Early Human Development (2008) **84**, 595–603

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用一种新开发的传感器在家中长期监测胎儿运动:介绍
产妇睡眠期间胎儿运动引起的产妇微唤醒

A long-term monitoring of fetal movement at home using a newly developed sensor: An introduction of maternal micro-arousals evoked by fetal movement during maternal sleep

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Received 26 December 2007; received in revised form 7 March 2008; accepted 11 March 2008

KEYWORDS
Fetal movement;
Pregnant women;
Micro-arousal;
Capacitive acceleration sensor;
Long-term monitoring

关键词
胎儿运动;孕妇;Micro-arousal;电容式加速度传感器;长期监测

背景:胎儿运动引起的孕妇睡眠障碍是众所周知的。胎儿运动被认为是胎儿健康的一个指标。然而，由于还没有一种简便可靠的方法来记录胎儿运动，对孕妇睡眠障碍和胎儿健康的心理生理学研究还没有完成。

Abstract 目的:为了解决这些方法上的问题，我们开发了一种新的具有静电容量的传感器，可以捕捉胎儿运动的加速度。

Background: Pregnant women's sleep disturbance due to fetal movement is well known. Fetal movement is thought to be an index of fetal well-being. However, as there has never been a way to easily and reliably record fetal movement, psychophysiological studies of pregnant women's sleep disturbance and fetal well-being have not been done.

Aims: To solve these methodological issues, we developed a new sensor with electrostatic capacity that can pick up acceleration of fetal movement.

Methods and results: Experiment I: We verified the reliability of our fetal movement recording system. Thirty-two pregnant women (from 19 to 39 weeks of gestation) were asked to lie down on a bed for about 1 h and to press a button as a subjective marker when they felt fetal movement. We simultaneously recorded maternal polysomnograms and fetal movement from the mothers' abdomens using a Medilog recorder. The mean of prevalence-adjusted bias-adjusted kappa for agreements, based on time between fetal movement signals recorded and subjective maternal markers, was substantial at 0.75. Experiment II: We recorded seven pregnant women's polysomnograms and fetal movement simultaneously during all-night sleep at home using our sensor during weeks 33 and 36 of gestation. We succeeded in recording maternal micro-arousals evoked by fetal movement. The mean value of the number of micro-arousals at 33 weeks was slightly larger than that at 36 weeks.

Conclusions: There was a high agreement between subjective maternal markers and fetal movement. Our recording system using the new sensor can be used for home monitoring of fetal movement.

结论:母体主观标记物与胎儿运动之间具有较高的一致性。我们的记录系统使用新的传感器可以用于家庭监测胎儿运动。

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doi:10.1016/j.earlhumdev.2008.03.001

胎动是了解胎儿健康状况的重要指标。当母亲感到胎动减少时，她们被要求去医院。然而，母亲对胎儿运动的感知是主观的。1933年，Sontag等人尝试用tamb0来客观记录胎儿运动。自那时以来,各种传感器是为了客观地记录胎儿的运动,如电磁设备,[10],electro-pressure敏感传感器[11],一个piezosensor [12], n我m p e n c e d e v i c e[13],和超声波多普勒设备(14、15)。许多临床医生和研究人员为开发使用多普勒设备进行记录的方法做出了贡献[14-16]。用多普勒仪检测胎儿运动和胎儿心率，现在被普遍称为无应力T测试，其临床贡献巨大。然而，一个长期的监测系统，特别是在家里使用，尚未建立。Patrick等人利用长时间卧床的母亲[17]超声扫描仪研究了24小时内胎儿运动和母亲心率之间的关系。这种实验条件是特殊的，无法在临床上复制。如果有一种方便的工具可以在家里长期记录胎儿运动，这将对有一定危险因素的孕妇有用。在国内发生宫内胎儿死亡的信息很少。一个方便的工具将有助于在高危病例中收集有用的信息。

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大约40年前，斯特曼尝试用压敏电极记录孕妇夜间睡眠时腹部的胎儿运动。他同时记录了胎儿运动和孕妇的多导睡眠图，但未能发现胎儿运动和母亲睡眠脑电图之间的关系，可能是因为压敏电极的灵敏度较低。此外，母亲的呼吸也可能是胎儿的运动。为了将胎儿运动监测用于诊断目的，传感器必须具有较高的灵敏度，并且该方法必须排除母体伪影。如果满足这些条件，就可以进行长期监测。

在这里，我们采用了一种新的静电电容传感器来检测胎儿运动的加速。在本研究中，我们将我们的胎儿运动记录系统称为FMAM，即胎儿运动加速度测量。我们进行了两个实验，I和II。我们在实验I中证实了主观母亲标记与我们系统记录的胎儿运动之间的高度一致性。在实验二中，我们清楚地发现孕妇睡眠时的微唤醒是由胎儿运动引起的。我们认为这种新的胎动记录系统将使我们能够在国内开发长期的胎动监测。

研究对象是居住在东京的有偿志愿者。32名孕妇(平均31.5岁，年龄24-43岁，初产妇6例，经产妇26例)参加了这项研究，在白天检测传感器的灵敏度。她们的妊娠周从19周到39周不等(平均妊娠年龄34周)。所有的母亲都很健康，没有高血压、肾脏疾病、糖尿病和睡眠障碍的历史，所有的产前怀孕都是正常的。所有的婴儿都很健康，没有神经问题。所有的母亲在参与研究之前都给出了书面知情同意。这项研究得到了东京精神病学研究所伦理委员会的批准(编号17-43)。

分析了该系统的可靠性。我们研究了胎儿运动的FMAM测量和母亲对胎儿运动的主观评价之间的一致性。孕妇早在妊娠20周就能识别胎动。他们对胎儿运动的主观评价在临床上被用作胎儿幸福的指标。白天，受试者将传感器放在腹部一个半小时。他们被要求躺在床上，当感觉到胎动时按下一个按钮作为主观标记。使用Medilog 8-ch盒式磁带录音机(Oxford Medical Ltd.，Oxford)同时记录孕妇的脑电图、下巴肌电图、EOG(左-右)、呼吸、心电图、主观标志物和胎儿运动。由于Medilog系统的频率响应为0.5-30 Hz(－3 dB)，其传感器的总响应为5-30 Hz。在596 K。Nishihara等人的实验的最后一部分是一个可移动的数字多导睡眠仪(Polymate, TEAC Ltd, T okyo)，它能够检查正在进行的信号，被用于5名受试者。在Polymate系统中，采样率为500 Hz/s，频率响应为0.5 ~ 500 Hz。传感器的总响应为5-200 Hz。在Medilog记录系统中，我们使用了校准器的按钮。在Polymate系统中，我们做了一个手持按钮。当我们使用新的传感器时，我们使用FMAM这个术语，而不管记录器是什么

1. Introduction

Pregnant women often have sleep complaints stemming from fetal movement, inability to find a comfortable sleep position, back pain, urinary frequency, and restless legs movement [1–3]. Some reviews have pointed out the importance of pregnant women's sleep disturbance in the last trimester from the aspect of maternal–fetal outcomes [4,5]. In particular, obstructive sleep apnea in pregnant women has been focused on because pregnancy-associated changes, for example, baseline obesity, neck circumference and gestational weight gain, tended to increase the risk factors of sleep apnea [6]. Severity of sleep-disordered breathing during pregnancy has been reported to improve following delivery [7]. Sleep-induced blood pressure increment in preeclampsia has been reported to be reduced using nasal continuous positive airway pressure [8]. However, it is unknown how fetus well-being is influenced by maternal obstructive sleep apnea. Although the number of polysomnographic and survey studies regarding pregnant women's sleep has been increasing [3,5], no studies have been performed as to the relationship between pregnant women's sleep quality and fetal well-being.

Fetal movement is an important index to know fetal well-being. Mothers are instructed to visit a hospital when they feel a decrease in fetal movement. However, maternal perception of fetal movement is subjective. In 1933, Sontag et al. made an attempt to objectively record fetal movement using tambours [9]. Since then, various sensors were developed in order to record fetal movement objectively, such as an electromagnetic device, [10], an electro-pressure sensitive sensor [11], a piezosensor [12], an impedance device [13], and an ultrasonic Doppler device [14,15]. Many clinicians and researchers have contributed to developing methodologies of recording using the Doppler device [14–16]. Detecting fetal movement and fetal heart rate with the Doppler device is now commonly known as the Non Stress Test, and its clinical contribution has been great. However, a long-term monitoring system, especially for use at home, has not been established. Patrick et al. studied the relationship between fetal movement and maternal heart rate over 24 h using an ultrasonic scanner with a long bed-rested mother [17]. That experimental condition was special and cannot be replicated clinically. If there were a convenient tool for recording fetal movement over the long-term at home, it would be useful for pregnant women with certain risk factors. There is little information about intrauterine fetal death occurring at home. A convenient tool would contribute to collecting useful information in high-risk cases.

About 40 years ago, Sterman tried to record fetal movement in pregnant women's abdomens using pressure sensitive electrodes during nocturnal sleep [11]. He simultaneously recorded fetal movement and pregnant women's polysomnograms but failed to find a relationship between fetal movement and maternal sleep EEGs, probably because the pressure sensitive electrodes had low sensitivity. In addition, maternal respiration might have been picked up as fetal movement. In order for fetal movement monitoring to be used for a diagnostic purpose, the sensor must have high sensitivity, and the method must exclude maternal artifacts. If these conditions are met, long-term monitoring will be possible.

Here, we employed a new electrostatic capacity sensor to detect acceleration of fetal movement. In the present study, we call our fetal movement recording system with a new sensor as FMAM, Fetal Movement Acceleration Measurement. We conducted two experiments, I and II. We confirmed in Experiment I a high agreement between subjective maternal markers and fetal movement recorded by our system. In Experiment II, we clearly showed that micro-arousals during pregnant women's sleep were evoked by fetal movement. We think this new fetal movement recording system will enable us to develop long-term fetal monitoring at home.

2. Experiment I

2.1. Methods

2.1.1. Sensor

We developed a small capacitive acceleration sensor (20 g, 2.8 cm in diameter). The sensor has two electrodes with electrostatic capacity, one of them is a movable diaphragm and the other is a fixed backplate. In order to detect acceleration of fetal movement, the diaphragm has a slight weight. Therefore, a change in acceleration appears as the amount of change ΔC in electrostatic capacity C between the diaphragm and the backplate arising from displacement of the diaphragm. The sensor has high output power, 700 mV at 0.1 G. Using the sensor through a biological-amplifier, we obtained higher sensitivity (more than one hundred times higher, 0.0001 G) than that obtained with the piezosensor commonly used in actigraphy. Piezosensor sensitivity is assumed to be 0.01 G or 0.05 G. The frequency response is from 5 to 200 Hz at −3 dB. The new sensor is entirely non-invasive.

2.1.2. Subjects

The subjects were paid volunteers living in Tokyo. Thirty-two pregnant women (mean 31.5 y, range 24–43 years, 6 primiparae and 26 multiparae) joined the study to check the sensitivity of the sensor during daytime. Their gestation weeks ranged from 19 to 39 weeks (median gestational age 34 weeks). All the mothers were healthy, with no history of hypertension, renal disease, diabetes, or sleep disorders, and all had a normal pregnancy before delivery. All the infants were healthy and had no neurological problems. All the mothers gave written informed consent before participating in the study. This study was approved by the ethical committee at the Tokyo Institute of Psychiatry (number 17–43).

2.1.3. Procedure

We analyzed the reliability of the FMAM. We studied the agreement between the fetal movement measured by the FMAM and subjective maternal evaluation of fetal movement. Pregnant women can recognize fetal movement as early as 20 weeks into gestation. Their subjective evaluation of fetal movement is used clinically as an index of fetal well-being. The subjects kept the sensors on their abdomens for one and a half hours during daytime. They were asked to lie down on a bed and press a button as a subjective marker when they felt fetal movement. The pregnant women's EEG, chin-EMG, EOG: left–right, respiration, ECG, the subjective markers, and fetal movement were simultaneously recorded using a Medilog 8-ch cassette tape recorder (Oxford Medical Ltd., Oxford). As the frequency response in the Medilog system was 0.5–30 Hz (−3 dB), its total response from the sensor was 5–30 Hz. In the

last part of the experiment, a movable digital polysomnograph (Polymate, TEAC Ltd, Tokyo), which is able to check ongoing signals, was used with five subjects. In the Polymate system, the sampling rate was 500 Hz/s, and the frequency response was 0.5–500 Hz. The total response from the sensor was 5–200 Hz. In the case of the Medilog recording system, we used the push-button of a calibrator. In the Polymate system, we made a hand-held button. We use the term FMAM regardless of the recorders, when we used the new sensor.

We instructed the women to relax and not to tense up too much. After we finished recording fetal movement, the mothers answered a questionnaire on types and occurrences of fetal movement compared with their usual occurrences. In order to record a wide range of fetal movement, two fetal movement sensors were fixed in place with double-sided tape. The first sensor was placed on the abdomen where the mothers strongly felt fetal movement, and the second sensor was placed where the mothers felt the next strongest movement.

Two subjects at 21 and 35 weeks of gestation were excluded from the data analyses for different reasons. The electrostatic capacity of the sensor for the subject at 35 weeks discharged, and the subject at 21 weeks apparently could not tell where her fetus moved most strongly, and she pushed the button only three times during 128 min.

We converted the number of subjective maternal markers from per recording time to per 1 h, because the recording time was different for each subject. Then, we calculated a level of significance for the number of subjective maternal markers using a one-way analysis of variance (ANOVA) in order to see any influence due to gestational weeks. The Scheffé test was used as a post-hoc test.

We used kappa statistics to calculate agreements between subjective maternal markers and the signals recorded by the sensor [18]. We evaluated one by one whether or not our recording system with the sensors picked up fetal movement when there were mothers' markers. The analysis was based on 10-second epochs. Since Cohen's kappa is influenced by the prevalence of occurrences of fetal movement, we adopted prevalence-adjusted bias-adjusted kappa (PABAK) tests [19]. We also calculated a level of significance for the agreements between them using a one-way ANOVA in order to see any influence of agreements coming from gestational weeks. Since fetal movement signals can occasionally be confused with maternal heartbeat, respiration, or body movement, we visually checked for such movement. We also excluded epochs while the mothers slept.

2.2. Results

Fig. 1 shows a polysomnogram taken with the Medilog recorder for one mother at 34 weeks of gestation. Channels 7 and 8 represent fetal movement, which was not affected by maternal respiration and heartbeat. The mother's indication of fetal movement is shown by the sine waves in channel 4. Fig. 2 shows a Polymate digital recorder polysomnogram of another pregnant woman at 29 weeks of gestation. There are two large fetal movement signals in channels 9–14. The markers by the mother in channel 6 correspond to the signals of fetal movement. Channels 9–11 were recorded with fetal movement sensor FM1, while channels 12–14 were recorded with FM2. The two sensors FM1 and FM2 were placed in different positions. In addition, the recording conditions were different in

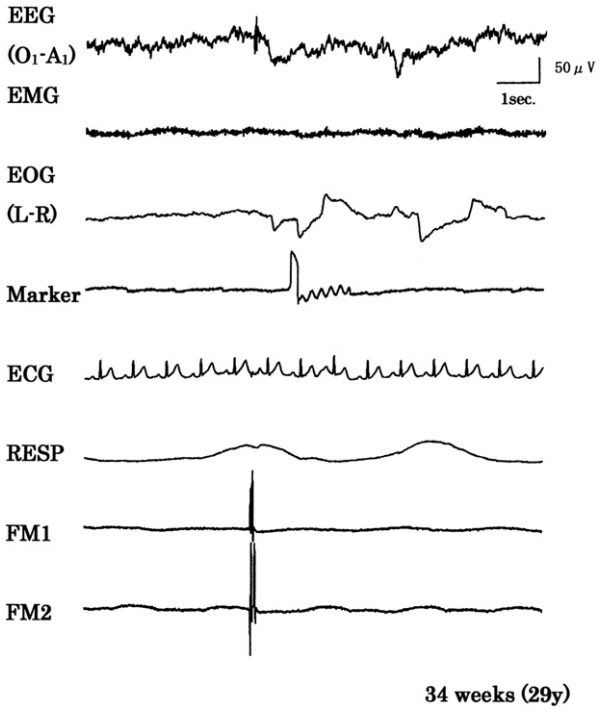

Figure 1 Fetal movement signals and subjective maternal markers using Medilog cassette tape recorder. Channel 1: Maternal EEG (O1-A1); Channel 2: Maternal EMG; Channel 3: Maternal EOG (Left–Right); Channel 4: Subjective maternal marker; Channel 5: Maternal ECG; Channel 6: Maternal respiration; Channel 7: Fetal movement; Channel 8: Fetal movement. The marker with sine waves by the mother (29 years, 34 weeks of gestation) in the fourth channel corresponds to the signal of fetal movement. The two sensors of fetal movement, Channels 7 and 8 were placed on the mother's abdomen around the location of the fetal legs. The FM2 sensor was placed where she mainly felt fetal movement, and the FM1 sensor was placed where she felt other strong movement.

frequency response and amplitude (see Fig. 2). The amplitude in channels 12–14 from sensor FM2 was larger than that in channels 9–11. The FM2 sensor was placed where the subject mainly felt fetal movement. Phonocardiograms are shown in channels 12–14.

Fig. 3 shows count values for subjective maternal markers of fetal movement for all the mothers in order of weeks of pregnancy (19–39). The count values of subjective maternal markers during 1 h had a significant difference in the different weeks of gestation ($F(12,17)=4.42$; $p<0.003$). The values at 29 weeks were significantly higher than those at weeks 35 and 37, as calculated using the Scheffé test.

The mean value of prevalence-adjusted bias-adjusted kappa (PABAK) in the agreement between subjective maternal markers and the signals recorded by FMAM was substantial at 0.75 ± 0.10. There were no significant differences on PABAK values for the subjects through the gestational weeks from 19 to 39 weeks ($F(12,17)=1.302$, $p<0.301$). The mean percentage of the agreement between subjective maternal markers and the signals recorded based on 10-second epochs was $87.7 \pm 4.7\%$ for all recording epochs. The mean percentage of epochs of disagreement was 12.3%, made up as follows: 8.5% of total recording epochs were epochs with signals recorded but

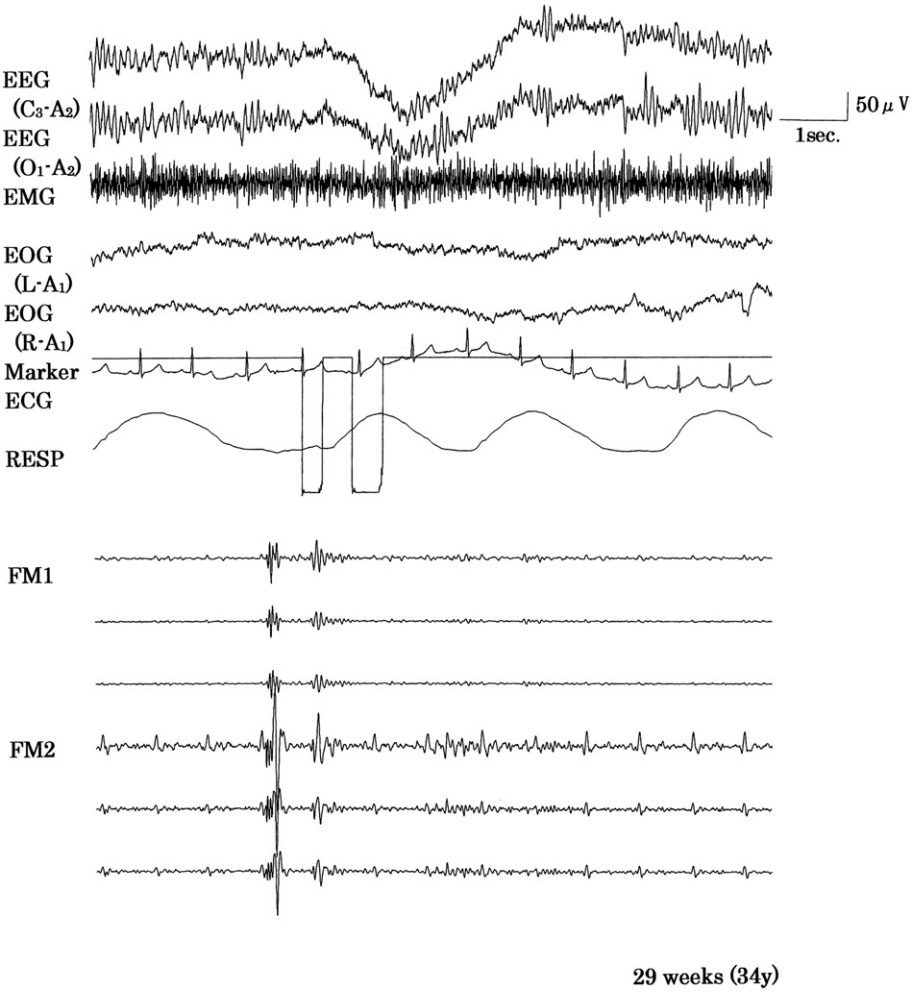

Figure 2 Fetal movement signals and subjective maternal markers using Polymate movable digital recorder. Channels 1 and 2: Maternal EEG (C3-A2, O1-A2); Channel 3: Maternal EMG; Channels 4 and 5: Maternal EOG (Left-A1, Right-A1); Channel 6: Subjective maternal markers; Channel 7: Maternal ECG; Channel 8: Maternal respiration; Channels 9, 10, and 11; Fetal movement (FM1); Channels 12, 13 and 14; Fetal movement (FM2). The markers by the mother (34 years, 29 weeks of gestation) in the sixth channel correspond to the signals of fetal movement. The two markers of square waves mean she felt fetal movement twice. The two sensors of fetal movement, Channels 9–11 and Channels 12–14, were placed on the mother's abdomen around the location of the fetal legs. The FM2 sensor was placed where she mainly felt fetal movement (Channels 12–14), and the FM1 sensor was placed where she felt other strong movement (Channels 9–11). In Polymate system, sampling rate was 500 Hz/s. Its frequency response from the sensor was 5–200 Hz in Channels 9 and 12, 15–100 Hz in Channels 10 and 13, and 15–30 Hz in Channels 11 and 14.

without subjective maternal markers; 3.8% were subjective maternal markers without the signals recorded.

Fetal hiccup movements are repeated movements at intervals of 2–3 s and continuing for several minutes [20]. Hiccup movements appeared in three of the subjects during recording time.

3. Experiment II

3.1. Methods

3.1.1. Sensor

We used the same sensor as in Experiment I.

3.1.2. Subjects

Seven subjects (mean 31.3 y, range 27–38 years, six primiparae and one multipara) participated in nocturnal recordings in both weeks 33 and 36 of gestation. The other conditions regarding the subjects were the same as in Experiment I.

3.1.3. Procedures

We used the new sensor for all-night recording. Maternal polysomnographic recordings (EEGs, chin-EMG, EOG: left–right, ECG and respiration) were made with a Medilog recorder at home. Two channels of fetal movements were simultaneously recorded using the new sensors. We placed the sensors in the same position as in Experiment I.

A micro-arousal was defined according to the criteria proposed by the American Sleep Disorders Association [21]. In short, micro-arousals were identified by an EEG frequency shift from more than 10 continuous seconds of sleep to more than 3 s of alpha and/or beta wave activity of arousal. We visually counted the number of micro-arousals evoked by fetal movement from sleep onset to final awakening in the morning

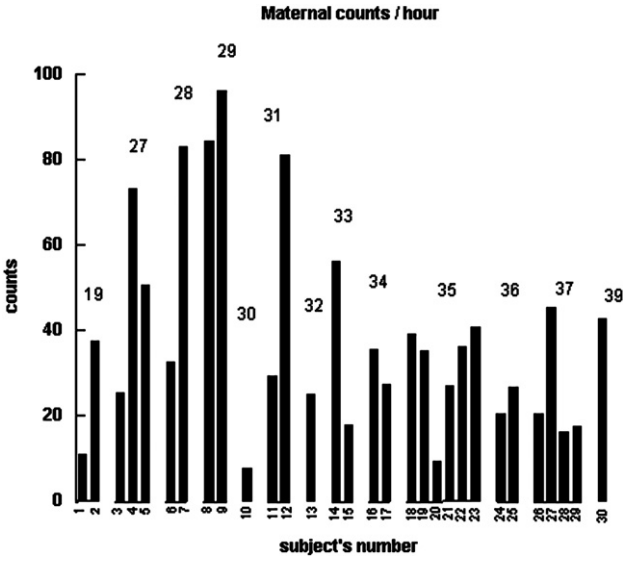

Figure 3 The count values of subjective maternal markers for fetal movement per hour. The count values exclude hiccup movements. The subjects are in order of gestational weeks with the number of weeks shown above the bar. There are no subjects from 20 to 26 and 38 weeks.

at weeks 33 and 36. After that, we compared the mean value in number of micro-arousals during the whole night at 33 weeks with that at 36 weeks using a paired *t*-test.

The mothers' sleep stages were visually scored minute by minute according to the criteria of Rechtschaffen and Kales [22].

3.2. Results

We were able to reliably record fetal movement through the night simultaneously with the pregnant women's polysomonograms, and we succeeded in recording maternal micro-arousals evoked by fetal movement. Fig. 4 shows an example of a typical micro-arousal. The pregnant woman, at 36 weeks of gestation, was in stage 2 sleep prior to fetal movement. Her EEG began to show alpha activity with slow eye movement and increased EMG activity when her fetus moved at FM1 and FM2. After her fetus stopped moving, she returned to stage 2 sleep.

Fig. 5 shows a typical diagram of maternal sleep stage, number of micro-arousals per minute, and fetal movement in a pregnant woman at 33 weeks of gestation. Since it is difficult to count fetal movements, an analog signal of fetal movement is represented as a compressed figure on a chart made at a slow speed and on a replay recorder made at a fast speed. Fetal hiccups (F-H) were observed before 2:00 AM and around 7:30 AM. Maternal gross movement (M-M), maternal heartbeats (M-H) and maternal respiration (M-R) were picked up as artifacts in the fetal movement channels depending on maternal body position. However, since we simultaneously recorded maternal EEGs, EMG, ECG and respiration, we could distinguish between maternal signals and fetal movement. At maternal wakefulness, around 3:20, 5:10, and 7:10, maternal gross movements were observed. During maternal REM sleep around 6:30, fetal movement signals included maternal respiration. In Fig. 5, there were short durations of maternal respiration and heartbearts that are not explained in the figure.

The mean value of the number of micro-arousals during night sleep at 33 weeks (72.4 ± 19.0) was slightly larger than that at 36 weeks (62.0 ± 18.8), but there was not a significant difference ($t = 1.445$, $df = 6$, $p < 0.199$). Micro-arousals evoked by fetal movement were observed in all the subjects, though not every fetal movement evoked a micro-arousal.

In the present study, the hiccup movements of fetuses were seen in five of the seven pregnant women and occurred once or twice each night. The total number of hiccup movements for the five subjects during both 33 and 36 weeks was 13. They were distributed throughout maternal sleep stages 2–4, REM sleep and wakefulness (stage 1:0, stage 2:5, stage

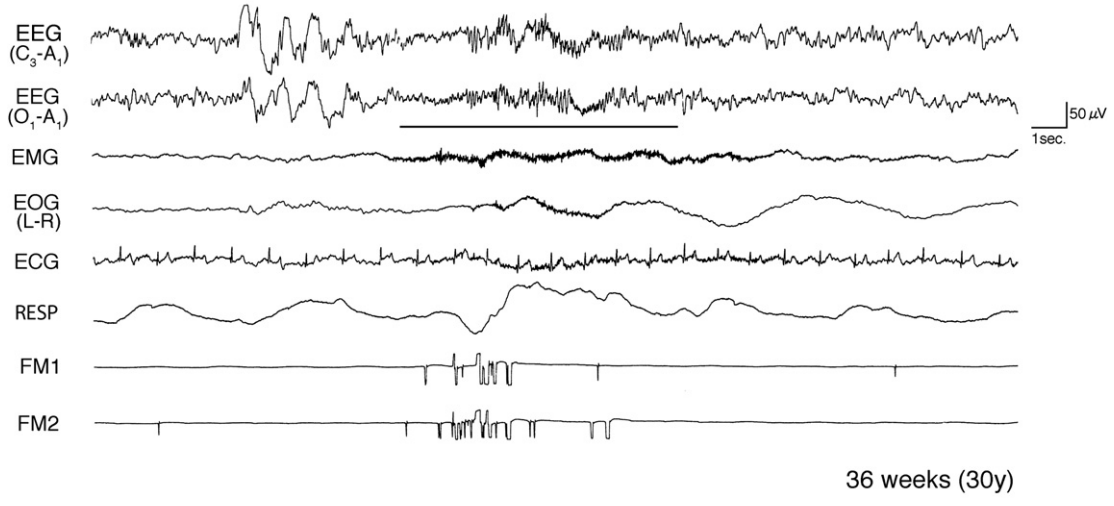

Figure 4 Maternal micro-arousals (at center) evoked by fetal movement during maternal sleep (see text). Channel 1: EEG C3-A1; Channel 2: EEG O1-A1; Channel 3: EMG; Channel 4: EOG left–right; Channel 5: ECG; Channel 6: respiration; Channel 7: Fetal movement (FM1); Channel 8: Fetal movement (FM2). The EEG section with the underline indicates maternal micro-arousal (mother: 30 years, 36 weeks of gestation.).

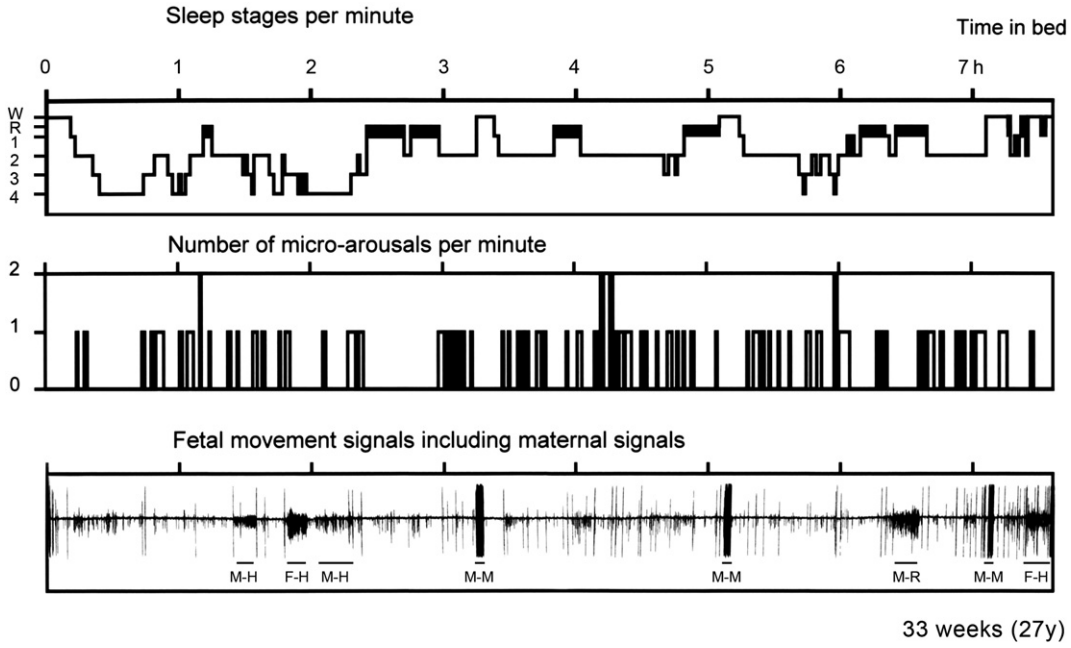

Figure 5 A typical all-night record of maternal sleep stage, maternal micro-arousal count per minute, and fetal movement at 33 weeks of gestation (pregnant woman: 27 years). The X axis indicates time (hours) after going to bed at 0:00. Maternal sleep stages are wake, REM, stages 1, 2, 3 and 4 from top to bottom. The black parts show REM sleep. Sleep stages 1, 2, 3 and 4 during Non REM sleep show depth of sleep. Maternal micro-arousals were counted once (short line) or twice (long line) per minute. Since it is difficult to count fetal movements, a compressed analog signal of fetal movement is represented. The fetal movement graph includes maternal gross movement (M-M), maternal heartbeats (M-H), and maternal respiration (M-R) depending on maternal body position. F-H means fetal hiccup movement. At maternal stage wake, around 3:20, 5:10, and 7:10, maternal gross movements are observed. During maternal REM sleep around 6:30, fetal movement signals include maternal respiration as an artifact.

3:3, stage 4:2, REM sleep:1, wakefulness:2). The mean hiccup movement duration was 6.2 min.

4. Discussion

4.1. Experiment I

Figs. 1 and 2 show fetal movement signals followed by maternal markers. There was a high agreement regardless of the recorders used. The agreement of PABAK, based on a 10-sec epoch, was 0.75, which is substantial from Landis's suggestion on kappa value [23]. These results mean that actual fetal movement signals recorded by the FMAM from pregnant women's abdomens are similar to subjective maternal evaluation. A previous study of maternal perception of fetal movement and ultrasound imaging has reported that most pregnant women are consistent and accurate in their perception of major fetal movement, despite a few women who were inconsistent and one who was completely unaware of major fetal movement [24]. This study suggests that PABAK values would naturally include maternal perception differences. The percentage of agreement based on time between maternal markers and the signals of FMAM was 87.7%, and the disagreement was 12.3%. The percentage of recorded epochs without subjective maternal markers to total epochs (8.5%) was larger than that for subjective maternal markers without signals recorded (3.8%). That meant that the FMAM was more sensitive than subjective maternal evaluation. Indeed, we often noticed cases in which the mothers did not press the button, but we found the signals recorded using the ongoing Polymate recorder. If a fetus moves quickly for a short time, a mother might not be convinced of fetal movement. In that case, our FMAM could detect her fetal movement. Johnson et al. reported that when using a Doppler device, maternal perception is related to the duration of fetal movement [25]. On the other hand, when a fetus continues moving slowly for a longer duration, a mother can feel her fetal movement. In that case, output levels from the FMAM would be small and would not clearly detect movement, because the sensor detects acceleration of fetal movement. There are several kinds of fetal movement that can be recorded from a pregnant woman's abdomen using an ultrasonic cardiotocograph: rolling, kicking, fetal breathing, hiccup movements, and others [16,26]. We were able to record strong rolling movements, kicking movements, and hiccup movements as seen in the subjective maternal markers and in the evaluations in the questionnaire. It is unknown whether we would be able to detect a small and slow rolling or fetal breathing movement. To simultaneously record ultrasound imaging and the FMAM would answer the above questions, and we are now preparing just such a recording.

Recording fetal movement using an ultrasonic Doppler device is common now. DiPietro et al. reported a high agreement on fetal movement using both ultrasound imaging and a Doppler actocardiograph from 20 weeks to 39 weeks of gestation [18]. They obtained a high agreement, kappa 0.88, based on 10-second epochs. However, they also reported that, for 35–39 weeks of gestation, there was an increased

percentage of fetal movement on the actograph in disagreement. Ultrasound imaging detected that movement had decreased, as compared with gestation of 20–25 and 28–32 weeks. Two reasons were implied in the discussion. The first reason was that, at 35–39 weeks of gestation, the fetus was not totally pictured in the ultrasound imaging. The second was that maternal respiration and/or other maternal signals from their large abdomens might have been included in the increase of recorded signals in the actocardiograms. In short, an ultrasonic Doppler device is highly sensitive, and it easily records other signals besides fetal movement. As our sensor has a slight weight and is small, if we pay attention to where we put it on the maternal abdomen, we can minimize the recording of respiration artifacts. The new sensor not only gets a high output, but also excludes high frequency signals arising from mothers. In our present study, there were no differences on PABAK from 19 weeks to 39 weeks of gestation. That means our FMAM can record from the beginning, when pregnant women first feel fetal movement.

In our study, there was a significant difference in the number of subjective maternal markers through the weeks of gestation, as shown in Fig. 3. The number at 29 weeks of gestation was significantly higher than those at weeks 35 and 37. According to a 4D ultrasound study, independent movement of extremities to all parts of the uterus was observed during 26–32 weeks of gestation, and during 37–38 weeks, the frequency of fetal movement decreased [27]. Another study reported that the number of spontaneous fetal movements tends to increase until 32 weeks, and then begins to decrease [28]. Our results agree with previous studies [27,28]. Since the recording time of fetal movement in previous studies and in our Experiment I was short, the frequency of fetal movement included the differences of both fetal development and experimental conditions. Thus, it is necessary to record fetal movement over the long-term.

4.2. Experiment II

In Experiment I, we focused on the high agreement between the signals recorded by the FMAM and maternal perception of fetal movement. Here, we objectively demonstrated that micro-arousals during maternal sleep were evidence of real fetal movement. Micro-arousals were identified by an EEG frequency having more than 3 s of alpha and/or beta wave activity of arousal during sleep. We succeeded in recording micro-arousals evoked by fetal movement, as shown in Fig. 4. Since the uterus is innervated by the afferent somato-sensory nerve, maternal micro-arousals are in part a manifestation of maternal response to fetal movement stimulus. Micro-arousals related to fetal movement are represented as EEG activity as a result of thalamocortical circuit modification [29]. We counted the number of micro-arousals evoked by fetal movement during night at both weeks 33 and 36 of gestation. The mean of the number of micro-arousals at 33 weeks was slightly larger than that at 36 weeks. As the number of mothers' nocturnal polysomnograms was small, there was not a significant difference between the two weeks. However, as shown in Fig. 3, when we collected a number of samples, we could see a significantly large number of micro-arousals at 33 weeks compared with 36 weeks. The number of micro-arousals seemed to be influenced by the number of fetal movements with a gestational week variation. The existence of micro-arousals evoked by fetal movements means a strong maternal–fetal relationship.

Sterman et al. attempted to record both pregnant women's sleep EEG and fetal movement using a pressure sensitive sensor. They initially reported that fetal movement increased during maternal REM sleep [11]. But, 11 years later, they could not demonstrate a relationship between mother and fetus [30]. Their sensor seemed to have low sensitivity. In addition, they did not examine the relationship between fetal movement signals and maternal respiration. In their study, maternal respiration signals during REM sleep were in all likelihood recorded as fetal movement, for example around 6:30 AM in Fig. 5, because the respiration rate during REM is irregular. Additionally, their sensor was so big (2.5 in.) that it easily picked up maternal respiration. Our sensor was smaller than theirs and had a higher sensitivity. Since we simultaneously recorded maternal respiration, we were able to discriminate between maternal respiration and fetal movement. As hiccup movements are characteristic and periodic signals, it is easy to find them with our system. Sterman et al. also reported there were no hiccup movements during slow wave sleep for pregnant women [11]. But, in our data, we observed hiccup movements in each sleep stage and during wakefulness, as shown in Fig. 5. Fetal hiccup movements were not influenced by maternal sleep and wakeful behavior. It has been reported that hiccup movements are diaphragmatic movements before 26 weeks of gestation and have a negative correlation with gestational age [31]. They occur predominantly during active episodes in fetuses and suggest a relationship with fetal development. However, their pathophysiological significance is still unclear. A long-term monitoring study would contribute to our understanding.

Long-term recordings of fetal movement would be useful to check fetal well-being. In general, fetal movement is thought to be an index of fetal health conditions. Although the clinical significance of a decrease in fetal movement is controversial [32], a sudden decrease in fetal movement has been reported for fetuses in serious trouble, including intrauterine fetal death [33]. Our method is entirely non-invasive and can be used at home for the long-term monitoring of pregnant women with high-risk pregnancies. Recently, one paper reported that fetal movement decreased during maternal sleep in preeclampsia, though detailed methods are unknown due to the abstract form of the report [34]. Our FMAM would be useful for recording fetal movement in preeclampsia.

Our FMAM can also be used to evaluate how sleep disorders such as obstructive sleep apnea in pregnancy stress the fetus. Indeed, one case report has suggested the possibility of significant changes in fetal heart rate during maternal snoring [35]. Some studies of late pregnancy reported that PaO2 and SpO2 during pregnant women's sleep were lower than those during non-pregnant women's sleep [7,36]. Fetal movement is unclear under maternal hypoxemia. To simultaneously record maternal sleep with sleep-disordered breathing and fetal movement would be necessary.

The existence of micro-arousal evoked by fetal movement opens the door to maternal–fetal relationship study. Recently, a psychophysiological study of maternal–fetal relationship that used an ultrasound system was reported [37]. The recording time of the ultrasound studies was a short period, and the authors did not record maternal EEGs, so their results were unclear. But, there was a positive correlation between

胎儿运动的长期记录有助于检查胎儿的健康状况。一般来说，胎儿运动被认为是胎儿健康状况的一个指标。虽然胎儿运动减少的临床意义有争议[32]，但胎儿运动突然减少已被报道在胎儿严重问题，包括宫内胎儿死亡[33]。我们的方法是完全无创的，可以在家里长期监测高危妊娠的孕妇。最近有一篇文章报道了子痫前期产妇睡眠期间胎动减少，但由于报道形式抽象[34]，具体方法尚不清楚。我们的FMAM将有助于记录子痫前期的胎儿运动。

综上所述，这是首个显示孕妇夜间睡眠时胎儿运动明显引起孕妇脑电图微唤醒的报告。主观的母亲标记物和胎儿运动记录的FMAM之间有很高的一致性。因此，FMAM记录的胎儿运动被证实为真实的胎儿运动。这一证据为胎儿健康、孕妇睡障碍以及母亲和胎儿关系的长期研究打开了大门。使用FMAM的记录方法是完全无创的，可以反复用于家庭监测胎儿运动

maternal skin conductance and fetal movement. Our FMAM would be useful to more closely observe the maternal–fetal relationship.

In conclusion, this is the first report showing that fetal movement during maternal nocturnal sleep clearly evoked micro-arousals on pregnant women's EEGs. There was a high agreement between subjective maternal markers and fetal movement recorded by the FMAM. Thus, the fetal movement recorded by the FMAM was confirmed as actual fetal movement. This evidence opens the door to long-term studies of fetal well-being, pregnant women's sleep disturbance, and the relationship between mother and fetus. The recording method using the FMAM is entirely non-invasive and can be used repeatedly for home monitoring of fetal movement.

Conflict of interest statement

This was not an industry-supported study. Drs. Nishihara, Horiuchi, Eto, and Honda have indicated no financial conflicts of interest.

Acknowledgements

This study was supported in part by a Grant-in-Aid for Scientific Research (C13671041, C17605013), provided by the Ministry of Education, Science and Culture of Japan. The authors thank Ms. A. Ishimura at her midwife clinic for helping us to recruit pregnant women. We also appreciate the cooperation of the women who joined our experiments.

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