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A computer-aided approach to detect the fetal behavioral states using multi-sensor Magnetocardiographic recordings

S. Vairavan [a,1], U.D. Ulusar [b], H. Eswaran [c,d], H. Preissl [d,e], J.D. Wilson [a], S.S Mckelvey [c], C.L. Lowery [c], R.B. Govindan [f,*]

[a] Graduate Institute of Technology, University of Arkansas at Little Rock, AR, USA
[b] Computer Engineering Department, Akdeniz University, Antalya, Turkey
[c] Department of Obstetrics and Gynecology, University of Arkansas for Medical Sciences, AR, USA
[d] Division of Biomedical Informatics, University of Arkansas for Medical Sciences, AR, USA
[e] MEG Center, University of Tubingen, Tubingen, Germany
[f] Division of Fetal and Transitional Medicine, Fetal Medicine Institute, Children's National Health System, 111 Michigan Ave, NW Washington, DC 20010, USA

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ABSTRACT

We propose a novel computational approach to automatically identify the fetal heart rate patterns (fHRPs), which are reflective of sleep/awake states. By combining these patterns with presence or absence of movements, a fetal behavioral state (fBS) was determined. The expert scores were used as the gold standard and objective thresholds for the detection procedure were obtained using Receiver Operating Characteristics (ROC) analysis. To assess the performance, intraclass correlation was computed between the proposed approach and the mutually agreed expert scores. The detected fHRPs were then associated to their corresponding fBS based on the fetal movement obtained from fetal magnetocardiogaphic (fMCG) signals. This approach may aid clinicians in objectively assessing the fBS and monitoring fetal wellbeing.

1. Introduction

Existence of behavioral states in human fetuses was reported for the first time in 1982 by Nijhuis et al. [1]. The Cardiotcograph (CTG), which is a real-time ultrasound, has been used to study fetal heart rate patterns (fHRPs). Fetal heart rate has been classified into four different patterns: 1F – characterized by a stable heart rate with small oscillation bandwidth of less than 5 beats per minute (bpm); 2F – characterized by a varying heart rate with frequency acceleration and decelerations over 10 bpm from the baseline with wider oscillation bandwidth greater than 5 bpm; 3F – characterized by a stable heart rate with no accelerations with oscillation bandwidth greater than 5 bpm; 4F – characterized by highly irregular heart rate (seemingly tachycardic) with frequent long lasting and large accelerations from the baseline with a wider oscillation. Nijhuis defined the fetal behavioral states (fBS) based on the temporal coincidence of the HRPs, fetal gross body movement (GBM) and eye movement (EM) observed for a 3-min window duration using the criteria mentioned in Table 1. Since then several studies have evidenced the importance of this finding in the determination of fetal wellbeing [2] and as indices of developmental aspects of fetal autonomic nervous system (ANS) [3].

The majority of these findings have been reported based on behavioral states observed from Doppler ultrasound CTG recordings. With the advent of SQUID (Superconducting Quantum Interference) technology, Fetal Magnetocardiography (fMCG) is now shown to be a feasible technique in the studying fetal heart dynamics [4–10]. The inherent advantage of fMCG is its superiority in acquiring fetal cardiac signals with high spatial and temporal resolution which in turn enhances the temporal analysis of fetal heart-rate. In addition, the spatial distribution of the SQUID sensors allows one to track the fetal movement as the sensors in the close proximity of the fetal position will have higher QRS amplitude compared to the neighboring sensors [11]. The magnetic signal corresponding to the fetal eye movement is unknown. However, Maeda et al. [12] reported that the inability to record the fetal eye movement does not preclude the proper assignment of fBS. They concluded as the states 1F, 2F, and 4F can be identified based on the variability in the HR and fetal movement, state 3F can be detected based on the lack of accelerations observed in the HR (Table 1). Hence it is possible to detect the fBS based on the parameters such as HR and fetal movement obtained from fMCG recordings. In a recent study fBS were found to be relevant for the

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* Corresponding author. Tel.: +1 202 476 5309.
E-mail address: rgovinda@childrensnational.org (R.B. Govindan).

[1] Present address: Currently with Proteus Digital Health, Inc., Redwood City, CA, USA.

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Table 1
Nijhuis definition for the heart-rate patterns and their associated behavioral states [1]. EM, GBM and HRP being eye movement, gross body movement and heart rate pattern, respectively.

Behavioral state	EM	GBM	HRP
Quiet Sleep (1F)	No	Incidental	A
Active Sleep (2F)	Yes	Periodic	B
Quiet Awake (3F)	Yes	Absent	C
Active Awake (4F)	Yes	Continuous	D

fetal brain function as auditory evoked brain responses emerge earlier in active states compared to passive states [13]. Thus the investigation of fBS seems to be relevant for the monitoring of fetal brain development and is important for the clinical interpretation of fetal Magenetoencephalogram results. However, an automated approach to characterize fBS is not available. To fill this void, in this work we propose a computer-aided approach based on linear de-trending procedure for an automated detection of fBS based on the patterns observed in HR and fetal movements obtained from fMCG. Two experts independently reviewed and scored the fMCG recordings for fHRPs and these expert scores were used as gold standard. The fHRPs were detected using the linear de-trending approach and thresholds used for the detection procedure were obtained using Receiver Operating Characteristics (ROC) analysis. The episodes of significant fetal movement and HR acceleration were marked in an objective manner and were used to associate the fHRPs to their corresponding fBS [14].

2. Materials and methods

2.1. Subject and data collection

A novel 151 SQUID array system, a device of its kind, was used to collect fMCG recordings. A total of 62 fMCG recordings were collected between 30 and 38 weeks of gestation from 39 pregnant women. All of them delivered healthy singleton neonates at term. This study was approved by the University of Arkansas for Medical Sciences (UAMS) Institutional Review Board and all mothers gave a written informed consent to participate in the study. Duration of the study varied between 6 and 30 min depending on maternal comfort. The fMCG data were sampled at a rate of 312.5 Hz. This retrospective study included a total of 62 recordings of which 40 were used for the training purpose and the remainder 22 recordings were used for the testing purpose. Among the 39 fetuses, 27 of them were delivered in UAMS. A detailed description of the recordings including gestational age (GA) in weeks at study (at the time of fMCG recording) and APGAR scores (1st and 5th min after birth) of the infants delivered at UAMS are shown in Table 2 for the training and testing recordings, respectively. The gestational age (GA) represents the age of the fetus in weeks calculated from the last menstrual cycle to the time of the study. All the infants had a "live birth" outcome. We lost follow-up of the rest of infants that were delivered at other centers.

2.2. Data analysis

The data were band-pass filtered between 1 and 50 Hz using the Butterworth filter with zero-phase distortion and the interfering maternal cardiac signal was attenuated using the signal space projection technique [15]. The signal space projection technique was developed in-house to attenuate the cardiac signals to study the fetal brain signals. In this approach the maternal R-wave was identified using adaptive Hilbert transform [16]. Mean maternal HR was calculated and samples corresponding to 40% maternal HR before R and sample corresponding to 60% of maternal HR after R were selected. The maternal cardiac cycles were averaged over all identified R waves. This procedure was carried out on all of the channels. The resulting averaged cardiac cycle was used to determine the signal space vectors corresponding to mMCG. The largest vector was identified from mMCG and this was projected out using Gram–Schmidt orthonormalization procedure. This procedure was repeated on the residual and the next signal space vector was selected and projected out. The procedure was stopped if the root mean square of the residue drops below a prefixed tolerance which was set to 350 femto Tesla. Typically, the procedure stops within 10 steps. We denote the signal space vectors identified in each step as $v_1, v_2,.., v_n$ and construct matrix V whose columns are v_i. V is a $m \times n$ matrix where 'm' is the number of sensors. Using V the projection operator P was constructed as: $P = I - (V^T V)^{-1} V^T$, where I is the identify matrix and 'T' being the matrix transpose. These vectors were projected out of the data matrix by multiplying data matrix with P. The resulting fMCG was used for further processing.

Table 2
Clinical data of the subgroup fetuses delivered at UAMS.

Subject ID	GA at study	APGAR	Weight	Delivery type	Gender
Training recordings					
1	34		7lb 5oz	Vaginal	F
3	37		7lb 6oz	Cesarean	F
4	33	9, 9	6lb 12oz	Vaginal	F
5	32	7, 9	7lb 3oz	Cesarean	F
7	34		9lb 5oz	Cesarean	M
10	36		7lb 10.5oz	Cesarean	M
13	37	7	7lb 8oz	Cesarean	F
15	32	9, 9	8lb 9oz	Cesarean	M
16	35		8lb 1oz	Vaginal	F
18	36		7lb 12oz	Cesarean	F
19	32	8, 9	9lb 4oz	Vaginal	M
22	32		8lb 8oz	Cesarean	M
23	32		5lb 10oz	Cesarean	M
25	36	8, 5	6lb 8oz	Vaginal	F
30	36	8,9	5lb 11oz	Vaginal	F
37	37		7lb 13oz	Vaginal	M
40	32		7lb 7oz	Vaginal	F
Testing recordings					
41	31	8	7lb 14oz	Cesarean	M
43	32	5, 8	7lb 13oz	Vaginal	F
46	35		7lb 2.5oz	Vaginal	M
47	34		7lb 2oz	Vaginal	M
48	34	7, 8	10lb 6oz	Cesarean	M
49	30		7lb 9oz	Cesarean	F
57	35		8lb	Vaginal	F
59	36	9, 10	9lb 4oz	Vaginal	M
60	36	8, 9	6lb 3oz	Cesarean	F
62	36	8, 9	6lb 3oz	Cesarean	M

The GA represents to the age of the fetus at study.
For 11 fetuses, the APGAR scores measured at 1st and 5th min after birth are given in 3rd column. For two fetuses, only one APGAR score measured at 1st min after birth was available.

The fetal R-waves were calculated using the Hilbert transform approach [17] and was followed by an adaptive scheme to correct for the missed and extra beats [18]. A more detailed description of the fetal R-wave detection can be found elsewhere [14].

By denoting τ_j as the time of occurrence of the jth R-wave, we compute the HR (in beats per minute [bpm]) at this instance as follows: $60/(\tau_j - \tau_{j-1})$, where the unit of τ is in seconds. In order to detect the fetal movement, at each R-wave we compute the center of gravity (**cog**) of the fetal heart vectors as the weighted average of the magnitude of the R-wave and the coordinate position of the sensor. To this end, we define the actogram (expressed in cm) (fetal movement) as, the distance between the **cog** computed at each R-wave and the average of **cog** from all the R-waves in a three