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Non-invasive fetal monitoring: Fetal Heart Rate multimodal estimation from abdominal electrocardiography and phonocardiography.

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Non-invasive fetal monitoring: Fetal Heart Rate multimodal estimation from abdominal electrocardiography and phonocardiography.

KEYWORDS:

Fetal Electrocardiography (ECG)
Phonocardiography (PCG)
Cardiotocography (CTG)
Fetal Heart Rate (FHR)

ABSTRACT:

Background: Fetal cardiac well-being is essential during labor as the delivery is at risk for fetal distress. Continuous monitoring by cardiotocography (CTG) is daily used to record the fetal heart rate (FHR) but this technique has important drawbacks in clinical use.

Objectives: We propose to monitor FHR with a non-invasive technique, using multimodal recordings of the fetus cardiac activity, associating electrocardiographic (ECG) and phonocardiographic (PCG) sensors. The aim of this study is to evaluate the quality of these multimodal FHR estimations by comparison with CTG, based on clinical criteria.

Methods: A clinical protocol was established and a prospective open label study was carried out in the University Hospital of Grenoble. The objective was to record thoracic and abdominal PCG and ECG signals on pregnant women over 37 WG (weeks of gestation), simultaneously with CTG recordings. Adapted signal processing algorithms were then applied on abdominal PCG and ECG signals to extract FHR. Quantitative evaluation was carried out on FHR estimations compared with FHR extracted from CTG.

Results: A total of 40 recordings were performed. Due to technical mistakes the analysis was made possible for 38. 35 recordings allowed a FHR follow-up by ECG or PCG, 30 recordings allowed a FHR follow-up by PCG only, 25 recordings allowed a FHR follow-up by ECG only and 20 recordings allowed a FHR follow-up by both ECG and PCG.

Conclusion: Reliable multimodal recording of FHR associating ECG and PCG sensors is possible during the last month of pregnancy. These positive results encourage the study of multimodal FHR recording during labor and delivery.

INTRODUCTION

Intrapartum assessment of fetal well-being is mandatory as labor is at risk of fetal acidosis [1]–[3]. Studying the fetal heart rate (FHR) enables to evaluate the risk of fetal acidosis relying on several criteria such as the rhythm baseline, the variability, the analysis of accelerations and decelerations [4]–[6]. Indeed, the FHR varies according to the state of hypoxemia or fetal hypoxia: the cyclic cardiac activity of the fetus reflects its neurological well-being at term[7]. This cyclic activity will be absent in cases of hypoxia, chorioamniotitis, neonatal infection, but also in certain iatrogenic contexts (oxytocin)[3][8]. If the question of fetal monitoring during labor no longer arises, the question of its modalities can be raised. The value of continuous fetal heart rate recording versus intermittent auscultation was once debated. The authors now recommend continuous monitoring[9]. Nowadays electronic fetal monitoring known as cardiotocography (CTG) is worldwide used to record the FHR. CTG recording is possible through two separate transducers: an ultrasonic sensor that continuously emits ultrasounds and detects motion of the fetal heart rate, and a pressure transducer that provides information on uterine contractions [10]. CTG is easy to use, it is a good screening tool to detect situations at risk of acidosis (high sensitivity of 80%) but suffers from a high risk of false positive results (30%) which makes it a poor diagnostic tool. This is partly due to the difficulties of interpretation despite rigorous definitions; indeed, studies show an important inter-observer disagreement [11]–[13]. This leads to an increased number of misdiagnosis of fetal distress and consequently to an increased unnecessary number of cesareans and assisted deliveries (vacuum, forceps) but has no impact on long-term neonatal prognosis [14]. It is estimated that 75% of cesarean sections indicated for risk of acidosis were unnecessary [14]; yet cesarean sections are not without risk, obstetricians daily observe an increasing number of women concerned by uterine scars and their complications such as the uterine rupture or abnormal placenta insertion [15]. As for instrument assisted deliveries, the use of an instrument increases the risk of maternal and neonatal morbidity [16].

Second line tests as fetal blood sampling were studied among systematic reviews. Indeed, to better identify foetuses that are at risk of intrapartum asphyxia, some authors have advised the realization of fetal scalp pH to guide obstetrical decision[17][18]. Some teams have also discussed the value of scalp ph analysis rather than scalp lactate analysis [19]. However, for many authors fetal blood sampling reported no evidence of benefit in reducing medical deliveries and showed a poor positive predictive value for intrapartum hypoxia[20]. Still, the review of the literature shows that the various authors do not agree on fetal scalp blood sampling usefulness in clinical practice[21], [22]. Fetal pulse oximetry has not been proved successful neither [14], [23].

Fetal well-being can also be assessed by the fetal electrocardiography (ECG), the fetal scalp ECG known for instance as the STAN technology consists in fixing an electrode on the fetus scalp, recording the fetal ECG signal and analyzing the waveform of the ST segment: a change in the ST segment expresses a risk of acidosis. However, there are many limits in its use: it cannot be used with fetus younger than 37 amenorrhea weeks; it cannot be performed before membranes rupture or an advanced dilatation of the cervix, and is contraindicated when there is an infection suspicion. This technology is actually safe to use only when used by a trained team in the defined indications, otherwise it can be falsely reassuring and misdiagnoses fetal acidosis [23], [24].

Regarding all the limits of classic CTG and second line tools, it appears the necessity of developing new techniques that would combine precision and safety of use to appreciate the fetal risk of acidosis. We investigate the possibility of non-invasive fetal monitoring with the use of abdominal multimodal sensors and adapted signal processing. We intend to estimate the fetal heart rate using non-invasive abdominal electrocardiography (ECG) and phonocardiography (PCG).

PCG signals, recorded thanks to cardiomicrophones, represent the sounds produced by the heart: among the more audible, S1 is the sound of the atrioventricular valve closing and corresponds to the beginning of the systole, S2 is the sound of the pulmonary and aortic valve closing and corresponds to the beginning of the diastole. This technology is used for adult cardiac activity monitoring [25] and is already known for the

measurement of fetal heart mechanical activity considering abdominal cardiomicrophonic sensors on pregnant women. Positioned on the abdomen, the sensor gives access to the heart sounds of the fetus, and one can suppose that there is very little interference with the maternal PCG. The fetal PCG is quite directly recorded by the abdominal microphones. However, this technology has not been fully investigated, mainly due to the processing of PCG signals and the difficulty of detection of S1 and S2 sounds for an accurate FHR estimation[26].

Non-invasive fetal ECG recording has been studied for years and some medical devices have already been developed, for instance the Monica Healthcare system [27]. However, the technologic developments of non-invasive fetal ECG are still in progress, mainly because of the difficult signal processing of abdominal ECG recordings. Indeed, the fetal ECG signal is a much lower signal than the maternal ECG signal on abdominal ECG recordings. This makes the extraction of fetal ECG and the detection of fetal R-peaks very difficult for a robust FHR estimation along real recordings [28]. Most of the published methodological solutions tend to increase the number of sensors to improve robustness of the extraction. However, this approach is not relevant for a clinical use, especially during delivery. Limiting the number of sensors is essential in real constrained situations, for ergonomics and ease of use, both for the patient and medical staff. Moreover, the fetal cardiac information is located on a restricted zone of interest on the mother abdomen. Therefore, it is relevant to favor few well-positioned sensors instead of many electrodes spread over. Our solution is to couple two complementary cardiac information acquired at the best-located position from two different technologies, an electrical cardiac information by ECG and a mechanical cardiac information by PCG. Using single ECG or PCG abdominal recordings, we proposed a new methodological way to estimate FHR without considering the precise locations of R-peaks or cardiac S1 and S2 sounds [29], [30]. Our purpose is therefore to compare these estimated FHR to FHR obtained by simultaneous reference CTG recordings, and to analyze the reliability of the proposed approach on real data. The present study follows a preliminary study which took place in the University Hospital of Grenoble Alpes in 2016 [31]. During this preliminary study, 9 recordings were produced among pregnant women from 25 to 38 weeks of pregnancy. The aim was to evaluate the feasibility in clinical practice. The present work is now a step forward. First, we focus on pregnant women in the last month of pregnancy. This physiological approach is the closest to our final goal which is the FHR recording during the stage of labor and delivery, to target precisely fetus with risk of acidosis and decide the need for an assisted medical delivery. Second, we also aim at increasing the number of subjects to get a consequent database available for signal processing developments.

MATERIAL and METHODS

A clinical protocol was established and an open-label prospective study was conducted from May 2019 to April 2021 at the University Hospital of Grenoble Alpes (study N°RCB: 2018-A03182-53). The primary objective of the study was to obtain a database of simultaneous ECG, PCG, and CTG signals during a 30-minute follow-up among 40 volunteer pregnant women from 37 weeks of gestation (WG).

Population:

Were included pregnant women over 18 years old, with a single pregnancy, in the 9th month of pregnancy (over 37 WG), with simple physiological monitoring and without any maternal or fetal complications. Patients with a BMI of less than 18.5 (underweight) or more than 30 (obese) at the beginning of the pregnancy, with a specific medical history, or who had used toxic substances during pregnancy (tobacco, alcohol, cannabis) were excluded. Patients with unclear pregnancy term or denial of pregnancy were also excluded from the study.

Signal Acquisitions:

Data acquisition was performed in the high-risk pregnancy obstetrics department of the Grenoble Alpes University Hospital. After signing the informed consent, the volunteer laid on her back in a comfortable position to minimize movement and electrical interference for a period of 30 minutes.

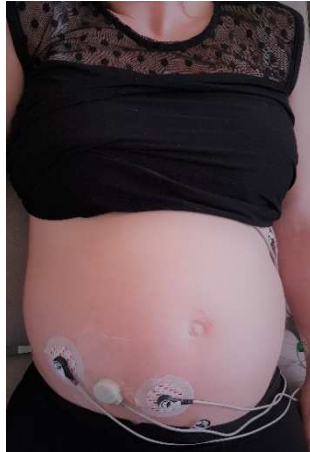


Figure 1: PCG and ECG sensors on the abdomen of the subject.

The position of the fetus was checked, especially the side of the fetal back. If necessary, an obstetrical ultrasound had been performed, in order to place all sensors in an optimal position. Acquisitions were performed using a PowerLab data acquisition system (ADInstruments). All ECG and PCG signals were sampled at 1 KHz.

The multimodal recording consisted then of:

- A thoracic ECG, using two thoracic bipolar electrodes on the maternal heart axis and a reference electrode on the maternal wrist (BioAmp, ADInstruments). This ECG signal was considered as the reference maternal ECG and noted ECGt.

- A thoracic PCG using a cardio-microphone (MLT201, ADInstruments) attached to the skin of the maternal thorax as close as possible to the maternal heart. This PCG signal was considered as the reference maternal PCG and noted PCGt.

- An abdominal ECG, using two abdominal bipolar electrodes across the axis of the fetal heart (Figure 1) and the same reference electrode as for the maternal ECG (BioAmp, ADInstruments). This abdominal ECG signal, named ECGa, was processed to extract fetal ECG information, as it will be described below in the signal processing section.

- An abdominal PCG using a cardio-microphone (MLT201, ADInstruments) held on the skin of the maternal abdomen as close as possible to the fetal heart (Figure 1). This PCG signal, named PCGa, was processed to extract the fetal PCG, as it will be described below in the signal processing section.

Simultaneous reference CTG monitoring (Avalon F20/F30, Philips) was recorded, allowing acquisition of a reference maternal heart rate, a reference fetal heart rate, and uterine contractions.

Once the sensors were placed, each monitoring session lasted approximately 30 minutes.

Signal Processing:

Because the PCG and ECG sensors are placed on the mother's abdomen, signal pre-processing of abdominal signals is first required to extract fetal signals from the mixture of maternal and fetal signals recorded simultaneously. The nature of ECG and PCG signals is different, therefore the processing required to extract the fetal ECG or PCG also differs.

The fetal ECG signal, noted ECG_f, is extracted from abdominal ECG_a by removing the maternal ECG component (citer Dia, 2022). This is achieved by 2 steps of filtering: a finite impulse response (FIR) high-pass filter between 5 and 33 Hz and a nonlinear adaptive filter (W Liu, 2010) using the simultaneously recorded thoracic and abdominal ECG signals (ECG_t and ECG_a).

Regarding abdominal PCG signals, a FIR bandpass filter between 20 and 250 Hz is applied to the abdominal PCG (PCG_a) to estimate the fetal PCG signal, denoted PCG_f.

Figure 2 shows a short sequence of ECG and PCG signals simultaneously recorded, before and after signal processing.

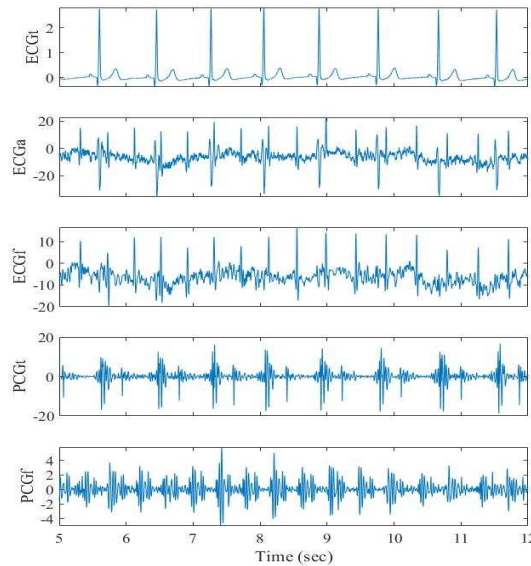


Figure 2: Acquisition and pre-processing of signals, from top to bottom: thoracic ECG, abdominal ECG, fetal ECG extracted from ECG_a, thoracic PCG and fetal PCG, band-pass filtered from abdominal PCG.

The second step of signal processing consists then in estimating FHR from fetal ECG and PCG. The heart rate from the ECG signal is classically estimated by detecting the R peaks of the ECGs (J Pan, 1985). However, despite adaptive filtering, the fetal ECG may still be disturbed by different types of noise such as maternal movements or electromyogram due to uterine contractions, which makes it difficult to detect each R wave. Considering PCG, detecting precisely S1 or S2 sounds is also difficult due to the shapes of the signals. Detection of temporal events in fetal signals is therefore a complex signal processing problem, that we proposed to circumvent with a new FHR monitoring algorithm [29], [30] based on the nonnegative matrix factorization (NMF), which is a matrix decomposition well adapted to extract specific features from the spectrogram of physiological signals. The proposed algorithm enables to follow the fundamental frequency of fetal ECG and PCG quasi-periodic signals, which corresponds to the fetal heart rate. Technical details of the algorithm are not described in the present paper. Thus, the different steps of the proposed method allow on the one hand the estimation of FHR by ECG, called FHR_{ECG} , and on the other hand the estimation of FHR by PCG called FHR_{PCG} .

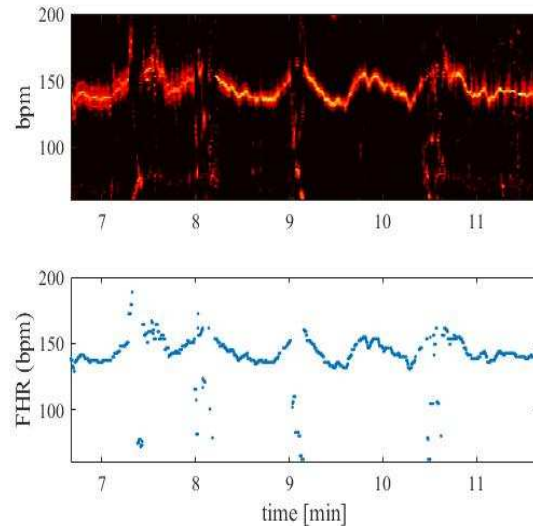


Figure 3: 5-minutes FHR estimation for one subject from an abdominal PCG signal, according to our proposed algorithm based on the NMF. The upper panel shows the image of the matrix carrying the temporal evolution of the fetal cardiac activity. FHR (lower panel) is extracted as the maximum of energy of the previous image.

Data analysis

In order to allow the analysis of the recordings and the comparison with the classical CTG, we performed a resynchronization between multimodal recording (ECG/PCG) and CTG recording. All FHR estimations were resampled every 250 ms (i.e. sampling frequency of 4 Hz) to match the usual sampling period of CTG devices.

The interpretation of the classical CTG is framed by the international guidelines of the FIGO (International Federation of Gynecology and Obstetrics) [32]. A correct interpretation requires a signal loss of less than 20% of the total monitoring.

As proposed by [29], to measure the reliability of the estimated FHR compared to the FHR provided by the CTG reference, we evaluated the set of outliers, i.e. the set of estimated FHR values that differ from FHR_{CTG} by more than 12.5 beats per minute (bpm). This confidence margin has been chosen according to the clinical fetal heart rate variability, which is judged normal when comprising peak-to-peak between 6 and 25 bpm [33]. We defined the ratio of outlier (RO) as the cardinality of the set of outliers, over the overall number of samples. Good reliability between FHR estimation and FHR reference is characterized by a small ratio of outliers (RO near to 0%) or by $1-RO$ near to 100%, as considered in the quantitative results in next part.

Pearson correlation coefficient (R) was also considered to quantify the similarity between FHR estimations from CTG and FHR from ECG or PCG after removal of outliers. The nearer to 100% the R value is, the better is the similarity between FHR estimations and FHR reference given by CTG.

At last, Bland and Altman tests [34] were carried out to assess the agreement between FHR reference and FHR estimation from ECG or PCG without outliers. The 95% limits of agreement were computed as the mean of the two values, minus and plus 1.96 standard deviations; a high degree of concordance between the two sets of measurements is characterized by small values of these limits of agreement.

Note that since CTG is considered as reference, no quantitative evaluation was carried out on periods where CTG was not available.

RESULTS

40 women were included and 40 recordings were performed. For one recording there was a handling error and the abdominal ECG signal was lost. For another recording, there was a loss of the CTG recording. Therefore, the resulting dataset is made of 38 recordings of fetal ECG and PCG signals, and corresponding FHR_{ECG} and FHR_{PCG} , simultaneous with FHR_{CTG} considered as the reference. Details for each acquisition are summarized in annex 1.

Population:

The mean term was 39 WG in patients with a mean BMI of $27\text{kg}/\text{m}^2$. The fetuses were in cephalic presentation except for 1 fetus in podalic presentation. 19 fetuses were right-backed (47%), 18 left-backed (45%), 2 anterior-backed (5%) and 1 posterior-backed (2.5%).

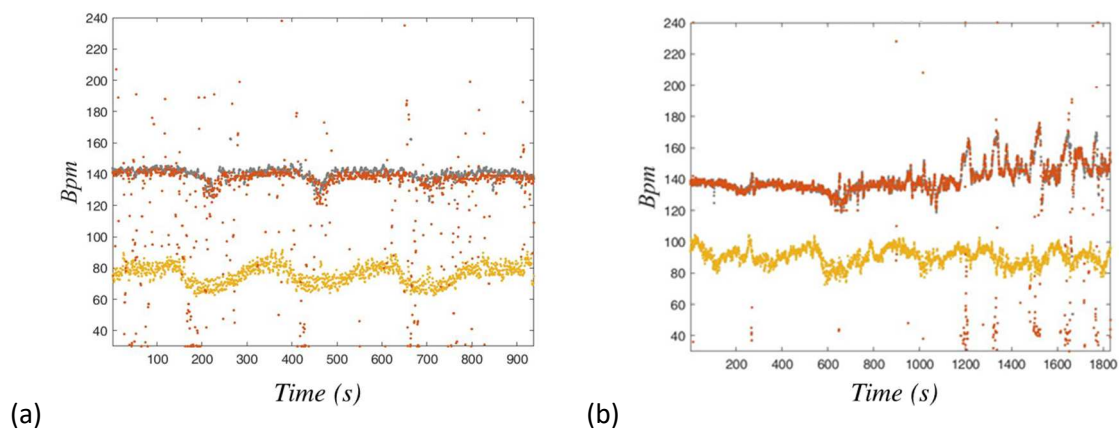
Acquisitions:

The recordings lasted an average of 29 minutes with an average of 7 % per recording of information loss or unanalyzable information while considering CTG.

A visual analysis of the CTG recordings was performed as usually realized in clinical practice: we analyzed the rhythm baseline, the variability, accelerations and decelerations. All CTG recordings were evaluated as normal, as this was expected since all women had normal pregnancy follow up.

A visual analysis of the temporal evolution of the fetal cardiac activity, extracted from the algorithm (Figure 3, upper panel) showed that 35 recordings allowed a FHR follow-up by ECG or PCG, 30 recordings allowed a FHR follow-up by PCG only, 25 recordings allowed a FHR follow-up by ECG only and 20 recordings allowed a FHR follow-up by ECG and PCG together. Some recordings (ECG and/or PCG) were not exploitable due to bad acquisition conditions, which have to be characterized, as it will be discussed in the last section.

Figure 4 illustrates some FHR estimations from ECG or PCG during the whole acquisition session for a selection of subjects.



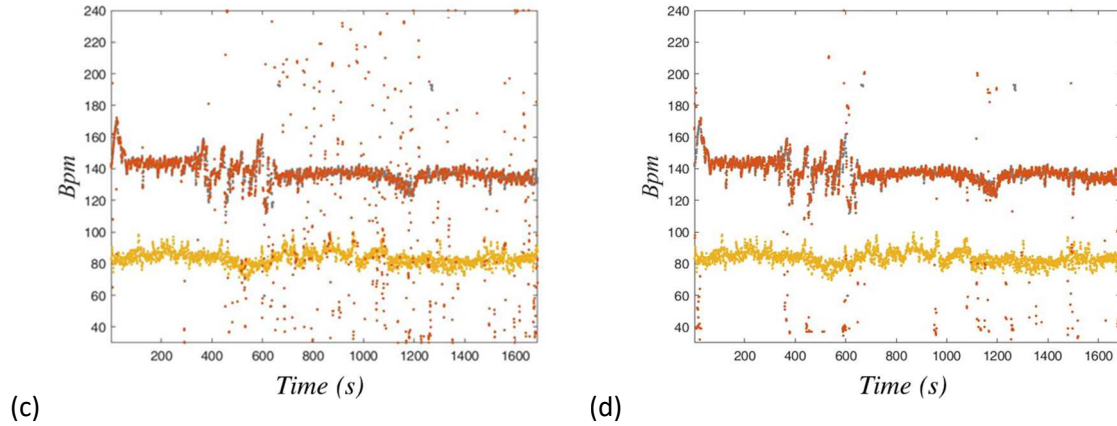


Figure 4: FHR estimations (red points) superimposed on reference FHR from CTG (gray points). The maternal heart rate is shown in yellow points. (a) Estimation from ECG for V2 (1-RO=82%) (b) Estimation from PCG from V23 (1-RO=93%) (c) Estimation from ECG for V10 (1-RO=90%) (d) Estimation from PCG from V10 (1-RO=93%).

Comparison to the CTG:

For quantitative comparison to CTG, we first consider the 1-RO score. Considering the first versions of algorithms [30] [29], for fetal ECG signals, we obtained an average score of 76% (thus a 76% concordance with the CTG). For PCG, the score is less successful and is evaluated at 52%.

While considering the Pearson correlation coefficient for FHR estimations without outliers, the mean values of R from fetal ECG or PCG signals are respectively 89% and 85%, this highlighting a very good similarity of FHR estimations from fetal signals with CTG reference. The good agreement of CTG measurements and those from fetal ECG and PCG signals is also underlined by the 95% limits of agreement of Bland and Altman tests. These limits are evaluated from 4 to 12 bpm for all subjects, with a mean agreement limit equal to 4 bpm for estimations from ECG and 6 bpm for PCG estimations, corresponding to a bias lower than 5%.

All individual results are available in Table 1 in annex.

These results are promising since the signal processing algorithms are still in progress.

DISCUSSION

The results on our study population are promising, since most acquisition sessions allowed the recording of maternal and fetal multimodal signals at the same time among women in the last month of pregnancy. Fetal data has been obtained according to a small number of sensors, one abdominal microphone sensor for fetal PCG signals and one pair of abdominal electrodes for fetal ECG. A CTG reference is available for FHR estimation comparisons and validations. We have observed a low lack of data on the various signals, which allows their interpretation.

Signal acquisition:

ECG signals are easy to record. For maternal ECG (thoracic sensor), it is easy to observe QRS complexes, and therefore the processing for maternal heart rate is robust. Fetal QRS complexes are much more difficult to observe on abdominal ECG signals. Indeed, fetal QRS are much smaller than maternal QRS that are always present on abdominal signals. Even if it is sometimes possible to visually make the difference between

maternal and fetal sources on abdominal ECG, in most cases, the fetal signal is hard to distinguish and signal processing is necessary to attenuate the mother contribution and enhance the fetal ECG, as it will be discussed in signal processing discussion part. Among the 38 acquisition sessions available, 25 are considered for FHR monitoring. The others have been discarded due to several reasons that still need to be understood and analysed. We can suppose that fetus' position, mother's BMI, gestation week, hiccups... can explain some difficulties of fetal signal acquisition. However, the first analysis does not highlight specific configurations that always work well or badly. Nevertheless, for the 25 fetal ECG signals available for analysis, the FHR monitoring is quite robust and the use of abdominal ECG remains of great interest.

Considering PCG signal, maternal and fetal PCG signals are easy to record thanks to only one microphonic sensor on thorax or abdomen. However, we realized that the abdominal sensor position and fixation are crucial for fetal heart sounds acquisitions. Indeed, attention must be paid to the interface between microphone and abdominal skin (contact between sensor and skin, and attenuation of ambient sounds). Then, when located directly above the heart, the sensor allows a robust FHR monitoring (concordance with CTG higher than 90%); this can be quickly degraded when the sensor is slightly shifted, which can be a difficulty with fetus movements. Moreover, we noticed that when the abdominal microphone is located next to maternal uterine arteries, the sensor will more likely record the maternal artery signal than the fetal heart signal. However, in our study, the use of PCG modality for FHR monitoring is encouraging since 30 sessions over 38 allowed fetal PCG acquisitions. A way to improve results with PCG signal acquisition is to work on the sensor properties (sensitivity and choice of uni- or-multi- directional microphones) and on its interface with maternal abdomen.

The aim of our project is to investigate the possibility of non-invasive fetal monitoring with the use of abdominal multimodal sensors (ECG and PCG) and adapted signal processing, in order to supplement CTG while signal losses or confusion between fetal and maternal rates. In that purpose, the first validation step is to show that FHR monitoring is comparable to reference CTG one in normal situations. That was the frame of the present study where quantitative evaluations were carried out only when CTG was available. However, visual inspection of recordings has also been made to analyze segments of CTG signal loss. As illustrated on Figure 5, for one recording, we have observed an accidental loss of information by CTG causing the stop of FHR recording and leading instead to the recording of the maternal cardiac activity. However, at the same time, the FHR was captured by the abdominal ECG sensor. This example shows the potential of the device: the multimodal recording of the fetal heart rate can overcome some of the shortcomings of the CTG.

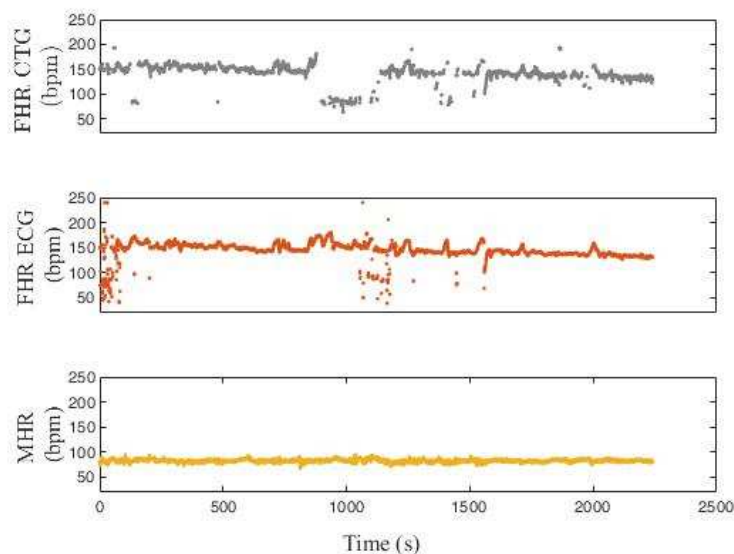


Figure 5: From top to bottom, fetal HR from the reference CTG, fetal HR estimated from abdominal ECG and maternal heart rate. Around 1000 seconds, CTG has lost FHR and recorded MHR, while ECG has kept monitoring FHR.

Signal processing and data analysis:

Results presented in this study correspond to the first versions of our proposed algorithmic solution, based on the harmonic following of the fetal signals[29], [30]. The estimation of FHR from abdominal ECG or PCG recordings provides promising results. Over the 25 abdominal ECG signals available for FHR monitoring, the concordance with CTG is encouraging with 75% in average. For some signals, we have already noticed that the maternal attenuation can be much more improved and work is under progress on that question. Moreover, some segments have suffered from signal saturations due to the acquisition material that will be redesigned for future studies. In the present paper, we have considered performance evaluated on whole recordings, without suppression of saturated and badly denoised segments. The same philosophy of performance evaluation has been considered for PCG signals, the entire recordings of the 30 PCG acquisition sessions provide an average result of concordance with CTG of 52%, lower than ECG. This can be explained by the fact that PCG signals processing is currently less developed than ECG one. PCG scores are attended to be improved with future versions of PCG algorithms.

Work is still in progress for the processing of all signals. Different algorithms are currently investigated to improve FHR estimations. These propositions are still under development and will be evaluated the proposed dataset. These new methods are mainly based on two principles. On the one hand, we aim to consider temporal properties of the fetal heart rate, to avoid too fast changes on heart rate values, and on the other hand to combine FHR estimations from ECG and PCG. For the first purpose, Figure 6 highlights the benefit of the proposed solution (Resendiz et al., 2022.) where many mistakes on the FHR estimations are corrected by the new solution. The second proposition is to consider multimodality and couple ECG and PCG recordings to limit as much as possible the loss of information. Indeed, we have sometimes observed fetal signal losses coming from either the abdominal PCG or ECG sensors but rarely from both sensors at the same time. We can therefore think that these signal losses are not related. Figure 7 shows preliminary results from Souriau et al work [36]. Two noisy FHR estimations from simultaneous ECG and PCG can be combined to provide a better FHR estimation. For now, this fusion algorithm has only been tested on a few specifically chosen subjects in order to show its feasibility. PCG signal processing for FHR estimation needs first to be improved, before applying this fusion algorithm on the whole database.

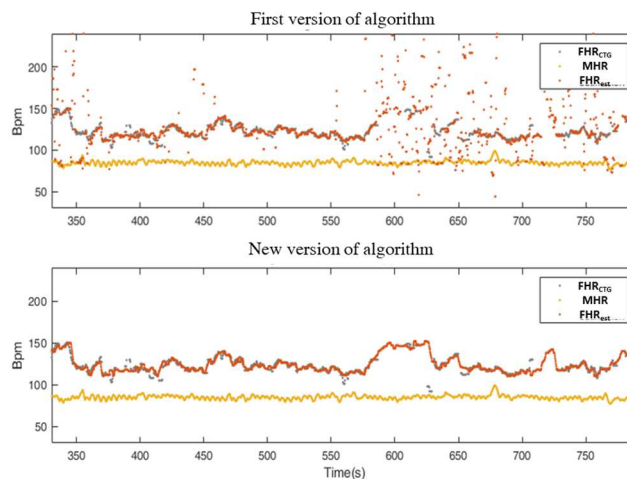


Figure 6: Extraction of FHR according to different algorithms. Figures show maternal heart rate (in yellow), and superimposed FHR from CTG (gray points) and ECG (red points) for one subject. With the first version of algorithm considered in the result part of this paper, the top figure highlights some estimation mistakes for fetal heart rate, that are corrected on the bottom figure, with the new algorithm under development.

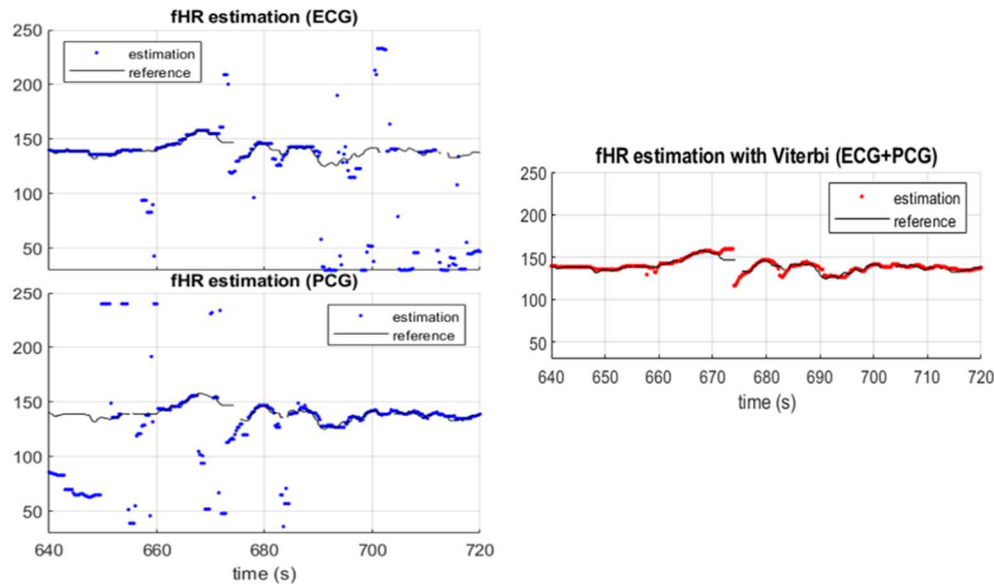


Figure 7: Estimation of FHR by merging estimations from ECG (top left) and PCG (bottom left) recordings [36]. The fusion of estimations (red points, right plot) allow a better concordance with CTG reference (black line).

Study population:

We focused our study on pregnant women during their last month of pregnancy, a good model for labor phase, since our ultimate goal is to record women during this phase of childbirth. However, signal acquisition and processing will certainly be very different if performed in the delivery room. Indeed, during labor, there is often a rupture of the water bag and thus the absence of the amniotic fluid interface. In addition, uterine contractions are much more repeated. These two parameters can influence the estimated FHR. We have discussed the limitations of CTG recordings during maternal pushing efforts; considering the increase of maternal heart rate in such efforts, would it still be possible to extract fetal ECG and estimate FHR from ECG modality? The whole process of labor can strongly affect our recording technique, and even if the model of fetuses at the end of pregnancy is of interest, there are still major differences between recording the FHR during the last month of pregnancy and during the labor phase. Therefore, the study should continue and allow recording in women in labor.

CONCLUSION

This work is part of a larger project which aims to investigate multimodal recording for FHR monitoring during labor. After these first analyses, we can conclude that it is possible to obtain reliable monitoring of the FHR by multimodal recording using abdominal PCG and ECG sensors. The work of extracting the most accurate and precise FHR possible is still in progress, with several algorithmic propositions of signal

processing. The next step of multimodal FHR recording during delivery should be considered in a specific study.

Finally, the recent literature review describes the monitoring of FHR from the patient's home using smartphone technology (L Yuan, 2019). This raises the question of the responsibility for the interpretation of these recordings. Indeed, if obtaining a fetal rhythm trace is made possible by new technologies, its automatic computer interpretation seems risky. In view of our experience, analysis by clinicians remains essential.

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ANNEX:

Table 1: Details on study population and signal acquisitions and performances scores including concordance with CTG (1-RO) from ECG and PCG estimations, Pearson correlation coefficient (R) and Bland & Altman 95% limits of agreement (mean ± 1.96 difference). Red boxes indicate unavailable recorded data. Orange boxes indicate none FHR estimations from the considered modality.

Volunteer	Population					Recording duration (min)	CTG signal loss (%)	ECG			PCG			
	Gestation weeks	BMI (before pregnancy)	BMI	Fetus presentation				1-RO (%)	R (%)	B&A (bpm)	1-RO (%)	R (%)	B&A (bpm)	
1	38+0	27	33,2	Cephalic	right-backed									
2	38+1	22	25,9	Cephalic	right-backed	16	11	99	59	-2 ± 6				
3	38+2	18,7	20,9	Cephalic	left-backed	28	3	82	93	1 ± 5	41	87	0 ± 8	
4	38+3	25,3	27,2	Cephalic	right-backed									
5	38+4	29,4	31,4	Podalic	right-backed	16	7				42	84	-1 ± 12	
6	38+5	19,5	22,2	Cephalic	right-backed	32	4				25	96	-3 ± 9	
7	38+6	19,2	22,5	Cephalic	left-backed	27	3	63	93	0 ± 7	89	95	0 ± 6	
8	38+7	19,9	24,6	Cephalic	left-backed	30	3	90	96	1 ± 6	90	96	1 ± 5	
9	38+3	26,5	32,3	Cephalic	right-backed	29	15	86	91	0 ± 9	15	91	0 ± 11	
10	38+1	20,9	26,4	Cephalic	left-backed	28	3	90	94	0 ± 5	93	94	0 ± 4	
11	37+4	24,3	27,2	Cephalic	left-backed	27	4							
12	39+4	21,6	29,3	Cephalic	right-backed	28	4	57	97	0 ± 7				
13	37+1	20,1	24,6	Cephalic	posterior-backed	30	9	95	95	0 ± 6				
14	38+4	20,2	24,4	Cephalic	right-backed	31	3	83	96	-3 ± 7	19	90	-3 ± 11	
15	37+5	19,3	22,2	Cephalic	right-backed	30	5	61	79	0 ± 8	32	75	0 ± 8	
16	40+0	20,3	26	Cephalic	right-backed	30	7	91	87	0 ± 5	65	86	0 ± 5	
17	38+0	20,6	27,1	Cephalic	left-backed	40	30				25	92	0 ± 9	
18	39+0	20,9	27,2	Cephalic	left-backed	30	4	91	94	0 ± 6	13	87	0 ± 9	
19	39+0	23,4	27,7	Cephalic	left-backed	32	11	74	91	0 ± 7	16	97	0 ± 9	
20	39+1	21,7	25,7	Cephalic	left-backed	30	3	75	94	0 ± 7	81	94	0 ± 6	
21	37+5	20	22,8	Cephalic	right-backed	30	4	68	88	0 ± 8	91	88	0 ± 6	
22	38+0	28,6	35,4	Cephalic	anterior-backed	26	4							
23	38+4	27,3	30,1	Cephalic	anterior-backed	31	3				93	96	0 ± 4	
24	37+0	24,2	29,3	Cephalic	left-backed	32	7				15	79	1 ± 11	
25	37+6	27,3	32,4	Cephalic	left-backed	30	5	43	88	0 ± 7	76	93	0 ± 5	
26	37+3	20,6	21,7	Cephalic	right-backed	32	11	95	92	0 ± 5	87	88	0 ± 6	
27	39+2	20,1	25,5	Cephalic	left-backed	30	4	44	79	0 ± 6	95	91	0 ± 5	
28	37+1	23,3	27,6	Cephalic	right-backed	31	10				65	89	0 ± 7	
29	37+4	24,4	30,2	Cephalic	left-backed	30	6	44	80	1 ± 9				
30	38+2	20,9	25,3	Cephalic	left-backed	22	2				12	87	1 ± 9	
31	38+0	29,4	34,2	Cephalic	left-backed	29	4	25	80	-2 ± 12	89	94	0 ± 7	
32	38+5	23,5	29,2	Cephalic	right-backed	20	4					0		
33	38+3	20,8	26,4	Cephalic	left-backed	30	11	92	92	0 ± 7		0		
34	38+0	24	28	Cephalic	right-backed	30	4				48	83	0 ± 7	
35	38+6	20,4	25,8	Cephalic	left-backed	34	12				46	90	0 ± 8	
36	37+5	21,7	26,4	Cephalic	left-backed	28	16				31	93	0 ± 7	
37	38+2	23,4	27,7	Cephalic	right-backed	27	5	98	93	0 ± 5	31	95	0 ± 8	
38	38+4	22,6	27,1	Cephalic	right-backed	25	4	61	94	0 ± 5	36	91	0 ± 8	
39	38+1	20,9	26,3	Cephalic	right-backed	30	6	94	93	0 ± 5	35	89	0 ± 7	
40	37+4	18,8	22,3	Cephalic	right-backed	42	22	89	96	0 ± 5	17	99	1 ± 7	
						29 min	7%	76%	89%	0 ± 4	52%	85%	0 ± 6	

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