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De-noising the abdominal phonogram for foetal heart rate extraction: blind source separation versus empirical filtering

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Abstract— **This work explored the suitability of using the foetal phonocardiogram (FPCG) blindly separated from the abdominal phonogram as a source for foetal heart rate (FHR) measuring in antenatal surveillance. To this end, and working on a dataset of 15 abdominal phonograms, the FPCG was estimated by using two de-noising approaches (1) single-channel independent component analysis (SCICA) to produce $FPCG_e$ and (2) empirical filtering to produce $FPCG_g$. Next, the FPCGs were further processed to collect the beat-to-beat FHR and the resulting time-series ($FCTG_e$ and $FCTG_g$) were compared to the reference signal given by the abdominal ECG ($FCTG_r$). Results are promising, the $FPCG_e$ gives rise to a $FCTG_e$ that resembles $FCTG_r$ and, most importantly, whose mean FHR value is statistically equivalent to that given by $FCTG_r$ ($p > 0.05$). Thus, the mean FHR value obtained from the $FPCG_e$, is likely to be equivalent to the value given by the abdominal ECG, which is especially significant since the $FPCG_e$ is retrieved from the noisy abdominal phonogram. Hence, as far as this study has gone, it can be said that, when using SCICA to de-noise the abdominal phonogram, the resulting FPCG is likely to become a useful source for FHR collection in antenatal surveillance.**

I. Introduction

Nowadays, it is generally accepted that current methods for biophysical antenatal surveillance do not really facilitate a comprehensive and reliable assessment of foetal well-being [1]–[3]. Alternatively, there is continuing development of existing technologies and research into non-invasive methods that aim to improve antenatal monitoring procedures [4]–[10]. These approaches rely on the detection of information regarding the cardiac function and foetal activity, which is done by means of passive transducers that sense electric, magnetic or vibration signals [11]–[14].

In our research, we have focused on detecting foetal vibrations by positioning an acoustic sensor over the maternal womb, which makes it possible to record the abdominal phonogram [15]. The signal, collected in a single-channel configuration, is composed of sources corresponding to the foetal heart sounds (FHS) and/or the foetal breathing/movements [15], which provide valuable parameters for well-being assessment (e.g. the heart rate variations). However, since the acoustic energy of the foetal components in the abdominal phonogram is very low, they become easily overcome by maternal and environmental sources whose characteristics turn the extraction of foetal information into a challenging task [12], [15]–[17].

To date, most signal processing methods in the literature rely on rigid empirical criteria that do not properly manage major changes in the SNR and irreversibly discard some extra and valuable information (e.g. maternal cardiac activity) [18]. Alternatively, in previous work, we have studied single-channel independent component analysis (SCICA) as a signal processing approach for separating the single-channel abdominal phonogram into its underlying components. The study, detailed in [19], exploited the rich time-structure in the abdominal phonogram and gave rise to an algorithm that, by learning a set of data-driven filters, de-noises the abdominal phonogram and manages to separate an independent trace corresponding to the foetal cardiac activity (i.e. the foetal phonocardiogram, FPCG) [18], [20].

Retrieving the FPCG from a noisy signal like the abdominal phonogram was encouraging and, most importantly, made it possible for the current study to focus on the next stage in our research, which was the evaluation of the FPCG estimated by SCICA ($FPCG_e$) as a source for measuring the foetal heart rate (FHR) and thus, for antenatal surveillance. To this end, the $FPCG_e$ trace was further processed to collect the beat-to-beat FHR and the resulting time-series was compared with a reference signal obtained from the abdominal ECG. Additionally, to test the performance of our data-driven approach against the traditional signal processing option, a generic FPCG ($FPCG_g$) was produced by means of a fixed filter and the collected FHR was also compared with the reference signal. The next sections will focus on describing the dataset, the general implementation of SCICA and the procedures followed to obtain the FHR time-series from $FPCG_e$ and $FPCG_g$. After that, the resulting FHR traces will be analyzed to establish their similarity to the reference signal and their reliability for antenatal surveillance purposes.

II. Materials and Methods

A. The abdominal phonograms dataset

Composed of 15 single-channel abdominal phonograms (3 or 5 min in length), it was obtained from 9 pregnant women (24 ± 3 years old, with foetal gestational ages between 33 and 40 weeks), who provided their informed consent to participate in the study. The setup was composed of a PCG piezoelectric transducer (TK-701T, Nihon KohdenTM) connected to a general purpose amplifier (DA100, Biopac SystemsTM) and the signals were digitized

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at a sampling frequency of 500 Hz. Additionally, the abdominal ECG was recorded as a reference signal.

B. Blind separation of the foetal phonocardiogram

The procedure for decomposing the single-channel abdominal phonogram has been detailed in [19], [20]. In a brief description, the single-channel signal is fragmented into L overlapped segments, $\{S_n\}_{n=1,\ldots,NT}$, each decomposed by SCICA in three steps. First, S_n is projected into an m-dimensional space by using the Method of Delays [21]. Second, m independent components (ICs) are calculated (by using the TDSEP algorithm proposed in [22]) and projected back to the measurement space to produce a set of m IC_ps. Finally, the foetal cardiac IC_ps are automatically grouped and summed to produce an estimate of the segmented FPCG.

The L resulting traces are then scaled and concatenated to form entire time-series that are suitable for further observation and analysis. To this end, and based on the idea by Corsini *et al.* in [23], this work used information in the overlapped sections of consecutive segments (S_β and $S_{\beta'}$) to estimate a scaling factor that, by adaptively correcting the scaling ambiguity of ICA, aimed to smooth sudden variations in the amplitude of the entire time-series. Here, such information was given by the area under the curves within the overlapped sections (a_β and $a_{\beta'}$), which made it possible to find a factor ($a_\beta/a_{\beta'}$) that, when applied to $S_{\beta'}$, produced a scaled segment suitable to be concatenated to S_β as

$$S_\beta(n+N_T)=\frac{a_\beta}{a_{\beta'}}S_{\beta'}(n+N_T-N_{ovl}), \quad (1)$$

for n= 1,…, N_{ovl}, or alternatively,

$$S_\beta(n+N_{ovl})=\frac{a_\beta}{a_{\beta'}}S_{\beta'}(n), \quad (2)$$

for n= 1,…, N_T, where N_T and N_{ovl} are respectively the length of the consecutive segments and the overlapped sections, and the concatenation procedure uses either (1) or (2) to retain the segment with the largest energy.

The whole scaling-concatenating procedure was repeated until the L FPCG traces retrieved by SCICA were adaptively scaled and concatenated into the entire $FPCG_e$ time-series.

C. Empirical extraction of the foetal phonocardiogram

This stage was conducted by de-nosing the abdominal phonogram with the traditional filtering approach. In this context, it is important to mention that the characteristics of the empirical filter used in this work were chosen to be similar to those of the data-driven filters learnt by SCICA [19], [20]. Thus, the entire abdominal phonogram was de-noised using a band-pass filter implemented by an FIR filter with 50 coefficients and fixed cut-off frequencies of 18.8 and 44.5 Hz to give rise to $FPCG_g$.

D. Collecting the foetal heart rate

Once a FPCG signal was available (either $FPCG_e$ or $FPCG_g$), it was further processed to collect the FHR by:

1) Locating the temporal positions of the FHS. This stage was conducted by processing the FPCG trace to produce single-peaks (related to the main heart sounds, S1 and S2) that were easily detected using a threshold. The procedure, applied to windows containing 5000 samples (i.e. about 25 heart beats) was implemented in four steps as:

Single-peaks generation: This stage first reduced large differences between low and high intensity sounds to ease the visual identification of the FHS. Thus, the FPCG in each window was transformed to produce a signal with variance one. Next, the resulting signal was normalised by the sigmoid function $FPCG_{norm}$= (exp(α) − 1)/(exp(α) + 1), where α= (FPCG − mean(FPCG))/std(FPCG). The normalised segment was then transformed to generate an envelope $e(n)$ by means of the Hilbert Transform, a useful approach for heart sounds detection [20], [24], [25]. Finally, to produce a single-peak per heart sound, $e(n)$ was filtered using an FIR band-pass filter with cut-off frequencies of 4 and 11 Hz. This made it easier to associate a single temporal position to each heart sound in the signal, which in this work was given by the maximum of the filtered envelope, $e_f(n)$.

Positions detection: In this step, the positions of the peaks of interest in the current $e_f(n)$ were found by manually establishing a threshold (thr).

Manual corrections: Due to the importance of an appropriate detection of the FHS positions, and knowing that the thresholding process might produce false positives (FP) and/or false negatives (FN), manual corrections were performed to remove high-intensity peaks (due to artefacts) or to insert low-intensity peaks (due to FHS). In this case, the positions of the foetal QRS in the abdominal ECG were used as a visual aid.

The procedure was repeated for each window until the entire FPCG trace was processed and the beat-to-beat temporal positions of the visually enhanced FHS were identified.

Final detection: This step was implemented to remove any possible influence of the enhancing procedure on the actual sounds positions in the FPCG. For this purpose, the positions estimated on the enhanced FHS became the reference for an algorithm to automatically find the peaks on the smoothed envelope of the original FPCG (i.e. without any normalisation), which gave rise to the final temporal positions of S1 and S2.

2) Calculating the beat-to-beat FHR. This parameter was calculated by measuring the beat-to-beat interval between heart sounds (i.e. S1-S1 or S2-S2) to produce the corresponding foetal Cardiotachogram ($FCTG_{S\text{-}S}$). Next, the abnormal intervals in $FCTG_{S\text{-}S}$ (i.e. sudden variations towards either lower or higher heart rates) were carefully examined to establish whether they were caused by wrongly detected FHS positions or by real variations in the cardiac intervals. Then, in those cases where the intervals were confirmed as incorrect, the $FCTG_{S\text{-}S}$ signal was manually amended according to the peaks in the FPCG envelope. Finally, and only to observe the $FCTG_{S\text{-}S}$ trend over time, the corrected $FCTG_{S\text{-}S}$ was interpolated at 4 Hz using a spline function and low-pass filtered using an FIR filter with cut-off frequency of 0.3 Hz and 20 coefficients.

D. Performance evaluation

This stage compared the time-series ($FCTG_{S1\text{-}S1}$ from $FPCG_e$ and $FCTG_{S1\text{-}S1}$ from $FPCG_g$) with the reference signal given by the foetal R-R intervals in the abdominal ECG

($FCTG_r$) [19]. To this end, two parameters were quantified (1) the statistical equivalence (paired *t*-test) between the mean FHR value given by the reference signal and the mean FHR value given by each of the two de-noising approaches studied in this work (i.e. blind separation by SCICA and empirical filtering) and (2) the mean square error (MSE) between each $FCTG_{S1\text{-}S1}$ and the corresponding $FCTG_r$.

III. Results

Figure 1 depicts the FCTGs obtained from one subject. From top to bottom, the $FCTG_r$, the $FCTG_{S1\text{-}S1}$ along with its trend (heavy line), and the $FCTG_{S2\text{-}S2}$ along with its trend (heavy line) are plotted. As can be seen, the noise level changes depending on the event used to measure the beat-to-beat interval (i.e. the foetal QRS complex, S1 or S2), being $FCTG_r$ the least noisy and $FCTG_{S2\text{-}S2}$ the noisiest time-series. Also, as shown by the region enclosed in the dashed rectangle, the level of noise in the $FCTG_{S\text{-}S}$ may change over time, sometimes to deteriorate the quality of the signals and others to improve it. Finally, regarding the FCTG trends, it can be observed that, even though the $CTG_{S\text{-}S}$ may be noisy, the low-pass filtering produces a trend whose beat-to-beat variations resemble the variations in the $FCTG_r$ time-series (especially in the $FCTG_{S1\text{-}S1}$ case). Some of these variations are pointed at by arrows to indicate that, whenever the $FCTG_r$ time-series goes either downwards or upwards, the $FCTG_{S\text{-}S}$ trends follow the same direction.

Table I presents (a) the mean FHR values of the CTGs obtained from the abdominal ECG, the $FPCG_e$, and the $FPCG_g$ signals and (b) the MSE values of the CTGs obtained from the two latter signals. In addition, at the bottom, the table shows the result of the *t*-tests conducted between the mean FHR values given by the reference signal and the mean FHR values given by either $FPCG_e$ or $FPCG_g$ (*p1* and *p2* respectively, for N= 15 cases). As can be seen in columns three and four, even though the mean FHR values obtained by each approach seem to be similar to the reference values in column one, only the first *p*-value is larger than 0.05 (*p1* = 0.695), whereas the second *p*-value is smaller than 0.05 (*p2* = 0.002). Thus, when collected from a blindly separated FPCG as in this work, the mean FHR value is more likely to be equivalent to the mean value given by the abdominal ECG than when collected from an empirically filtered FPCG.

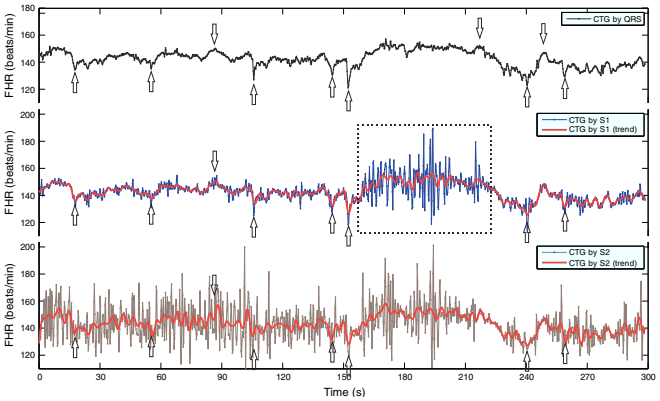

Figure 1. CTGs collected from one subject. From top to bottom, the $FCTG_r$, the $FCTG_{S1\text{-}S1}$ along with its trend (heavy line), and the the $FCTG_{S2\text{-}S2}$ along with its trend (heavy line). The arrows point at upwards/downwards variations in the FHR that are present in the reference signal as well as in the trends of the FCTGs by S1 and S2.

TABLE I. Mean FHR and Mean Square Error (MSE) values of the CTGs collected from the FPCG estimated by de-noising the abdominal phonogram using SCICA and an empirical filter. Also, at the bottom, the p-values (*p1* and *p2*) between the values collected from these two approaches and the reference signal.

	Mean FHR (beats/min)			**MSE (beats^2/min^2)**	
Subject	***CTG_r***	***$CTG_{S1\text{-}S1}$ from $FPCG_e$***	***$CTG_{S1\text{-}S1}$ from $FPCG_g$***	***$CTG_{S1\text{-}S1}$ from $FPCG_e$***	***$CTG_{S1\text{-}S1}$ from $FPCG_g$***
1	142.67	142.66	143.12	30.99	33.22
2	154.23	154.22	154.52	13.73	15.04
3	149.70	149.71	150.44	25.26	39.03
4	127.84	127.83	128.00	11.38	17.54
5	145.64	145.66	147.75	151.00	153.90
6	141.42	141.45	141.64	35.09	45.02
7	148.46	148.49	148.72	18.28	29.61
8	145.06	145.01	146.44	153.31	196.35
9	146.40	146.38	148.16	182.69	239.39
10	136.37	136.34	137.37	59.51	75.51
11	142.52	142.52	142.74	11.29	15.68
12	162.30	162.31	164.47	155.75	264.58
13	142.76	142.74	143.49	44.03	60.38
14	148.29	148.26	149.21	74.70	96.61
15	155.70	155.74	160.08	644.02	718.09
Mean	**145.96**	**145.95**	**147.08**	**107.40**	**133.33**
Std	**8.15**	**8.16**	**8.79**	**160.43**	**181.96**
p-value		*p1= 0.695*	*p2= 0.002*		

Regarding the MSE values, columns five and six indicate that the errors produced when collecting the FHR from the $FPCG_e$ are consistently smaller than the errors produced when collecting the parameter from the PCG_g. This means that the level of variations (i.e. noisiness) introduced when collecting the FHR from $FPCG_e$ is more likely to be lower than the noisiness introduced when collecting the FHR from $FPCG_g$. In other words, when measuring beat-to-beat FHR, the values collected from the FPCG estimated by SCICA are more likely to present smaller errors than the values collected from an empirically obtained FPCG.

IV. Discussion

This work explored the suitability of using the FPCG blindly extracted from the abdominal phonogram as a source for FHR measuring in antenatal surveillance. Results are promising, entire independent sources of the FPCGs underlying the abdominal phonogram have been estimated and further processed to obtain the beat-to-beat FHR time-

series. Moreover, signals collected from a dataset of 15 blindly estimated FPCGs showed (1) that measuring the beat-to-beat FHR by using S1 (i.e. $FCTG_{S1\text{-}S1}$) and S2 (i.e. $FCTG_{S2\text{-}S2}$) was suitable and (2) that both time-series are more likely to present larger beat-to-beat variations than the reference FCTG (i.e. CTG_r). Such variations, here referred to as noisiness, have been found to be larger and more frequent in $FCTG_{S2\text{-}S2}$ than in $FCTG_{S1\text{-}S1}$. This situation can be explained by the typical lower amplitude of S2 in the estimated FPCGs in this study, which means that the signal to noise ratio (SNR) of the FHS becomes an important factor when measuring the beat-to-beat intervals.

To deal with the noisiness problem, and aiming to produce a FCTG closer to CTG_r, the $FCTG_{S1\text{-}S1}$ and $FCTG_{S2\text{-}S2}$ time-series were low-pass filtered to obtain their trend. The resulting signals are more alike to the trend of the reference CTG but, as can be noticed, the filtered $FCTG_{S2\text{-}S2}$ is still noisier than the filtered $FCTG_{S1\text{-}S1}$ and therefore noisier than the $FCTG_r$. Moreover, the noisiness in $CTG_{S2\text{-}S2}$ may turn into slow oscillations that might be easily taken as normal variations and lead to wrong interpretations about foetal status, which is an inconvenient outcome. Based on these results, and knowing that lower SNR values of S2 were likely to persist in the estimated FPCGs, the calculation of the instantaneous FHR by means of S2 was excluded of this study (at least until a more robust CTG estimation method becomes available).

Finally, after statistically testing the information collected in this study, it can be said that the FPCGs retrieved by de-noising the abdominal phonogram using SCICA are likely to be useful for antenatal surveillance of FHR. In particular, as far as the study described in this work has gone, it has been observed that the mean values of the FHR collected from the signals estimated by SCICA are statistically equivalent to the values given by the abdominal ECG. Conversely, the mean FHR values collected from the signals retrieved by the empirical filter have been statistically different to the FHR collected from the abdominal ECG. Thus, although further research on a larger dataset must be performed, results achieved in this work point at the feasibility of using the FPCG obtained by de-noising the abdominal phonogram with SCICA as a source for FHR measuring in antenatal surveillance. Future work will focus on studying spectral and non-linear information provided by the FCTG time-series and their comparison with the information provided by the reference FCTG.

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