Fetal Stimulation by Pulsed Diagnostic Ultrasound

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Objective. To show that pulsed ultrasound from a clinical ultrasonic imaging system can stimulate the fetus. Stimulation is defined mainly as increased fetal gross body movements in response to excitation.

Methods. Fetuses of a group of 9 volunteer women (mean gestational age, 33.37 weeks; range, 25–40 weeks) were evaluated for body movement under 3 different conditions: (1) control, with no ultrasound exposure; (2) ultrasound in continuous wave Doppler mode; and (3) pulsed ultrasound in pulsed Doppler and B modes. A conventional external fetal monitor, with negligible ultrasonic output, was used to monitor fetal gross body motions. After an initial rest period of 3 minutes with 1 or no fetal motion, fetuses were monitored for an additional 3 minutes under the exposure criterion defined for each condition. Resulting fetal motions under the 3 conditions were compared using the Wilcoxon signed rank test. Results. The test showed that fetuses moved significantly more frequently under condition 3 (mean ± SD, 3.43 ± 1.93 movements per minute) than under condition 1 (0.40 ± 7.33 movements per minute) or condition 2 (0.63 ± 7.67 movements per minute); \( P = .004 \) and \( .016 \), respectively. Fetal movements under conditions 1 and 2 did not differ significantly.

Conclusion. Diagnostic ultrasound may stimulate fetal body motion. Key words: fetal motion; ultrasound; stimulation; fetal hearing; sound; radiation force.

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Abbreviations
CW, continuous wave; CWD, continuous wave Doppler; PDB, pulsed Doppler and B modes; HRC, heart rate change; HRr, heart rate in the observation period; HRs, heart rate in the rest period

Although ultrasound is not audible to the human ear, under certain circumstances it can produce a low-frequency sound in the object exposed to it. This phenomenon has attracted attention recently because of its application in the fields of imaging and material characterization.\(^1\)\(^-\)\(^5\)

The physical phenomenon behind this effect is the “radiation force” of ultrasound. Although this phenomenon has been known for a century,\(^6\) its implications in medical ultrasound have been studied only in recent years. Radiation force results from changes in the energy density of the ultrasound as it interacts with an object.\(^7\) Objects that are highly reflective (such as bones) cause abrupt changes in the energy density and therefore receive a stronger radiation force.

Diagnostic ultrasonic scanners normally transmit sequences of high-intensity ultrasound pulses into the human body. Interaction of these pulses with organs produces a cyclic pushing force on the interfaces. Because ultrasound beams are designed to be narrow, this force...
exists only in a small region (beam cross section) on the organ interface, acting as a needle that repeatedly taps the object as the beam is scanned across it. This effect causes the object to vibrate at the pulse repetition frequency. The pulse repetition frequency for most diagnostic scanners is in the range of 1 to 10 kHz, which happens to be in the audible frequency range. In utero sound generation by obstetric ultrasound has been reported by Arulkumaran et al.\textsuperscript{8,9}

The radiation force of a continuous wave (CW) sound beam on a perfect reflector, \( F \), is given by \( F = \frac{2P}{c} \), where \( P \) and \( c \) are the total incident sound power and sound speed, respectively.\textsuperscript{6,7} This force is a steady "pushing force" in the sound propagation direction and should not be confused with the instantaneous oscillating pressure wave. For a typical ultrasonic imaging system and probe, such as the one used in our experiment, the average pulse intensity at the focus is about 130 W/cm\(^2\). Assuming a focal area of 1 mm\(^2\), the resulting radiation force is 1.7 mN. This force is rather small, but because it is exerted on a small focal cross section, the pressure in this region is 1700 Pa, which is a significant pressure value. When exerted on the hearing structure, these repeated momentary pressure pulses can cause significant vibration in the hearing system. Continuous wave ultrasound with a constant amplitude, on the other hand, can only produce a static pressure, which does not result in any audible sound.

The radiation force of ultrasound is highly localized, that is, exerted only in a small focal region on the object. If in an obstetric examination the fetal head is in the focal region of a scanner, the vibration will be produced on any calcified bone such as the ossicle structure of the ear. This vibration is significantly different from the natural way sound travels to the fetus. The fetal cochlea is not very sensitive to sound traveling through the body, because particle displacement on both sides of the eardrum is much less than in air, and because the sound acts with equal pressure on the oval and round windows. Through radiation force, ultrasound can generate audible sound directly within the fetal head, which could be conducted to the cochlea efficiently, especially if the malleus, incus, and stapes are targeted by the ultrasound beam. These bones are ossified in the fourth month of gestation,\textsuperscript{10} becoming highly reflective and thus likely to receive a stronger radiation force from the ultrasound beam. Any resulting ossicle movement will act directly on the oval window but not on the round window. Therefore, the vibration will be efficiently conducted to the cochlea. Ultrasound-generated sound can also be heard by adults when the beam is focused directly on the labyrinth.\textsuperscript{11} The above-mentioned principles motivated us to investigate the existence of a fetal stimulation effect by obstetric ultrasound.

Possible side effects of ultrasound, particularly on the fetus, have been under investigation for years. Previous studies of stimulating effects of ultrasound on the fetus\textsuperscript{12} have been inconclusive, probably because only CW ultrasound was used.

Our main hypothesis was that an ultrasonic imaging system can stimulate the fetus. We further hypothesized that only pulsed and not CW ultrasound has such a stimulating effect on the fetus. In this study, stimulation was measured mainly by increased fetal gross body movements in response to the excitation (ultrasound). A heart rate increase was a secondary effect that was also considered. We tested our hypotheses by exposing a group of fetuses to the ultrasonic field of a diagnostic scanner in both pulsed and CW modes and recording fetal activities. Then we compared these results with the results of a control study in which no ultrasound was used. A study of the health risks of this stimulation is beyond the scope of this paper.

**Materials and Methods**

To evaluate fetal reactivity to stimulation by ultrasound, we measured fetal body motions in the presence and absence of the ultrasonic field of a clinical scanner. A clinical ultrasonic scanner (128XP; Acuson Corporation, Mountain View, CA) with a 2-MHz probe (V2), a fetal monitor (1350A; Hewlett-Packard, Palo Alto, CA), and a sound level meter (CEL-266; CEL Instruments, Kempston, England) were used. The spatial peak time–averaged intensities (defined as the highest intensities within the field averaged over an entire scan period) of the ultrasonic fields produced by the scanner and its probe were 277, 286, and 144 mW/cm\(^2\) in the pulsed Doppler mode, CW Doppler (CWD) mode, and B-mode (the common imaging mode of ultrasound), respectively. (Acuson 128XP Computed Sonography System Service...
Manual, 1995). These values are typical in modern scanners. Melendez et al.\(^{13}\) have shown that the fetal monitor of the type used here is capable of recording single or clustered fetal extremity movements that are either isolated or combined with trunk motion. The fetal monitor records individual fetal movement, lasting up to 4 seconds, as an “all-or-none” phenomenon and places a dot on a paper chart. If the motion continues longer, more dots are recorded. The intensity of the ultrasound produced by this machine was only 1.5 mW/cm\(^2\) at 990 kHz (Hewlett-Packard M1350A Series 50 Fetal Monitor Service Manual, 1990), which was less than 1% of the scanner intensity; hence its potential effect on the fetus was negligible in comparison with that of the scanner.

To investigate possible interference between the fetal monitor and the scanner, we placed their probes 4 cm apart in a water tank, facing each other. The scanner was set at the combined pulsed Doppler and imaging modes, and the fetal monitor was set to record at its normal mode. We found that the ultrasonic field of the scanner probe did not interfere with the motion (introduced by tapping on either probe) detection function of the fetal monitor in any way. However, the scanner caused the heart rate monitor to show false readings; that is, in the absence of any motion, the heart rate reading should have been zero, but because of the interference from the scanner, the fetal monitor showed large numbers in a random pattern, even without tapping on the probes. We concluded that we could use both machines simultaneously on a patient when we were recording fetal motions. To measure the heart rate, however, the ultrasonic power of the scanner had to be turned off.

To test the hypothesis that ultrasound has a stimulating effect on the fetus, we studied fetuses who were initially at rest (defined below) and observed their body motions and heart rate acceleration during the introduction of ultrasound to their head and ears. The results were then compared with the results of a parallel control study on the same fetuses with no exposure to ultrasound. To test the hypothesis that fetal stimulation depends on the ultrasonic waveform, we exposed the fetuses to both pulsed and CW ultrasound sources of comparable average intensity levels at separate times and compared the resulting fetal reactions.

The initial rest state may be defined as the period when the spontaneous body motion drops below its average value. Average fetal gross body movements in the third trimester have been reported to be in the range of 0.5 to 1.9 movements per minute depending on the measurement method.\(^{14-17}\) For the purpose of our experiments, we determined the initial rest period as a 3-minute period during which the fetus made 1 or no movement as indicated by 1 or no dot on the chart (the rest period defined here should not be confused with the fetal sleeping period). Once a rest state was reached, we continued observing fetal movements for an additional 3-minute period during which the fetus was exposed to the ultrasonic field of the scanner.

A group of patients (n = 9) with normal pregnancies and healthy fetuses at gestational ages ranging from 25 to 40 weeks (median, 33.85 weeks; mean ± SD, 33.37 ± 4.45 weeks) were studied after Institutional Review Board approval and informed consents were obtained. This age group was chosen because fetal response to acoustic stimulation begins around the 25th week.\(^{18}\)

To test the 2 hypotheses, the experiments included 3 conditions: (1) evaluation of the fetal movements with no stimulation (control study); (2) evaluation of the fetal response to CW ultrasound; and (3) evaluation of the fetal response to pulsed ultrasound at an intensity level comparable with that of the CW ultrasound. Experiments were conducted in random order on each patient. Patients were not informed of which condition (2 or 3) was set at any time. Patrick et al.\(^{14}\) have shown that the amount of gross body motion is not correlated with maternal meals. Therefore, we did not control mothers’ meal times before the experiment. No patient ate meals during the experiment. Of 9 experiments, 3 were performed in the midmorning (9 AM–12 PM), and 6 were performed in the afternoon and evening (4–8 PM). The fetal position within the uterus was known to the physician before the experiments.

**Control Study (Condition 1)**

The patient was asked to rest on a bed and remain still for the duration of the test. The room was kept quiet throughout the experiments (airborne noise measured with the sound level meter averaged =62 dB [re 20 μPa]). Gross fetal movements in the third trimester have been reported to be in the range of 0.5 to 1.9 movements per minute depending on the measurement method.\(^{14-17}\) For the purpose of our experiments, we determined the initial rest period as a 3-minute period during which the fetus made 1 or no movement as indicated by 1 or no dot on the chart (the rest period defined here should not be confused with the fetal sleeping period). Once a rest state was reached, we continued observing fetal movements for an additional 3-minute period during which the fetus was exposed to the ultrasonic field of the scanner.

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movements were monitored continuously by the fetal monitor to identify a fetal rest period. Once a rest period was identified, we continued observing the fetus for an additional 3 minutes (no ultrasound was used here). The heart rate was also recorded during the experiment.

**Stimulation by CW Ultrasound (Condition 2)**
The patient and experimental conditions were as in condition 1, except that an ultrasonic scanner, set on the CWD mode, was used during the observation period. Initially, we set the scanner on standby (with the “freeze” button on), a setting on which it produced no ultrasound. Gross fetal movements were monitored continuously by the fetal monitor to identify a fetal rest period. At the end of the 3 minutes of rest, the ultrasonic probe of the scanner was placed on the patient’s abdomen and pointed toward the fetal head and ears. The ultrasound exposure procedure included 6 intermittent exposures. The scanner was switched to the active mode for 10 seconds and then switched to standby for 20 seconds. The switching was done by means of the freeze button without loss of contact between the probe and the patient’s body. This cycle was repeated 6 times. Hence, the total observation time, beginning with the first ultrasound exposure, was 3 minutes. Intermittent exposure to ultrasound allowed the fetal monitor to properly record the heart rate in those 20-second intervals when the ultrasound was off. The 6 episodes of ultrasound exposure were marked on the fetal monitor chart (using the remote event marker of the monitor) for future reference. The scanner’s speaker was turned off during all experiments to avoid any unwanted noise in the room.

**Stimulation by Pulsed Ultrasound (Condition 3)**
The patient and experimental conditions were as in condition 2, except that the ultrasonic scanner was set on the combined pulsed Doppler and B modes (PDB) during the observation period. This setting was chosen because it allowed the scanner to produce its highest ultrasound intensities. Ultrasound exposure intervals were the same as in the previous condition. The scanner’s speaker was turned off during all experiments.

**Results**
A typical fetal monitor chart, recorded from 1 patient during fetal stimulation in the PDB condition, is shown in Figure 1. The fetal monitor recorded 3 traces, including fetal heart rate, fetal movements, and uterine activity. Ultrasound exposure intervals are marked by thick black blocks. Figure 1 indicates that the fetus was at rest for at least 3 minutes before the ultrasound was turned on. After the introduction of pulsed ultrasound, the fetus started moving frequently. It is noticeable that the heart rate reading was stable, even during the ultrasound exposure intervals. In other words, the fetal monitor readings were not affected by the presence of ultrasound from the scanner. That is because in this experiment the ultrasound probe was not facing the fetal monitor probe; both probes were facing the fetus. Hence, interference was not enough to cause errors in the fetal monitor readings.

Fetal motion count data in the observation periods are shown in Table 1. Of the 9 patients, 2 could not participate in the CWD condition because of limitations in available time. That did not affect the results of our main study (condition 3, with pulsed ultrasound), which is the focus of this article and was designed to test our main hypothesis (that pulsed ultrasound can stimulate the fetus). The mean number of movements listed in Table 1 indicates that the fetus moved more often in the PDB condition than in the control and CWD conditions. The results of the CWD and control conditions were very similar.

We defined the heart rate, in either the monitoring or observation period, as the maximum heart rate that was maintained for at least 10 seconds in that period. In the observation period, the heart rate was measured during the three 20-second nonexposure intervals. Table 2 shows the heart rate, in beats per minute, for the control and PDB conditions. The heart rate change (HRC) in a fetus was defined as $HRC = HR_{ob} - HR_{r}$, where $HR_{ob}$ and $HR_{r}$ were the fetal heart rates in the observation and rest periods, respectively. The mean ± SD HRC in the control and PDB conditions were $-0.8 ± 5.0$ and $8.3 ± 8.3$ beats per minute, respectively.

To compare the number of movements in the 3 conditions, we used the Wilcoxon signed rank test. Probability values for control versus PDB, control versus CWD, and PDB versus CWD con-
ditions were \( P < .004, .750, \) and .016, respectively. This test indicated that the number of fetal movements in the PDB condition was significantly greater than those in the control and CWD conditions and that the results of the CWD condition were similar to those of the control condition.

To test the hypothesis of fetal HRC as a result of exposure to ultrasound, we used the Wilcoxon signed rank test. We found \( P = .750 \) for the control group, meaning that there was no significant change in the heart rate from the test periods to the observation periods. The results were quite different for the PDB condition, for which we found \( P = .020 \), which indicates that the heart rates in the observation periods were significantly different than in the corresponding rest periods.

We also used the Wilcoxon signed rank test to test the HRC of each fetus in the control study (no ultrasound) versus the HRC in the PDB condition. We found that the HRC in the PDB condition was more significant than the HRC in the control condition \( (P = .020) \).

**Discussion**

Previous studies on stimulating effects of ultrasound\(^{12}\) have been inconclusive, apparently because the experiments used CW ultrasound. The aim of this study was to investigate the capability of clinical ultrasound, especially in the pulsed mode, to stimulate the fetus.

The fetal movement data presented in Table 1, as well as the results of the Wilcoxon signed rank test, indicate that the PDB condition stimulated the fetus to become significantly active, whereas CW ultrasound of approximately equal intensity was basically nonstimulating. The lack of fetal stimulation by CW ultrasound is in agreement with results presented by Hertz et al.\(^{12}\) Fetal heart rate acceleration is generally correlated with fetal physical activities.\(^{13}\) The Wilcoxon signed rank test of the fetal heart rate data indi-
cated that the HRC was significant in the PDB condition, confirming the results obtained from the fetal movement data. The absence of fetal response in the CWD condition eliminates the physical contact of the probe with the abdomen as a potential source of stimulation. The small \( P \) value \((P = .016)\) resulting from comparison of the motion data in the PDB condition versus those in the control condition indicates that the number of samples used \((n = 9)\) was sufficient to arrive at a statistically meaningful result.

Obstetric literature relies heavily on observations obtained by ultrasonographic imaging to study normal and abnormal fetal movement behaviors. Our findings indicate that the ultrasound itself may stimulate fetal movement. Thus, what has been perceived in the literature as undisturbed fetal behavior may in fact be disturbed fetal behavior caused by an artificial stimulation source (ultrasound). The results obtained in this study should contribute to the general field of fetal science and should aid the general understanding of fetal movement. In particular, this report should be of value to those investigators who study the fetus in terms of movement and use ultrasonic scanners to evaluate this parameter, for example, those who perform biophysical profile tests, fetal body motion studies, and fetal hearing tests. If, during the course of such tests, pulsed ultrasound (in the form of B-mode or pulsed Doppler ultrasound) is intentionally or accidentally projected on the fetal head, then the potential for fetal stimulation exists. The focus of this study was to show that pulsed ultrasound can stimulate the fetus. Our results can be further expanded by studying the stimulation effects of different machine settings, the effects of exposing other fetal parts to ultrasound, and the effects of various fetal parameters, such as age.

### References

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