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Piezoelectric vibrator-stimulated potential and heart rate accelerations detected from the fetus

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ABSTRACT

Objectives: The fetus is well known to have a substantial capacity for sound recognition in the uterine environment. The aim of this study was to develop a sound stimulus system equipped with a piezoelectric vibrator (PV), record the PV-stimulated potential (PVSP) of the fetus and monitor changes of the fetal heart rate (FHR) under PV stimulation.
Methods: The relationship between the input voltage applied to a piezoelectric vibrator and the sound pressure generated in the uterus was calibrated based on a model of the maternal abdomen. Fourteen fetuses for the measurement of the PVSP and 22 fetuses for the measurement of the heart rate changes from low-risk pregnant women were recruited.
Results: The PVSP responses were obtained in 9 out of 14 fetuses. All the tested fetuses accelerated the FHR after the 2 kHz tone stimulation at 70 dB intensity generated by PV from 32 to 37 weeks gestational age.
Conclusions: Using a newly developed sound stimulus system equipped with PV, the electric responses of a fetus recorded from electrodes placed on the mother's abdomen may be closely related to the auditory evoked response. Significant accelerations of FHR were objectively, accurately and readily obtained after the sound stimulation.

1. Introduction

The fetus is well known to have a substantial capacity for sound recognition in the uterine environment [1]. In premature human infants [2–4], auditory-evoked potentials can be recorded from 25 to 28 weeks gestational age (GA), and otoacoustic emissions are elicited as early as 30 weeks GA [5]. Furthermore, a number of studies revealed fetal cortical activation in response to auditory stimuli using both magnetic resonance imaging and magnetoencephalography [6]. For both functional brain imaging techniques, the recorded response rates were between 50 and 70% at 0.5–1 kHz and 90–120 dB. The fetal brain responses to sound can be used to evaluate language learning, speech perception and development as well as the auditory ability. However, the less than perfect response rate together with the cost and availability of equipment may prevent it from becoming a standard tool to examine the fetal auditory capability.

Pregnant sheep were anesthetized and the fetus exteriorized through a cesarean section, examined with electrodes and a bone oscillator and then returned to the uterus. Then, the uterus and abdomen were closed. After recovery from surgery, auditory brainstem responses were detected from the fetus between 111 days and 136 days GA (Normal gestation is 145 days), which is a good animal model for human studies because of similarities in the physics of transmission and the early development of the inner ear function prenatally [7]. On the other hand, clinical research to observe auditory brainstem responses or otoacoustic emissions, which may directly assess the auditory function, has not yet been applied during the prenatal period.

So far, the fetal auditory system functioning has been studied indirectly by observing the behavioral responses to a sound stimulus. Some evidence suggests that the onset of a body movement

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response evoked by vibroacoustic stimulation occurs at about 25 weeks GA with increasing numbers of fetuses responding with increasing GA [8–11]. The physiological response of the heart rate change has been robustly demonstrated by several studies. Fetuses from 30 to 36 weeks GA responded to airborne sound stimuli with accelerations in the heart rate [12–14]. However, the sound delivered through a loudspeaker was variably estimated to be attenuated in uterine from 0 to about 40 dB [15–17], which is considered to be responsible for the heart rate variability in response to high or low intensity sound [1,18–20]. Moreover, the body movement and cardiac responses induced by vibroacoustic stimulation may be mediated by the vestibular hair cell and cutaneous receptors in addition to the cochlear hair cells [21]. Thus, in order to evaluate the actual auditory sensitivity of the fetal cochlea, a consistent and reliable monitor of the heart rate that employs sound stimulation of the correct intensity for the fetal hearing organ could enable the identification and assessment of fetal hearing loss, thereby improving further the screening for deafness.

In the present study, we developed a sound stimulus system equipped with a piezoelectric vibrator (PV) to stimulate the fetus through the maternal abdomen. The piezoelectric vibrator-stimulated potential (PVSP) responses of the fetus were recorded from electrodes placed on the mother's abdominal skin wall. Moreover, the heart rate changes of the fetus could be observed using a similar sound system. The present study may contribute to fundamental improvements in fetal hearing screening.

2. Materials and methods

The study included three series of experiments; (i) development of a piezoelectric vibrator to produce the acoustic stimulation, (ii) measurement of the PVSP from the fetus and the determination of the best condition of sound stimulation and, (iii) assessment of the heart rate changes induced by the best sound stimulation induced by PV. In the measurement of PVSP, a total of 14 fetuses (1 at 35 GA, 3 at 36 weeks GA, 9 at 37 weeks GA, and 1 at 38 weeks) from low-risk pregnant women attending prenatal clinics at Juntendo University Hospital were recruited. To examine the heart rate changes stimulated by PV, a total of 22 fetuses from low-risk pregnant women participated, in which 16 fetuses at 32–33 weeks GA, 18 at 34–35 weeks GA, 15 at 36–37 weeks GA were involved. Neonatal outcome measures confirmed the GA and good health of the fetuses. At delivery, all infants were diagnosed as healthy, term newborn on medical examination. After delivery, normal development of auditory function in all infants was confirmed by automatic auditory brainstem responses and behavioral responses to sound. The study was conducted with the approval of Juntendo Hospital. The pregnant women provided informed, written consent prior to participation.

Because bone conduction is a more effective means of sound transmission for fetuses than air conduction, a suitable device of applying sound stimulus to fetuses through bone conduction was developed. This sound stimulus system consisted of a function generator (WF1944, NF Corporation, Japan), a piezo-driver (AS-904, NF circle design block, Japan), and a piezoelectric vibrator (AE1414D16F, NEC Tokin, Japan). Auditory signals generated by the function generator were amplified by the piezo-driver and were input into the piezoelectric vibrator. In order to evaluate whether the sound stimulus was adequate for fetuses, the relationship between the input voltage applied to the piezoelectric vibrator and the sound pressure generated in the uterus was calibrated based on a model of the maternal abdomen (Fig. 1), in which a simulated abdominal wall was constructed of sponge rubber and the fetal auditory organ was substituted with a hydrophone. Tap water was used to represent the amniotic fluid (750, 1,500, and 2400 ml).

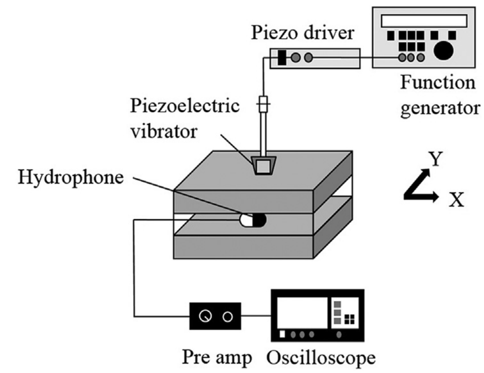

Fig. 1. Block diagram of the calibration of a piezoelectric vibrator. The artificial model of a maternal abdomen, the abdominal wall of which was constructed of sponge, rubber and a hydrophone serves as the fetal auditory organ. Tap water is used to represent the amniotic fluid.

In order to measure the PVSP from a fetus, the PV was placed on the surface of a pregnant woman's abdominal wall above the fetal head fixed in the cephalic position, which was identified by a Doppler echogram, in order to minimize electric noise derived from fetal movement. AS controls, non-pregnant women were also examined. Recording electrodes were placed on the surface of the abdominal wall above the fetal head and the reference electrode was placed on the femur. We used standard conducting electrodes 5 mm in diameter as the recoding electrodes and a disposable electrode sheet as the reference electrode. Each electrode was fixed with paste and adhesive tape to hold it in place. The PVSP responses were amplified, filtered between 100 Hz and 3 kHz and averaged over 1000 trials using a Neuropack EMG/EP measuring system (Nihon Kohden, Japan). Time synchronous averaging was used in order to remove random stimulus and power supply artifacts. This examination was done three times with sound stimulation and three times without as the control trials. The acoustic stimuli used for the PVSP measurement consisted of tone bursts of 2 kHz. A tone burst signal consisted of a single sine wave and a silent part of a single tone and repeated at 100 msec intervals. The stimulation used in our study had a rise/fall time of 0.1 msec and plateau time of 2 msec.

Generally, when the arrangement of the electrodes is changed, the shape of the measured potential curve also changes even if the signal source remains unchanged. The PVSP response curves are therefore expected to be quite different from those of the conventional ABR. Although some statistical approaches have been adopted for the response detection in conventional ABR measurements [22,23], the immediate applicability of these methods to the PVSP response curves is uncertain because this is the first time to measure the PVSP responses and their statistical features have not been clarified. In this research, therefore, we aimed at detecting the vibrator-induced synchronized potentials as the first step toward developing a fetal hearing test, and introduced our original method to estimate the similarities among the results obtained from repeated measurements.

Correlation coefficients were used to estimate the similarity of the amplitude of the PVSP. First, the 4-points-moving-averaged potential curves of each trial were generated (Fig. 2A). Second, the correlation coefficients of combinations of two of the three potential curves were respectively calculated using the data obtained during 2 msec (40 points). We estimated that there was a similarity among the three curves in the short segment if all three correlation coefficients were positive (Fig. 2B). A train of sets of the three correlation coefficients were calculated in the short segments moving in steps of 0.5 msec (10 points) in the same way. The