OBSTETRICS

Clinically accurate fetal ECG parameters acquired from maternal abdominal sensors

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OBJECTIVE: We sought to evaluate the accuracy of a novel system for measuring fetal heart rate (FHR) and ST-segment changes using noninvasive electrodes on the maternal abdomen.

STUDY DESIGN: Fetal electrocardiograms were recorded using abdominal sensors from 32 term laboring women who had a fetal scalp electrode (FSE) placed for a clinical indication.

RESULTS: Good-quality data for FHR estimation were available in 91.2% of the FSE segments and 89.9% of the abdominal electrode segments. The root mean square error between the FHR data calculated by both methods over all processed segments was 0.36 beats per minute. ST deviation from the isoelectric point ranged from 0–14.2% of R-wave amplitude. The root mean square error between the ST change calculated by both methods averaged over all processed segments was 3.2%.

CONCLUSION: FHR and ST change acquired from the maternal abdomen is highly accurate and, on average, is clinically indistinguishable from FHR and ST change calculated using FSE data.

Key words: fetal electrocardiogram, fetal monitoring, labor

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Continuous fetal heart rate (FHR) monitoring during labor is utilized in >85% of labor episodes in the United States and represents the standard of care,[1] although there is scant evidence to demonstrate that the use of the technology improves newborn or maternal outcomes.[2] Encouraging data demonstrate that intrapartum fetal electrocardiogram (fECG) analysis can reduce newborn acidemia, hypoxic ischemic encephalopathy,[3] and cesarean deliveries.[4] However, the only clinically available device for fECG analysis—the STAN monitor from Neoventa (Moindal, Sweden)—requires an invasive fetal scalp electrode (FSE), limiting its use to a subset of pregnant women who are laboring with ruptured membranes and a dilated cervix.

The potential utility of noninvasive fECG for fetal evaluation is significant. However, to date, there has been no systematic study proving that fECG can be extracted noninvasively without distorting important clinical parameters, such as the ST segment. Prior reports have shown the capacity to measure FHR using electrodes on the maternal abdomen, but none have demonstrated the capacity to accurately record the fECG waveform with sufficient fidelity to evaluate the morphology.[5] Recently, we developed a novel real-time signal processing approach for extracting fECG that mitigates many of the issues involved in extracting an accurate and clinically relevant electrocardiogram (ECG). This study evaluates the performance of our technique in extracting FHR variations and ST levels from laboring patients and compares them to invasive scalp electrode data.

MATERIALS AND METHODS

We recorded data from 32 term laboring women who had an FSE placed for a clinical indication and consented to participate in this study. Enrollment occurred sequentially, and there were no exclusion criteria. The study was conducted during the first and second stages of labor. Demographic information about the studied subjects is summarized in the Table.

Data were recorded using an E-TROLZ (North Andover, MA) physiologic monitoring platform, which samples 32 channels at 1 kHz. Standard gel-adhesive ECG electrodes (Red-Dot; 3M, St. Paul, MN) were used in a standard configuration developed to maximize the chances of having electrodes adjacent to the fetal heart. The general configuration of the abdominal

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TABLE
Demographic data of studied subjects

Demographics (n = 32)	Median	Range
Maternal age at delivery, y	32	19–40
Gestational age at delivery, wk	40	35–41
Nonwhite mother, %	41	
Multiparous, %	47	
Birthweight, g	3459	1840–4110
Female baby, %	50	
1-min Apgar score	8	2–9
5-min Apgar score	9	8–9
Body mass index	30.4	21.7–45.1
Epidural during study, %	97	
Pushing during study, %	9.4	

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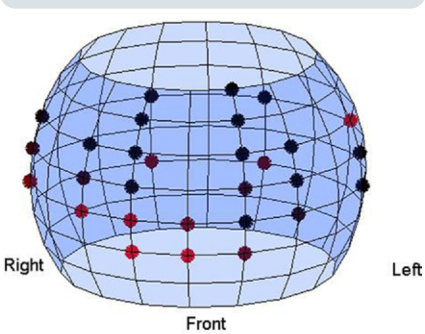
electrodes is illustrated in Figure 1. Electrodes were placed based on anatomic landmarks (the umbilicus, xyphoid process, pubic symphysis, axilla, and spine are used to locate electrodes), and as a consequence, the distance between electrodes varied with the maternal abdominal girth. The number of electrodes was

FIGURE 1
Abdominal electrode location



Locations of abdominal electrodes and corresponding signal quality on each electrode (*red* = high, *black* = low).

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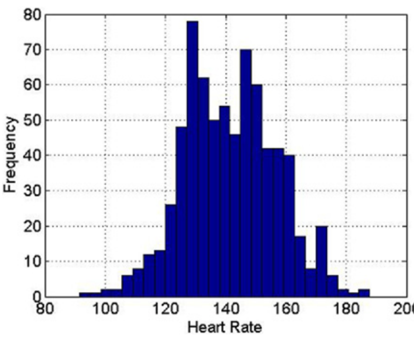
arbitrarily chosen based on the capacity of the recording device, and allows for excellent coverage of the maternal abdomen, sides, and back. The specific location of the electrodes is unimportant, as the analysis is done based on the physiologic signal alone, without consideration to the location of each electrode. No patient skin preparation was done prior to electrode placement. Both the abdominal ECG data and the scalp ECG were preprocessed for removal of interference from maternal ECG (mECG), as well as power line contamination and other sources of background electrical noise, including maternal muscle artifact.

Our fetal extraction method was then applied to the abdominal data. For the extracted and filtered abdominal data, each beat was located using a standard QRS detector.[6] Each beat was segmented ±20 milliseconds around the fiducial point (R-peak). FHR was calculated from the reciprocal of the median RR interval scaled by a factor of 60. Median FHRs were calculated from 1012 10-second segments from the processed abdominal data and gold standard scalp fECG. Data were recorded for between 9–28 minutes from each subject, and we analyzed the first 10 seconds of every 30-second epoch of data for all 32 subjects. As a consequence, between 17–56 10-second segments were analyzed for each subject. Data were analyzed after delivery had occurred, and no research data were available to clinicians managing the subjects' labor.

We used a new method of extracting fECG from a mixture of mECG and fECG that uses a priori information concerning the cardiac signals, including their pseudoperiodic structure, to improve the performance of existing techniques and to design novel filtering techniques specific to fetal cardiac signal. By using a realistic model of an individual fetus' ECG,[7-9] which is tracked over time using a Kalman filter framework,[10] a low-distortion representation of the maternal beat could be extracted from the fECG/mECG mixture.[8-14] Although the Kalman filter and its extensions are now considered to be classic tools in the signal processing community, our approach involves customizing these techniques

FIGURE 2
Histogram of heart rates of studied fetal electrocardiograms



(1012 electrocardiograms segments used in histogram.)

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for fetal cardiac signals, to develop realistic dynamic models that are able to follow the temporal variations of the fECG in highly noisy environments. We have extended these frameworks and developed novel methods for tracking nonstationarities in both the noise and signal. Unlike other computational approaches, this method successfully cancels mECG, with minimal distortion (in the relevant clinical parameters) of the fECG.

The color coding in Figure 1 is an example that illustrates the signal quality from a given set of electrodes for 1 patient at a particular instant in time. The signal quality will vary across patients (and over time for a particular patient). This is often due to changes in maternal or fetal position and hence, not all sensors are used at any given point in time. However, it is difficult to predict which sensor locations are optimal in advance. We therefore, used an over-complete set of electrodes and a series of signal quality measures to determine automatically which sensors contribute most of the information at any given point in time.

Isoelectric levels and ST levels were estimated from a subset of 271 10-second segments from the same data. Adult ST analysis was performed on an average window, rather than on individual beats,[15-17] and therefore, an average beat was calculated for each 10-second segment for use as an analysis template. Each beat was also cross correlated with