al., 1976; Nyman et al., 1991; Querleu, Renard, & Versyp, 1981; Walker et al., 1971). Given ethical considerations and the fact that when the membrane is ruptured most of the amniotic fluid escapes, thus probably modifying the in utero transmission of acoustical signals, a growing number of studies have been performed with hydrophones surgically inserted into the uterus of pregnant goats (Bench, Anderson, & Hoare, 1970) and, more frequently, pregnant sheep (Gerhardt, 1989; V Vince et al., 1982; Vince et al., 1985) and, more frequently, pregnant sheep (Gerhardt, 1989; V Vince et al., 1982; Vince et al., 1985). The comparisons confirmed the validity of the measurements, suggesting that the model may be useful in studies of sound transmission in utero. © 1998 John Wiley & Sons, Inc. Dev Psychology 33: 203–219. 1998

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have demonstrated that their transmission depends on: (a) the frequency composition of the signal, and (b) the in utero location of the acoustic transducer (Peters, Abrams, Gerhardt, & Griffiths, 1993a). Frequencies below around 400 Hz suffer almost no pressure attenuation and may even be enhanced, relative to the external level (Peters, Gerhardt, Abrams, & Longmate, 1993b). The attenuation increases as a function of the frequency of the signal up to a maximum of 10 to 30 dB (Querleu, Renard, Versyp, Paris-Delrue, & Crépin, 1988; Richards, Frentzen, Gerhardt, McCann, & Abrams, 1992; V Vince et al., 1982; Vince et al., 1985) for frequencies around 4,000 to 6,000 Hz. Studies performed by V Vince and colleagues (1982; Vince et al., 1985), Gerhardt, Abrams, and Oliver (1990), and Richards et al. (1992) suggested that in utero sound transmission is likely to occur according to a nonlinear pattern. More precisely, a recent study analyzing transmission of airborne sounds from 50–20,000 Hz conducted by Peters et al. (1993a) in sheep demonstrated, among other frequency-related effects, that: “...from 12,500 to 20,000 Hz there was a reversal of the attenuation pattern showing that the effectiveness of transmission gradually improved again...” (p. 22). Concerning the location of the transducer, isosonic curves defined by Peters et al. (1993b) in sheep demonstrated that the in utero pressure level of an airborne source decreased when the distance to the source of the hydrophone placed in the cavity was increased.

These data indicate that in utero sound transmission occurs according to a non-linear model which needs to be investigated in more detail. This would be easier if one could use a simple, reliable model to study the characteristics of this transmission. The present study aimed at testing whether plain spherical rubber spheres filled with water could be used to model the human...
intrauterine acoustic environment. Using a better signal-to-noise ratio transducer than those employed in previous studies, sound transmission of a sweeping pure tone was measured inside rubber spheres using a suspended hydrophone. The effects of systematic variations in several parameters of the situation were analyzed: size of the sphere, location of the hydrophone within the sphere, presence of sound reflecting elements in the vicinity of the sphere, distance to the sound source, and location of the external reference microphone. Sound transmission of the same sweeping pure tone inside the uterus of pregnant ewes was then measured with the help of the surgically implanted hydrophone. This was performed in various experimental settings designed to investigate the effects of similar parameters of the situation as in the sphere measurements within the constraints imposed by the use of a biological model.

METHODS

Stimuli

Pure tone signals of frequency sweeps were delivered by a Bruel & Kjaer (BK2604) generator and fed via a 40-W Technics amplifier (SU600) to an encased SÜPRAVOX (RTF) loudspeaker and AUDAX (TW8) tweeter phased-tuned at 4,000 Hz. Automatic sweeping of the sine wave signal by the generator ranged from 100 Hz—the lower boundary for the large loudspeaker to emit an undisturbed signal at high pressure levels—to 20,000 Hz. The pressure of this signal was kept stable, alongside the sweeping procedure up to 100 dB at the external transducer (microphone) level, by feeding it back to the compression input of the sine wave generator.

Data Collection

Transmission of the stimulus into a model or a sheep uterus is defined by comparing the external pressure (EX) of this stimulus to the internal one (IN). Because the EX pressure of this signal was constant along the sweep range, values of the IN signal reflected the relative transmission of this signal into the volume (model or sheep uterus). The EX pressure was recorded by the reference microphone of a Bruel & Kjaer (BK2203) sonometer, placed either (a) close to the sphere model or to the sheep, like all previous studies (various SITE locations) or (b) close to the source of the signal (the SOURCE location). This last “unusual” location seemed to us to be more natural because it should take into account the effects of the environment on the stimulus transmission.

The IN pressure was recorded by two identical samples of a small, experimental laboratory hydrophone enclosed in a rectangular rubber envelope (45 mm × 25 mm × 15 mm thick). We used this type of transducer because it had a good signal-to-noise ratio, better than the BK 8103 hydrophone used in most recent intrauterine measurement studies (Querleu et al., 1981; Gerhardt et al., 1988; Gerhardt, 1989; Richards et al., 1992; Peters et al., 1993a; Peters et al., 1993b). For example, for a 100 dB SPL (ref 20 mPa) 1,000 Hz signal, respective signal to noise ratios for the BK 8103 and for our hydrophones were 14.2 dB and 49.3 dB, the noise level measured on the C scale. A greater sensitivity is required to perform measurements over the whole auditory range using signals at pressure levels compatible with commercial loudspeakers as well as to record speech signals, as will be shown in a subsequent article. Comparative calibration of the two types of hydrophones within the range of this study (100–20,000 Hz) did not reveal major discrepancies of our transducer from the flat response curve of the BK 8103.

Data Processing

The IN signal was fed through the flat 40 dB preamplifier (laboratory-made) of the hydrophone to a BK 2103 paper recorder. The paper speed on the recorder was set at 3 mm/s and pen linear displacement was 125 mm/s: These two parameters provided a reliable recording of pressure variations. An on-line check of the quality of the IN and EX signals, sent to the channels of a dual trace oscilloscope (GOULD OS 4000 model), allowed us to avoid collecting sound artifacts (e.g., wind noises which may overwhelm the system). Xerated copies of the paper recordings were enlarged by 154%, scanned via a graphic tablet (Trust 1202), and fed into a computer graphics system (Quattro Pro Windows 5.0, Borland) for graphic editing. All figures shown in this article were produced in this manner. No average curve was defined for any environmental setting because replication of measurement performed at short time intervals in this setting produced highly similar curves.

RUBBER SPHERES STUDIES

Models

Spheres made of 0.1–1 mm thick rubber, open at the top and filled with water, were used as models. Except...
when the effect of the environment was studied, spheres hung outdoors 1.5 m above the floor of a gallows located 15 m from the closest building. The diameter of the sphere, distance between the loudspeakers and the sphere, EX transducer location relative to the sphere and to the source, IN transducer location in the sphere, and structure of the environment were systematically varied in order to determine the effects of variations in these stimulus characteristics. The hydrophone (IN transducer) was secured to a rod that maintained it in the location under study.

Results

Size of the Sphere. The first series of measurements concerned the effect of varying the size of the model. These measurements were performed with the EX transducer 5 cm from the largest diameter of the sphere, at the same distance (2 m) from the loudspeakers as the center of the sphere, the location where the hydrophone hung from a rod.

Transmission curves shown in Figure 1 were obtained from three models with a respective diameter of 11, 19, and 40 cm. They displayed globally similar three-component patterns as a function of increasing sine wave frequency. First, the IN pressure remained stable from 100 Hz to approximately 500 Hz. Second, it fell gradually, between 6 – 10 dB to a frequency over which we then observed a series of pressure peaks and drops showing the presence of a resonance system. This rather complex pattern was modulated by the size of the model according to the following rule: the larger the model, the lower the frequency where the attenuation started and the first pressure peak was found; above 10,000 Hz for the 11 cm sphere, above 7,500 Hz for the 19 cm sphere, and above 3,500 Hz for the 40 cm sphere.

Location of the Hydrophone in the Sphere. The second series of measurements concerned a major issue regarding the modeling of sound transmission to a fetus, the effects of changing the location of the IN transducer in the model. This is a particularly important variable, given the fact that except for the last weeks of gestation the human fetus' head location in utero changes. The results of these location changes are shown in Figure 2.

Vertical Location. In the 19-cm sphere, the hydrophone was located on the same vertical plane as the microphone, either close to the top (Panel a), the center (Panel b), or the bottom (Panel c) of the model. Comparing curves a, b, and c indicates that variations in the vertical location caused relatively minor changes...
in the transmission of the sweeping pure tone: more pressure peaks and drops were found between 1–2 kHz for the bottom curve (Panel c). This last effect may be due to standing waves generated between the floor and sphere. However, on the whole, the three curves obtained from different locations of the hydrophone along the same vertical plane as the reference microphone were subjected to the same environmental and resonance rules. **Horizontal Location.** The hydrophone was located on the same equatorial plane as the microphone, relative to the loudspeaker: in the frontal location (Panel d), a few millimeters behind the rubber wall closest to the loudspeaker; in the central location (Panel b); and at the rear wall (Panel e). The curve recorded at the frontal location showed no pressure loss before the first pressure peak, at around 10 kHz, contrary to what was found for central and rear wall functions, where a gradually increasing loss starting over 500 Hz was apparent. In the rear location, moderate peak pressures were found around 1,000 Hz, while at higher frequencies the peak pressures appeared to be partially suppressed when compared with curves for other locations. Perhaps this last effect reflects acoustic shadowing by the sphere. **Intensity of the External Pressure.** The third series of studies measured the effect of varying the dB level of the sweeping signal. The hydrophone was in the center location and the reference microphone was in the same lateral location as before. The transmission curves within the 19-cm sphere from the sine wave signal emitted at 80 dB (top curve) and at 90 dB (bottom curve) from the loudspeakers located 2 m from the hydrophone are shown in Figure 3. Based on visual inspection, the two curves in the figure are very similar. Further measurements performed at these two external pressures in other hydrophone locations failed to reveal any noteworthy differences. **Location of the Reference Microphone.** We mentioned earlier that in all previous measurement studies the reference microphone was situated close (20–5 cm) to the pregnant woman’s or ewe’s abdomen, usually facing the sound source in what we will term the SITE setting. The next series of measurements investigates the effect of varying the location of the microphone in this setting. **Effects of Variations in SITE Setting.** The three locations of a microphone hung at the equatorial diameter level of the 40-cm sphere, depicted in Figure 4,
were explored in this set of measurements. For the Type I location, the microphone was placed 5 cm in front of the sphere, facing the source. In the Type II location, the microphone was placed at the side of the sphere, relative to the source, at a distance of 5 cm, as was the case for the first three series of measurements presented above. Here, the microphone and the hydrophone were the same distance from the source. In the Type III location the microphone was placed 5 cm behind the sphere, relative to the source. For all microphone locations, the hydrophone was located at the center of the sphere.

As shown in Figure 4, for the Type I and, even more prominently, for the Type III location, resonance systems were present in the midfrequencies (1 ± 5 kHz) that were not found for Type II location, suggesting that—for the center location of the hydrophone—there was less disruption in this frequency range. High frequencies peaks (over 10 kHz) were somewhat weaker when the reference microphone was behind the sphere (Type III). These results confirmed the choice of the Type II location for all SITE measurements reported in this article, except the present ones.

Placing the microphone close to the source (in a SOURCE setting) might be more informative about in utero sound transmission than the SITE setting because in natural settings most acoustical stimuli are not emitted very close to the maternal abdomen. This issue is investigated in the next series of measurements.

SITE Setting versus SOURCE Setting. The top curve in Figure 5 shows the IN pressure obtained when the microphone was placed at the Type II SITE setting, close to the 19-cm sphere, and the bottom curve shows the IN pressure obtained when the microphone was located close (20 cm) to the loudspeakers (SOURCE setting). In both conditions, as before, the distance between the loudspeakers and the source was 2 m and measurements were performed outdoors. The two curves differed widely within both the low and medium frequency bands. When the reference microphone was near the SOURCE there was a pressure drop in the low frequency band, and the usual pattern of gradual attenuation in the midfrequency range was absent. In the high frequency band, above the main pressure peak, the curves were similar.

Effects of Varying the Acoustic Structure of the Environment.

Addition of a Panel to the Outdoor Paradigm Condition. The lower curve in Figure 6 shows the effect
FIGURE 4 Effects of varying the location of the microphone around a 19-cm-diameter rubber sphere on transmission curves for a sine wave sweeping signal into this sphere. Three locations (Type I: in front of the sphere, Type II: next to the sphere, and Type III: behind the sphere) are tested.

Indoor Measurements. The number of reflecting elements was increased when the measurements were taken indoors, in a large room. Curves shown in Figure 7 were obtained from a hydrophone suspended in the middle of the 25-cm sphere hung in a barn (5 m × 6 m × 5 m) at three distances (2 m, 1 m, and 0.5 m, respectively) from the loudspeakers. Major changes concerned mainly the low and medium frequency range (up to 2,000 Hz). When the distance between the loudspeakers and the sphere was 2 m, a series of pressure oscillations were found within these frequency bands. Reducing this distance to 1 m smoothed these oscillations, indicating that they were probably due to signal reflections from the surrounding elements. This effect disappeared when the sound source was very close to the sphere at a distance of 0.5 m. Clearly, in a reflective environment, the spectral characteristics of the signal reaching the fetus are modulated as a function of the position of the sound source.

SHEEP STUDIES

Subjects
Two pregnant ewes (Ile de France breed), each of them carrying twin fetuses on the 143rd gestational day of gestation, were involved in this section of the study. The animals had been supplied by the Institut National de la Recherche Agronomique (Nouzilly breeding center, France). The experimental laboratory and the veterinary surgeon had received an official agreement for performing experiments on animals according to

short
standard
long
FIGURE 5  Effects of changing the location of the microphone from the vicinity of a 19-cm-diameter rubber sphere (SITE location) to the vicinity of the signal source (SOURCE location) on transmission curves for a sine wave sweeping signal into this sphere.

FIGURE 6  Effects of placing a plywood panel 1.5 m behind a rubber sphere on transmission curves for a sine wave sweeping signal into this sphere.
FIGURE 7  Effects of varying the distance between the signal source and a rubber sphere on transmission curves for a sine wave sweeping signal into this sphere when measurements are performed indoors.

Experimental Settings

Measurements for both ewes were performed indoors with the animals lying on a surgical table (a) first when narcotized and (b) second, after they had been sacrificed using a 3-g injection of Nesdonal. Additional outdoor measurements were performed on Ewe 1, the animal (a) lying on a table, (b) suspended by a harness with the body horizontal and the legs downwards.

For every measurement the loudspeakers were placed facing ewe’s left flank, at a distance of 1 m, or 0.5 m indoors 2 m, or 1 m outdoors. The microphone was placed in the Type II SITE setting, similar to the one chosen in the sphere studies, i.e., 5 cm from the ewe’s abdomen (above the abdomen when the ewe was lying on a table and below the abdomen when the ewe was hung outdoors).

Two hydrophones were secured in every animal, each at a different depth in the uterine cavity. This allowed the investigation of the effect of the location of the hydrophone within the uterus. They were implanted according to the following surgical procedure. The ewe, fasting from the day before, was first narcotized with a mixture of halothane (ICI) at 5% in air. A tracheal cannula was inserted and connected to an assisted air supply. Narcosis was maintained throughout the live measurements, with a reduced halothane percentage. The animal was then secured on her back to the surgery table and her abdomen was shaved. To prevent amniotic fluid losses, hydrophone implantation was performed using a technique designed by one of us, a veterinary surgeon (A. L.). After having pulled up a portion of the uterus containing one of the fetuses, the amniotic membranes were sewn together along the perimeter of a 15 cm rectangle. The membranes were then incised, like a buttonhole, along the longitudinal axis of this rectangle. The edges of the incision were then opened and held up firmly, higher than the amniotic fluid level. Each hydrophone was sutured on the back of a lamb fetus. The lambs were then replaced in utero in order to have one hydrophone located close to the abdominal sheep wall at incision level (Shallow Hydrophone: SH) and the other one located deeper in the uterine cavity (Deep Hydrophone: DH). Relative locations of the hydrophone in each animal lying on the surgery table were given by the surgeon (see location of hydrophones for Ewe 1 and 2 in Figures 8 and 9). Tight closure of the uterine incision was obtained by pulling on both ends of the rectangularly sewn thread—like the drawstring on a purse. The uterus and the gastro-intestinal tract were replaced in their initial location and the abdominal incision was sewn and clipped.

A data-collection technique which allowed the drawing of only one IN pressure curve at a time meant that SH and DH curves were not obtained simultaneously. This had no influence on the shape of the curve of each hydrophone because repetition of measurements performed in the same environmental settings at short time intervals produced highly replicable curves.

Results

Effect of Varying Acoustical Settings on Curves Obtained by the Two Hydrophones. In utero transmission to the Deep Hydrophone and the Shallow Hydro-
Transmission curves for a sweeping sine wave signal into the uterus of a pregnant sheep (Sheep 1) defined for a deep (DH) and a shallow (SH) hydrophone. Measurements have been performed (a) indoors on the surgery table, the sheep first alive and narcotized then later sacrificed, (b) outdoors far from buildings, the dead sheep either lying on a table or suspended from a tripod.

A global look at each column of curves on both figures indicates that, while showing the paradigmatic transmission curve defined above, each hydrophone setting (SH or DH) induces local modulations of this pattern that are to be found on all curves recorded with the hydrophone whatever the changes in the sheep or environment acoustical settings. These modulations controlled by hydrophone location are more salient in Sheep 1 than in Sheep 2. It can be seen that midfrequency attenuation starts at a lower frequency and is slightly larger for the DH curve than for the SH one. High frequency resonance peaks are more likely to be found for the DH than for the SH. DH and SH patterns differ less in Sheep 2 than in Sheep 1, except in the presence of a pressure drop below 0.5 kHz on the SH curves that could still be found after the sheep had been sacrificed and some unexpected peaks around 800 Hz that could be due, for instance, to surgical table resonance.

Thus the sheep patterns—especially the DH ones of Sheep 1—are modulated by experimental settings as follows:

Effects of Global Environment: Indoor versus Outdoor Measurements (Sheep 1 only, Figure 8). In the low and medium range the outdoor curves (DH and SH) are smoother than the indoor ones, a phenomenon already found in the rubber spheres which is presumably due to a reduction in the number of reflecting elements in the vicinity of the sheep or sphere. One may notice in the DH curves of the table condition that the first two pressure peaks found on the two indoor curves at 5.5 and 7.4 kHz are found at slightly weaker frequencies (5 and 7 kHz) on the outdoor curve. This could be due to a slight displacement of DH in the ewe uterus occurring when the animal was transferred outdoors, even a slight change in the location of the IN transducer might alter sound reception of the signal.

Living versus dead sheep (Figures 8 and 9). For each animal and each hydrophone location the curve obtained in a living sheep and the curve obtained in the same animal after it has been sacrificed are very...
similar up to 1.5 kHz. Over this frequency the attenuation is moderately stronger in the dead sheep and thus makes the high frequency pressure peaks look more salient.

**Effects of Local Environment: Outdoor Measurements, Sheep Lying on a Table versus Hanging from a Tripod (Sheep 1 only, Figure 8).** On both hydrophones the attenuation started at a lower frequency when the sheep was lying on a table than when hanging. For the DH, high frequency peaks were also higher in the table setting than in the hanging setting.

**Sheep versus sphere model.** A dead animal hung outside is the closest sheep setting to a rubber sphere hung outside. Thus, a comparison between curves obtained for the DH in Sheep 1 and the hydrophone located in the center of a 30-cm rubber sphere is shown in Figure 10. The sheep and the sphere are both located 1 m from the loudspeakers. The global transmission patterns are quite similar, however, for low to medium frequencies, the sphere curve is smoother (less disrupted) than the sheep one. The pressure peaks found between 2 and 6 kHz on the sphere curve have a poor amplitude on the sheep curve; indeed they are more salient in other DH curves of this sheep shown in Figure 8.

**Effect of the Distance to the Sound Source.** Figure 11 shows the curves obtained indoors for the DH hydrophone when the signal source was located 0.5 m and 1 m from Sheep 1 dead, lying on the surgery table. Pressure oscillations in the low to midfrequency range are weaker when the sound source is closer, an effect already demonstrated in the sphere studies.

**Location of the Reference Microphone.** The rubber model studies have shown that placing the microphone beside this model at the same distance of the source as the hydrophone induced less disruptions in the midfrequency range of the curve than placing it in front of or behind the model in relation to the source. This question was not investigated in the sheep studies.

**SITE Location versus SOURCE Location.** Changing the location of the EX transducer was also tested using the sheep preparation. Figure 12 shows the effect of placing the reference microphone close (20 cm) to the loudspeakers (at the SOURCE setting), versus placing it close to the sheep (e.g., in the same vertical plane.
FIGURE 10  Transmission curves for a sweeping sine wave signal into the uterus of pregnant sheep (Sheep 2) dead and into the 30-cm-diameter rubber both suspended outdoors.

FIGURE 11  Transmission curves defined indoors in the uterus of a sheep the signal source located 1 m or 0.5 m from the sheep.
FIGURE 12 Effects of changing the location of the EX microphone from a SITE location (close to the sheep) to a SOURCE location (close to the signal source) on the transmission curves defined in the uterus of a sheep.

and at the same distance from the source as the IN transducers and 5 cm above the animal—at the SITE position). The sheep was 2 m from the loudspeakers. As in the rubber sphere studies, the curves differed in the low to medium frequency range (up to 2,000 Hz) for the SOURCE curve. There were two marked peaks in this range. These peaks may be due to reflections of the signal from elements in the room. For the SITE curve, these peaks were almost invisible. Conversely, in the high frequency range, there was almost no difference between the two curves.

**DISCUSSION**

This study aimed at determining, with the help of a nonbiological model of the mammalian uterus—a rubber sphere filled with water—details of the intrauterine transmission of external acoustical signals. The ecological validity of this model was established by comparing the measurements obtained with the sphere to those obtained within the uterus of a pregnant sheep—the animal model commonly used in place of the human uterus.

**Summary of Effects of Setup Recording Variations**

**Nonbiological Model.** The transmission curves of a sine wave stimulus sweeping between 100 to 20,000 Hz were recorded from within the sphere model using a prototype hydrophone with a high signal/noise ratio. A stable pressure of the external signal was maintained over the signal frequency range by a compression device fed back from a reference microphone. With the hydrophone located in the center of a sphere and the microphone located beside the sphere, both at the same distance from the source, a paradigmatic three-components curve was defined between 100 and 20,000 Hz. The pressure recorded by the hydrophone was stable in the first component of the curve, the low to medium frequency between 100 to about 1,000 Hz. A second component of the curve appeared at higher frequencies when this pressure fell gradually, reflecting an attenuation of the external signal. In what can be seen as a third component of the curve, a series of rapid peaks and drops of the inside pressure was found above a certain frequency, the value of which depended on various parameters. The peaks and drops reflected the presence of resonance systems. Our mea-
measurement technique brought only relative transmission measurements, but if we rely on recent work (Gerhardt, 1989; Peters et al., 1993a) with which the pattern of our data agrees, we can assume that there was little to no attenuation of the external pressure on the first component of the curve.

The effects of changing various parameters of the experimental setup were studied. When the size of the model was varied, we found that increasing it lowered the frequency at which the first pressure peak could be found. It also increased the number and amplitude of disruptions of the curve in the first component—probably due to reflections of the external signal from the ground. When changing the location of the hydrophone in the sphere, we found that vertical displacement of this hydrophone (i.e., in a plane perpendicular to the axis or the loudspeakers) produced few modifications on the curve, except for an increase of presumed ground interference in the first frequency component when the hydrophone was at the bottom location. By contrast, horizontal displacement in the hydrophone location induced major changes in the curve. For the central location curve, placing the hydrophone near the front wall of the sphere—the one facing the sound source—made the second component of the curve disappear, that is, there was no attenuation at any frequency. Placing the hydrophone near the back wall of the sphere, made the attenuation in the second component start at a little lower frequency and be larger. These effects are more likely to be caused by internal model propagation phenomenon than by the increase of the distance to the source.

Increasing external pressure by 10 dB did not induce any salient effects on the curve. External variations in microphone and sound field had several effects. Changing the location of the external microphone near the sphere (a few centimeters in front, beside, or behind the sphere as relative to the sound source) induced only moderate pressure fluctuations in the first and second components of the curve for the in-front and behind locations. Placing the reference microphone close to the sound source (SOURCE setting) instead of close to the model (SITE setting) substantially modified the pattern of the curve. Major changes were found in the low frequencies (pressure drops) and medium frequencies (pressure oscillations and suppression of attenuation). When a sound-reflecting plywood panel was introduced behind the model, pressure oscillations in the medium frequency range were produced. Performing indoor measurements in a large room caused similar modifications in the low frequency range. These presumably ground effects were smoothed when the sphere was moved closer to the source.

**The Biological (Sheep) Model.** In the second part of this work transmission measurements of the same sweeping signal were performed in various acoustical settings, two hydrophones simultaneously surgically secured each in a different location within the uterus of a pregnant sheep. Two sheep were successively implanted. Indoor data were collected from the living sheep, first when narcotized and after they had been sacrificed. Additional outdoor data were collected from Sheep 1 after it had been sacrificed. When we compared the sphere and sheep data collected in close conditions—rubber sphere and dead sheep hanging outdoors—the transmission curves displayed very similar patterns. Indeed, for the sheep curve, the low frequency component was more disrupted than for the sphere curve, while the attenuation in the medium frequencies in the second component was present in a wider range.

Varying the acoustical setting of the experiment induced the same type of changes in the pattern of the sheep curves than in the sphere curves. Concerning the location of the hydrophone in the sheep uterus, a comparison of the curves obtained for the two locations of the hydrophone in the hung outdoor setting (thus Sheep 1) showed that for the deep location (DH), attenuation in the second component started at a lower frequency than for the shallow one (SH). Also, pressure peaks of a moderate amplitude were more likely to be found for the deep location than for the shallow one. Of course, the sheep measurements do not demonstrate the suppression of the attenuation found in the sphere for the front location of the hydrophone. But none of the shallow hydrophones had been, mostly for practical reasons, sutured in as frontal location as in the sphere. They were between the top and the front location of the sphere and this may partly explain why they still show a midfrequency attenuation. The sheep curve obtained for the deep hydrophone located close to the center of the uterus is very close, when measures are performed in identical outdoor settings (for Sheep 1) to those for the sphere.

Concerning microphone location, as for the sphere data, when the microphone was placed close to the loudspeakers, at the SOURCE location, alterations in the low frequency range of the curve were promoted relative to that recorded close to the sphere at the SITE location.

Placing the sheep on a table instead of hanging it in the outdoor measurements increased the number of local oscillations on the curve of the deep hydrophone, an effect similar to placing a plywood panel behind the sphere in the rubber model studies. This effect of reverberation of the signal on environmental elements evidenced when sphere measurements were performed...
indoor compared to outdoor measurements was also found for the sheep measurements. Moreover, as for the indoor sphere curve, pressure oscillations in the low to midrange were smoothed when the distance to the signal source was reduced.

Comparisons of (indoor) measurements performed within a living sheep or a dead one showed that they were probably components of physiological noises associated with respiratory support of the animal, spread over a wide frequency range in the living sheep, which partially masked the attenuation in the midfrequencies and the pressure peaks displayed on the curve of a dead sheep.

GENERAL COMMENTS

Thus, this study confirms and emphasizes the fact that in utero transmission of an external acoustic signal is not a simple linear phenomenon. The three-component curve we found agrees with recent sheep data reported in the Introduction. However, the use in this study of a nonbiological model and of a sweeping sine wave signal technique allowed the first systematic study of physical parameters which are thought to modulate intrauterine sound transmission. It also helped to determine, on the third component of the curve, the nature of the reversal of the attenuation pattern demonstrated by Peters et al. (1993a) and mentioned in an earlier study performed by Vince et al. (1985). According to our measurements, this reversal was due to the presence of pressure peaks and drops, corresponding to the development of resonance systems.

The use of a model, and especially a nonbiological one, which is a simplified analog of a natural object and exaggerates the effects of stimulus variations, helped in demonstrating the reality of this odd phenomenon. In fact, the amplitude of the resonance systems found was larger and the frequency where they appeared at a relatively high frequency, just over the third peak, which is a simplified analog of a natural object and exaggerates the effects of stimulus variations.

The inverse relationship between the size of the sphere and the pressure peaks displayed on the curve of a dead sheep, would alert the mother (Birnholz & Benacerraf, 1983). At this gestational age the fetus is barely able to show a startle response that would alert the mother (Birnholz & Benacerraf, 1983). The occurrence of such a series of resonances might explain the unexpected increased responsiveness of end of gestation fetuses with increasing pitch of a octave band noises (emitted at 500 Hz, 2,000 Hz, and 5,000 Hz) found previously by Lecanuet, Granier-Deferre, and Busnel (1988). A linear attenuation model would predict decreasing responsiveness as a function of increasing frequency.

We have mentioned that many of our sheep data agree with that of Peters et al. (1993a), although the two studies differed on several points: presence of fetuses in uterus versus uterus filled with water, model of hydrophone used, and type of acoustical signal emitted (compressed sweeping sine wave versus white noise). However, we were not able to confirm for the high frequencies the paradoxical effect of attenuation increase when the emitted sound level increased found by Peters et al. We found, in the rubber spheres, that a 10 dB increase in the external pressure of the sine wave signal did not change transmission into the spheres at any frequency. Concerning low frequencies, we were not in a position to look for this effect because our sine wave stimulus began its sweep at 100 Hz, a frequency higher than the ones on which the effect was demonstrated. Thus, the effects evidenced by Peters et al. might be either unique to the sheep or be due to loudspeaker limits, as they were found at very low and very high frequencies where the output of loudspeakers may be nonlinear.

In another article, Peters et al. (1993a) demonstrated what they called a “wrapping around” effect of the internal pressure of broadband noise recorded in 45 locations of an empty uterus of a sheep filled with...
water that was gradually falling from the periphery of the uterus to the center. Our sphere data concerning the effect of varying the location of the hydrophone did not demonstrate such an effect. They suggest that the transmission curve is modified, mostly in its mid-frequency range as a function of the distance to the wall facing the sound source. It is unlikely that this effect relies on the use of a mechanical vibrator. We have to screen systematic variations of the location of the hydrophone in the horizontal diameter of our sphere model.

The drop of internal pressure found for the mid frequencies in the dead animals as compared to the living one is probably due to the absence of high components of physiological noise (assisted respiratory device, for instance). They are unlikely to be due to the absence of biological background noise (heart beat sounds, placental noises, etc.), the components of which are mostly low frequency ones below our 100 Hz threshold. The fact that living biological tissue does not convey and/or reflect sound waves the same way as dead tissue may also account for differences between curves recorded in living versus dead sheep.

Owing to the number of parameters that modulate the in utero sheep transmissions, a statement supported by the comparison between the two pairs of curves obtained by the hydrophones located in our two sheep, we agree with the observations of Peters et al. of high interindividual variability of the measurements, which may depend largely on morphological characteristics of the animal and on the acoustical structure of the environment.

Our data showed that moving the external reference microphone—at which level the sine wave pressure was held stable—from SITE setting (close to the model or the sheep) to SOURCE setting (close to the loudspeakers) appeared to produce major changes in the transmission curve outdoors, where the only element is the ground. SOURCE measurements demonstrated that the EX signal can be quite severely modified by radiation before it reached the model or the sheep. It is modified by radiation, by attenuation as a function of the distance to the hydrophone, and by reverberation of the walls and global environment indoors. The SOURCE measurement technique gives a better idea of the transmission of acoustic signals in the ecologically valid environment of ovine and human fetuses which live in sound reflecting environments.

The present study demonstrated that it is possible to use a simple, nonbiological model to study the respective role of some of the parameters interfering with the in utero transmission of external sounds. Characteristics (the size and presumably the shape) of the uterine cavity, the location of the recording device (and thus of the fetal ear) in this cavity, the acoustical structure of the environment, and of the signal seem to play an important role in the modulation of this transmission. Using a nonbiologic model allows for easy systematic investigation of these parameters.

NOTES

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