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Original Article

Non-invasive fetal monitoring using electrocardiography and phonocardiography: A preliminary study

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ABSTRACT

Background. – Continuous fetal monitoring is commonly used during pregnancy and labor to assess fetal wellbeing. The most often used technology is cardiotocography (CTG), but this technique has major drawbacks in clinical use.
Objectives. – Our aim is to test a non-invasive multimodal technique of fetal monitoring using phonocardiography (PCG) and electrocardiography (ECG) and to evaluate its feasibility in clinical practice, by comparison with CTG.
Methods. – This prospective open label study took place in a French university hospital. PCG and ECG signals were recorded using abdominal and thoracic sensors from antepartum women during the second half of pregnancy, simultaneously with CTG recording. Signals were then processed to extract fetal PCG and ECG and estimate fetal heart rate (FHR).
Results. – A total of 9 sets of recordings were evaluated. Very accurate fetal ECG and fetal PCG signals were recorded, enabling us to obtain FHR for several subjects. The FHR calculated from ECG was highly correlated with the FHR from the CTG reference (from 74% to 84% of correlation).
Conclusion. – This work with preliminary signal processing algorithms proves the feasibility of the approach and constitutes the beginnings of a unique database that is needed to improve and validate the signal processing algorithms.

1. Introduction

The aim of intrapartum surveillance techniques focused on the assessment of fetal heart rate (FHR) is to determine when it is necessary to act quickly in order to avoid severe neonatal injury. Nowadays cardiotocography (CTG) is the most often used monitoring technique during labor. In France, according to the oversight authority, the "Haute Autorité de Santé", in 2002, CTG was used in 99% of cases. However, the literature is unequivocal: CTG continuous FHR monitoring has no impact on the long-term neonatal prognosis, but leads to an increased rate of caesarian section and instrumental deliveries. For lack of anything better, the French National College of Obstetricians and Gynecologists recommends continuous CTG FHR monitoring during labor [1,2]. However, in clinical practice, CTG monitoring has major drawbacks: not only can CTG traces suffer from high inter- and intra-observer variability in interpretation, but the FHR is also often confused with the maternal heart rate, especially during expulsive efforts. Signal losses are frequent, and even more so when the recording is performed at an early gestational age or when the woman has a high body mass index (BMI [3]).

Other monitoring techniques exist to assess fetal health. Scalp ECG, where a single scalp electrode is placed on the fetal scalp, is considered as gold standard [1]. Unfortunately, it has restrictive conditions of use: it can only be used when the cervix is dilated enough and the waters are broken.

These considerations highlight the necessity of developing new techniques which would combine the precision of scalp ECG and the safety and ease of use of CTG. The first non-invasive fetal ECG (fECG) was described by Cremer at the beginning of the 20th century [4]. This technology was not used for a long period because of technical difficulties in extracting the fECG from the abdominal recording, with a very low signal-to-noise ratio of the fECG

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compared to the maternal ECG [5]. In recent years, this very promising technology has developed significantly thanks to progress in signal processing, but fECG extraction is still a recurrent academic challenge in signal processing. Indeed, even if the many proposed algorithms have proven their worth on signals from a calibrated database (mainly PhysioNet, in the context of the Computing in Cardiology Challenge 2013), when they run into clinical reality and are applied to signals acquired in real situations, they fail [6]. It is commonly accepted that the non-invasive extraction of a usable fECG is not yet methodologically solved [7–9]. Moreover most of the methods are based on the use of a large number of electrodes, which is not suitable for clinical use.

An original approach is proposed here and differs from previous published solutions. It consists in detecting the same phenomenon by two complementary modes, using electrophysiological sensors (ECG) and microphonic type acoustic sensors that can register phonocardiographic signals (PCG), and then in combining them. The goal is to increase the reliability of monitoring FHR. This preliminary study aimed to introduce this non-invasive multi-modal monitoring technique and to evaluate its feasibility in clinical practice.

2. Material(s) and method(s)

Our prospective open label study took place from January to May 2016 in Grenoble University Hospital, France. This study is part of the MAPO-RCVQ protocol, approved by the local ethics committee, "Comité de Protection des Personnes Sud Est V" and authorized by the French supervisory authority, "Agence Nationale de Sécurité du Médicament".

Volunteer women presenting a pregnancy with normal progression after 24 weeks of gestation were included after a normal routine ultrasound scan, medical consultation for inclusion and signing written consent.

Pathological pregnancies or those with inaccurate dating were excluded.

2.1. Signal acquisitions

Each pregnant woman was equipped with one maternal ECG, through two thoracic bipolar electrodes and one reference electrode, and two abdominal ECGs, through four abdominal electrodes and one reference electrode (BioAmp enhancer, ADInstruments), as well as two cardio-microphones (MLT201) held on the skin by belts. All signals were acquired at a sampling frequency of 1000 Hz. In parallel, the reference FHR was simultaneously recorded by an Oxford system CTG (Sonicaid Team Duo). The position of the fetus was checked, especially the side of the fetal back, by an obstetrical ultrasound scan. This allowed the sensors to be placed in an optimal position. Once the sensors were positioned each monitoring session lasted about 15 min. The subject was supine and in a comfortable position so as to minimize electrical interference of muscular origin. Data were first analyzed online during the acquisition session in order to change the position of the sensors if necessary, and then off-line for data analysis.

2.2. Signal processing

The signal processing methods used in this study are preliminary algorithms to highlight the feasibility of the method; they are still in development to improve their performance.

Adaptive kernel filters were considered for fetal ECG extraction using two simultaneously measured ECG signals (thoracic and abdominal) [10]. The abdominal ECG (ECGa) was a mixture of mother and fetal ECG, in which the maternal ECG was considered as the noise and the fetal ECG as the signal to be estimated. The thoracic ECG (ECGt) was the reference signal and it is (possibly non-linearly) correlated with only the maternal ECG recorded by the ECGa. The adaptive kernel filter, whose input signal is ECGt, optimizes signal expression so that its output is as close as possible to the maternal ECG contribution in ECGa. In other words, the filter models signal propagation through the mother's tissues between the mother's heart and the abdominal sensor. Finally, the fetal ECG estimation (fECG) is the difference between the noisy recording (ECGa) and the output of the adaptive kernel filter. fECG were extracted for all subjects and fetal heart rate (FHR_{ECG}) was estimated by detecting the R-waves of the fECG signal and applying a median filter.

PCG signals obtained with microphones were filtered with a passband filter from 20 to 250 Hz. The filtered thoracic PCG signal was termed mPCG, for the mother's PCG, and the filtered abdominal PCG signal was termed fPCG, for the fetus. The envelopes of the fPCG signals were calculated and called efPCG, on which fetal heart sounds S1 and S2 could be detected. Fetal heart rate from fetal PCG (FHR_{PCG}) was estimated from the time difference between the S1 sounds.

2.3. Data analysis

A comparative analysis based on correlation of FHR estimations was performed between CTG (the reference technique) and the 2 other methods, PCG and ECG.

Linear interpolation and resampling at 10 Hz of FHR_{CTG}, FHR_{ECG} and FHR_{PCG} was done for all subjects. Then correlation coefficients were calculated between synchronized FHR_{CTG} and FHR_{ECG} or FHR_{PCG}.

Sequences with signal loss during CTG recordings were not considered in the correlation computation.

3. Results

Seven women at between 24 and 39 weeks of gestation were included. All presented a normal BMI. Three were nulliparous, 3 primiparous and 1 multiparous. Fig. 1 is a picture of one patient with required sensors and electrodes for CTG, PCG and ECG during recording. Fetuses all had a cephalic presentation, except for one with a breech presentation. Data acquisition was carried out at two different gestational ages for two of the women, giving a total of 9 sets of recordings.

Fig. 1. Picture of one patient with required sensors and electrodes during recording.

3.1. Signal processing

The figures illustrate the processing applied to signals. Fig. 2 shows simultaneous thoracic and abdominal ECG recordings. Processing of the latter allowed the estimation of a fetal ECG signal, in which R-waves could be detected.

Fig. 3 shows PCG signals from the thorax and the abdomen, corresponding respectively to mPCG and fPCG. Fetal heart sounds S1 and S2 can be detected in the envelopes of the fPCG signal.

3.2. Qualitative observation of the signals

No CTG was recorded in two of the data acquisitions sessions. For recording 1, at gestational age of 34 weeks, corresponding to the vernix period, the fECG signal was difficult to detect. For recording 8, at 31 weeks of pregnancy, we also failed to capture the fECG, probably for the same reason.

Recordings 4 and 9 correspond to the same women at two different gestational ages. The fECG was visible on the abdominal ECG but it was highly disturbed by a periodic noise signal, which we attributed to muscular interference, making extraction of fECG from ECGa by the current signal processing algorithms impossible; no FHR_{ECG} was estimated for these recordings. This phenomenon was also observed for recording 2, especially at the beginning but it later stopped allowing an estimation of FHR_{ECG} during the second part of the acquisition period. Further investigation of this phenomenon is needed to explain it.

For recording 7, the fECG was clearly visible in the recording, but due to the early gestational age (25 weeks) the quality of CTG was very poor, with about 50% signal loss, rendering the computation of a correlation coefficient meaningless.

Considering the PCG signals, the visibility of fPCG was erratic on the abdominal PCG recordings of most of the women. PCGa is highly sensitive to noises (ambient noise, digestive rumbling or respiratory sounds, etc.). At present our algorithms are able to process the signals efficiently for short periods of time only. Processing of the PCGa needs to be improved to extract fPCG. At present the available algorithms are not sufficiently well devel-

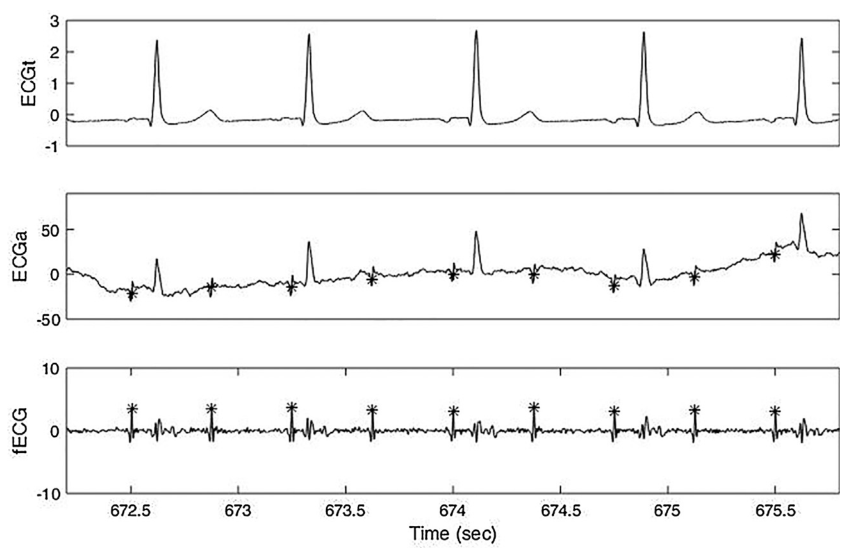

Fig. 2. Thoracic and abdominal ECG signals, and the fECG extracted from ECGa. Stars correspond to the fetal R-waves detected on the fECG (and reported on ECGa).

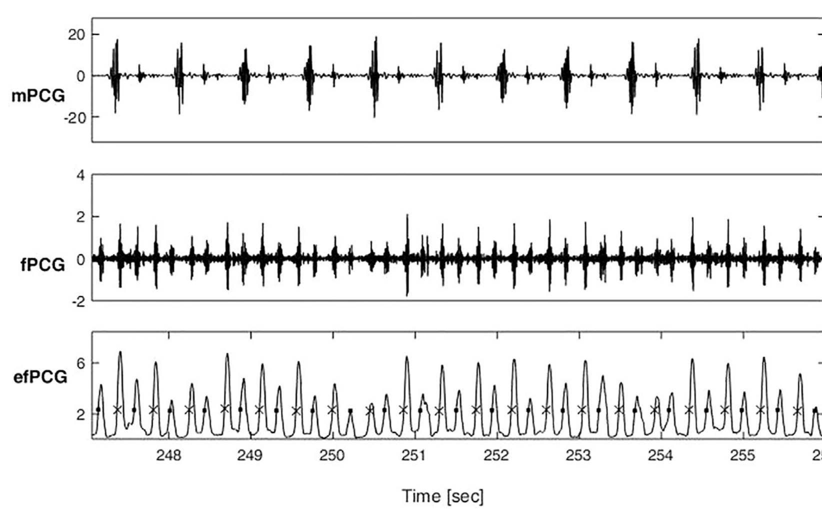

Fig. 3. Thoracic (mPCG) and abdominal (fPCG) PCG signals, and the envelopes efPCG for fetal PCG. Black crosses correspond to S1 heart sounds detected on the ePCG; black points correspond to S2 heart sounds.

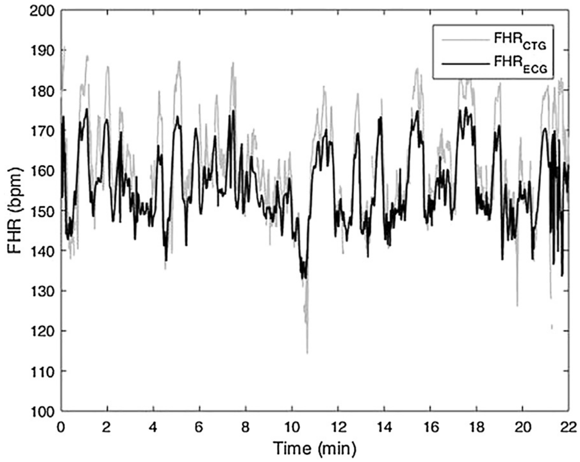

Fig. 4. Fetal heart rate estimated from ECG and CTG from recording no. 5 over 22 min.

oped to make a comparison of FHR_{PCG} and FHR_{CTG} over long periods of time for all subjects. We found that PCGa is not sensitive to maternal heart sounds.

3.3. Data analysis

Fig. 4 shows an example of the superimposition of acquisitions of the fetal heart rate from ECG and CTG over 22 min, illustrating a high degree of correlation.

For the 4 subjects with CTG and ECGa signal recordings processed by the current versions of our algorithms, the FHR_{ECG}–FHR_{CTG} correlation values ranged from 74% to 84% for acquisition periods varying from 4 to 22 min.

PCG analysis was performed on acquisitions from 2 subjects over shorter sequences than for ECG, as explained above. For these subjects, the FHR_{PCG}–FHR_{CTG} correlation values were 75% and 80% for acquisition periods of 5 min.

4. Discussion

This study included only a small number subjects as it was a feasibility study aiming to demonstrate that PCG and ECG signals are usable, and can be compared with CTG, the reference technique. Our goal is to analyze the performance of several PCG and abdominal ECG signal processing methods by comparing the FHR they give with reference CTG data.

Our analysis suggests that there is a significant correlation between FHR_{ECG} and FHR_{CTG}, and between FHR_{PCG} and FHR_{CTG}.

It was not always possible to obtain a perfectly analyzable ECG or PCG signal. Nevertheless, the two techniques rarely failed simultaneously. This reinforces our hypothesis that the association of both techniques can increase the reliability and robustness of the monitoring.

4.1. Limitations to the fECG acquisition

Between 28–32 and 37–38 weeks of gestation a layer of vernix caseosa, a fatty substance of sebaceous origin, covers the fetus and electrically isolates it. This makes fECG recording difficult as it limits the amplitude of the fECG signal on the abdominal ECG recording [5,11]. A number of studies have observed the detrimental effects of this layer on fECG extraction but these limitations have not been consistently reported [8].

Unlike other studies [5,6], we were rarely hampered by fetal movements. When we were able to record fECG thanks to one of the 2 sets of abdominal electrodes, even if the fetus was very active, there was very little signal loss.

Furthermore, there is high variability between individuals in the amplitude of the electric signals due to several factors (age, sex, ethnicity, BMI, thoracic morphology and heart position). This was already known from experiments in adults and we foresaw this as a limitation in fECG recordings. In addition to this inter-individual variability, some recordings were sometimes scrambled due to muscular contractions. Thus it is likely that uterine contractions masked the QRS components of the fECG signal. This problem could be solved by more advanced signal processing.

4.2. Advantages of phonocardiography

The recent literature on PCG is scarce, the technique being eclipsed by the development of CTG monitoring during the 1980s. PCG signal processing is challenging and requires complex algorithms in order to estimate the FHR_{PCG}. Nevertheless, recently Kovacs et al. showed that FHR can be precisely measured thanks to the acoustic methods they developed, although there is some signal loss as it is not always possible to identify all fetal heart beats [12]. Our results are in line with their findings.

4.3. Perspectives

The signal processing of our data is still at a preliminary stage. Our present results show the feasibility of this approach but more development is needed before it can be used in day-to-day obstetrical practice [13]. We have set up the data analysis procedure so as to analyze and compare the different signal processing methods. Each time a new fECG extraction method or a new PCG analysis method needs to be tested, we can compare it to our reference CTG data and estimate whether the new method is more efficient than the previous ones.

Our recordings are compiled in a new database, which is richer than the existing database, Physionet [5,8]. ECGa and PCG signals are recorded simultaneously along with the CTG reference, over relatively long periods, in conditions close to those of clinical practice.

In the present study we processed the unique ECGa and PCG separately, in order to evaluate the feasibility. Our future goal is to develop a reliable, sturdy and precise device that couples ECG and PCG so as to efficiently monitor fetal heart rate [14].

Authors contributions

SG designed the study, collected data and wrote the manuscript.

JFJ designed the study, collected data, performed the analysis and wrote the manuscript.

VE and PH revised the manuscript.

PYG and BR designed the study and revised the manuscript.

All authors read and approved the final version of the manuscript.

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Competing interests

The authors declare that they have no competing interest.

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