Annotated real and synthetic datasets for non-invasive foetal electrocardiography post-processing benchmarking

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**ABSTRACT**

Non-invasive foetal electrocardiography (fECG) can be obtained at different gestational ages by means of surface electrodes applied on the maternal abdomen. The signal-to-noise ratio (SNR) of the fECG is usually low, due to the small size of the foetal heart, the foetal-maternal compartment, the maternal physiological interferences and the instrumental noise. Even after powerful fECG extraction algorithms, a post-processing step could be required to improve the SNR of the fECG signal. In order to support the researchers in the field, this work presents an annotated dataset of real and synthetic signals, which was used for the study “Wavelet Denoising as a Post-Processing Enhancement Method for Non-Invasive Foetal Electrocardiography” \cite{1}. Specifically, 21 15 s-long fECG, dual-channel signals obtained by multi-reference adaptive filtering from real electrophysiological recordings were included. The annotation of the foetal R peaks by an expert cardiologist was also provided. Recordings were performed on 17 voluntary pregnant women between the 21st...
Specifications Table

| **Subject** | Biomedical Engineering |
|-------------|------------------------|
| **Specific subject area** | Non-invasive foetal electrocardiography |
| **Type of data** | Biosignals: ECG, real (1) and synthetic (2) - .csv files |
| | Annotations (fECG QRS position) - .csv files |
| **How data were acquired** | 1. Portable physiological measurement system |
| | Instruments: hardware, software |
| | Model and maker: Porti7 hardware and PolyBench software, by TMSi, The Netherlands |
| | 2. Physiological signal simulator |
| | Instruments: software |
| | Model and maker: FECGSYN tool [2–4] |
| **Data format** | Raw |
| | Filtered |
| | Annotations |
| **Parameters for data collection** | 1. Pregnant women between the 21st and the 27th week of gestation with healthy foetuses |
| | 2. Maternal ECG at 90 bpm, fECG at 150 bpm, SNR of fECG relative to maternal ECG at –18 dB, only white and pink noise, unique foetal and maternal heart positions and unique electrode map |
| **Description of data collection** | 1. Real biopotentials acquired with the subject at rest, in a comfortable semi-sitting position. Prior to the electrodes' application on the abdomen and torso, a mild skin treatment was performed to reduce the skin contact impedance |
| | 2. Synthetic biopotentials were created with the FECGSYN tool [2–4] in order to have access to the fECG signal corrupted by artificial noise but free from the maternal ECG interference |

(continued on next page)
Value of the Data

- These data are useful to benchmark different fECG denoising algorithms.
- These data are mainly conceived for researchers working on non-invasive fECG signal processing.
- By including the real raw signals acquired with surface ECG electrodes on the maternal body, the data can be also used to test non-invasive fECG extraction algorithms.
- These data are particularly important, considering the lack of annotated fECG datasets in early pregnancy.

1. Data Description

The dataset is composed of 63 .csv files for the real data and 120 .csv files for the synthetic data.

Regarding the real recordings, 63 .csv files include:

(I) 21 .csv files consisting of raw and processed recordings (each data file containing: three non-coplanar maternal ECG leads, horizontal, vertical and oblique abdominal leads, extracted horizontal, vertical and oblique fECG leads).
(II) 21 .csv files composed of only the extracted fECG leads used in [1].
(III) 21 .csv files reporting the R peaks annotation for the corresponding data file. The annotation files present the number of samples in which the cardiologist labelled the R peaks.

Regarding the synthetic data, there are:

(I) 40 .csv file storing the completely clean fECG, the pink and the white noise.
(II) 40 .csv files reporting the R peak annotations provided by the FEGSYN tool [2–4].
(III) 40 .csv files storing the simulated extracted abdominal fECG created by the summation of the completely clean fECG, the pink and the white noise, as used in [1].

Table 1 illustrates the structure of the proposed dataset. The signals used in [1] are those identified as Real_FECG_n (with the annotations in Real_FECG_n_ann) for the real dataset, and Synth_FECG_n (with the annotations in Synth_ann_n) for the synthetic dataset. The files Real_Traces_n can be useful for the researchers willing to try different fECG extraction algorithms before the post-processing stage. For both the real and synthetic data, sampling frequency is 2048 Hz. The chosen format allows an easy importing by different software processing tools.

All real and synthetic data are meant to be used as a benchmark for fECG post-processing techniques, thus enabling the homogeneous analysis of different denoising algorithms, applied after the fECG extraction process, which is still missing in the scientific literature. Moreover, these data can also be used as raw signals for the evaluation of different foetal QRS detection algorithms and fECG extraction methods, providing the annotation of the foetal QRS complexes.
Table 1

Dataset description. For both the real and synthetic data, sampling frequency is 2048 Hz.

| DATA             | FILES                  | FILE STRUCTURE BY COLUMN                                                                 |
|------------------|------------------------|-----------------------------------------------------------------------------------------|
| REAL DATA        | 21 .csv files named    |                                                                                         |
|                  | Real_Traces_n          | 1. first maternal ECG lead                                                               |
|                  |                        | 2. second maternal ECG lead                                                              |
|                  |                        | 3. third maternal ECG lead                                                               |
|                  |                        | 4. horizontal abdominal lead                                                             |
|                  |                        | 5. vertical abdominal lead                                                               |
|                  |                        | 6. oblique abdominal lead                                                                |
|                  |                        | 7. fECG extracted from the horizontal lead                                              |
|                  |                        | 8. fECG extracted from the vertical lead                                                 |
|                  |                        | 9. fECG extracted from the oblique lead                                                  |
| SYNTHETIC DATA   | 21 .csv files named    | The selected two fECG signals used in [1]. Table 4 lists the selected leads.            |
|                  | Real_FECG_n            |                                                                                         |
|                  |                        | Sample numbers related to foetal R peaks (manual annotations)                           |
|                  |                        |                                                                                         |
|                  | 40 .csv files named    |                                                                                         |
|                  | Synth_FECG_n           | 1. noisy fECG signal contributing to the horizontal abdominal lead (free from maternal interference) |
|                  |                        | 2. clean fECG signal contribution to the horizontal abdominal lead                       |
|                  |                        | 3. additive pink noise                                                                  |
|                  |                        | 4. additive white noise                                                                  |
|                  |                        |                                                                                         |
|                  | 40 .csv files named    |                                                                                         |
|                  | Synth_components_n     |                                                                                         |
|                  |                        | Sample numbers related to foetal R peaks (provided by the FECGSYN tool)                 |
|                  |                        |                                                                                         |
|                  | 40 .csv files named    |                                                                                         |
|                  | Synth_ann_n            |                                                                                         |

2. Experimental Design, Materials and Methods

The dataset is composed of two parts, real and synthetic signals, in order to analyse all possible effects introduced by fECG post-processing algorithms. In this regard, while the former enables an actual analysis of their outcome in real applications, a ground truth of the noiseless fECG waveforms is provided only by synthetic signals. Thus, only in the latter case an evaluation of possible morphological distortions due to the processing stages can be carried out.

2.1. Synthetic Dataset

An open-source simulator for non-invasive fECG research was adopted to create a small synthetic dataset [2–4]. The tool can be freely downloaded.\(^1\)

By means of this tool, it is possible to generate several maternal-fECG mixtures, selecting the beat-to-beat variability, heart rate baseline value and changes, the SNR of the fECG relative to the maternal ECG (\(SNR_{fm}\)), the SNR of the maternal ECG relative to noise (\(SNR_{mn}\)), the position and orientation of the foetal and maternal hearts, foetal movements and uterine contractions. The toolbox calibrates the physiologic and noise components with respect to the maternal ECG signal by choosing the \(SNR_{fm}\) and the \(SNR_{mn} \).

For the creation of the dataset presented in this work, all parameters were selected in order to simulate physiologically plausible recordings and, wherever possible, in accordance with the real dataset acquisition setup. Specifically, the sampling frequency was set to 2048 Hz, as in the real dataset, and the signal duration to 10s. The maternal and foetal heart rates were assumed to be fixed at respectively 90 and 150 bpm. The maternal heart coordinates were imposed equal to \([\frac{3}{2}\pi, 0.2, 0.4]\) and those of the foetus to \([-0.412, 0.284, -0.300]\). The coordinates of the virtual surface electrodes detecting the abdominal ECGs were set to \([-0.524, 0.500, -0.250]\) and \([0.785, 0.500, -0.250]\), which correspond to the schematic representation depicted in Fig. 1.

\(^1\) Available at [http://fernandoandreotti.github.io/fecgsyn/](http://fernandoandreotti.github.io/fecgsyn/)
Virtual electrodes capture unipolar signals, referenced to a common GD electrode, so that a single differential lead was digitally created by subtracting the signal detected by the electrode 2 to the one detected by the electrode 1.

By construction, the differential abdominal lead was obtained completely free of the maternal ECG components, as it would happen when the signal is produced by a perfect fECG extraction stage. For the same reason, we avoided adding realistic noise sources mimicking muscular artefacts, baseline wander and electrode movements. Conversely, white and pink noises created by using the OSET toolbox [5] were added to the abdominal lead, with amplitudes chosen according to the desired SNR. Since the FECGSYN tool does not allow to set directly the SNR of fECG relative to noise, we set the $SNR_{fn}$ to $-18\,\text{dB}$, whereas $SNR_{nn}$ was linearly varied in the range between $3\,\text{dB}$ and $15\,\text{dB}$ producing the 40 synthetic signals released in this dataset. Table 2 lists the SNR level characterizing each synthetic trace.

The signals accompanying the synthetic dataset used in [1] (Synth_FECG._n, i.e. the abdominal fECG signal with added pink and white noises scaled as in Table 2, and the associated foetal QRS annotations provided by the FECGSYN toolbox, Synth_ann.n) are provided along with the clean fECG signal on the abdominal lead and the noise sources (white and pink) properly scaled to give rise, by summing them to the clean fECG, to the noisy synthetic fECG signal. Such signals, stored in the Synth_components.n files, can be useful for the computation of some performance metrics characterizing the capability of the post-processing algorithms to preserve the fECG morphology, such as root-mean-square error and linear or non-linear correlation coefficients.

Two examples of the abdominal lead for two virtual foetuses included in this dataset are shown in Figs. 2 and 3.

2.2. Real dataset

The real dataset was derived from 21 recordings that were acquired at the Division of Paediatric Cardiology, San Michele Hospital, Cagliari (Italy) by the authors. The recording protocol was approved by the Independent Ethical Committee of the Cagliari University Hospital (AOU
Table 2

SNR\textsubscript{mn} values for all the signals composing the synthetic dataset.

| SIGNAL          | SNR\textsubscript{mn} [dB] | Signal      | SNR\textsubscript{mn} [dB] |
|-----------------|----------------------------|-------------|----------------------------|
| Synth_FECG_1    | 3.00                       | Synth_FECG_21 | 9.15                       |
| Synth_FECG_2    | 3.31                       | Synth_FECG_22 | 9.46                       |
| Synth_FECG_3    | 3.62                       | Synth_FECG_23 | 9.77                       |
| Synth_FECG_4    | 3.92                       | Synth_FECG_24 | 10.10                      |
| Synth_FECG_5    | 4.23                       | Synth_FECG_25 | 10.38                      |
| Synth_FECG_6    | 4.54                       | Synth_FECG_26 | 10.69                      |
| Synth_FECG_7    | 4.85                       | Synth_FECG_27 | 11.00                      |
| Synth_FECG_8    | 5.15                       | Synth_FECG_28 | 11.31                      |
| Synth_FECG_9    | 5.46                       | Synth_FECG_29 | 11.62                      |
| Synth_FECG_10   | 5.77                       | Synth_FECG_30 | 11.92                      |
| Synth_FECG_11   | 6.08                       | Synth_FECG_31 | 12.23                      |
| Synth_FECG_12   | 6.39                       | Synth_FECG_32 | 12.54                      |
| Synth_FECG_13   | 6.69                       | Synth_FECG_33 | 12.85                      |
| Synth_FECG_14   | 7.00                       | Synth_FECG_34 | 13.15                      |
| Synth_FECG_15   | 7.31                       | Synth_FECG_35 | 13.46                      |
| Synth_FECG_16   | 7.62                       | Synth_FECG_36 | 13.77                      |
| Synth_FECG_17   | 7.92                       | Synth_FECG_37 | 14.08                      |
| Synth_FECG_18   | 8.23                       | Synth_FECG_38 | 14.38                      |
| Synth_FECG_19   | 8.54                       | Synth_FECG_39 | 14.69                      |
| Synth_FECG_20   | 8.85                       | Synth_FECG_40 | 15.00                      |

Fig. 2. Example of the signals involved in the creation of a horizontal abdominal lead of the synthetic dataset, characterized by an SNR\textsubscript{mn} of 3 dB. From top to bottom, the clean FECG signal, the pink noise, the white noise, and the noisy FECG signal obtained by their sum. Amplitudes are dimensionless.

Cagliari) and performed following the principles outlined in the Helsinki Declaration of 1975, as revised in 2000. The volunteers provided their signed informed consent to the protocol. The recordings were carried out with the patient in a comfortable semi-sitting position. Before applying the electrodes, mild skin treatment was performed on the maternal abdomen by using an abrasive gel (NuPrep, by Weaver and Company, USA) to reduce the skin contact impedance.

The signals originated from 17 pregnant women satisfying the inclusion criteria during the dataset acquisition time frame, i.e. healthy foetuses between the 21st and 27th weeks of gestation. For each voluntary woman, only one recording session was performed, from which the good-quality abdominal signals’ segments were extracted. The relevant anamnestic information
Fig. 3. Example of a 15 dB horizontal abdominal lead of the synthetic dataset (lowest plot) along with the three components giving rise to it: the pure foetal ECG signal (upper plot), the pink noise (second row) and white noise (third row). Amplitudes are dimensionless.

Table 3
Real dataset relevant anamnestic information (foetal presentation: L: left, R: right, O: occiput, S: sacrum, T: transverse, P: posterior A: anterior). Abdominal signals acquired from the same foetus are grouped together in the same row.

| REAL SIGNAL | week of gestation | foetus presentation |
|-------------|-------------------|---------------------|
| 1           | 24                | breech,             |
| 2           |                   | LST                 |
| 3           |                   |                     |
| 4           | 21                | breech,             |
| 5           |                   | RSP                 |
| 6           | 24                | breech, RSP         |
| 7           | 26                | vertex, ROP         |
| 8           | 25                | breech, RSP         |
| 9           | 25                | vertex, ROP         |
| 10          | 24                | vertex, LOP         |
| 11          | 21                | breech, RSP         |
| 12          | 25                | breech, RSP         |
| 13          | 24                | breech, LSP         |
| 14          | 24                | breech, LSP         |
| 15          | 21                | vertex,             |
| 16          |                   | OP                  |
| 17          | 22                | breech, LSP         |
| 18          | 24                | vertex, LOP         |
| 19          | 26                | vertex, ROP         |
| 20          | 25                | breech, LSP         |
| 21          | 23                | vertex, LOP         |

is provided in Table 3. The gestational epoch was selected to have the best morphological accuracy for the transabdominal signals. The lower limit is due to the small size of the foetus heart, that cannot guarantee a good signal acquisition, whereas the upper limit allows reducing the influence of the vernix caseosa, a waxy insulating biological layer completely covering the foetal skin between the 28th to the 32nd week of gestation [6]. During this time frame, the fECG signal propagation towards the maternal abdomen is hampered, making the foetal signal hardly detectable with surface electrodes. After the 32nd week of gestation, this layer is usually
while unipolar signal validated mainly filter the phase processing. to device coefficients ECG leads be algorithms other from decomposition fECG 1–2 indicated common-mode for channels and characterized non-invasively for the raw signal is influenced by the number of used channels in the measurement. Three differential channels were used on the maternal thorax for the acquisition of a reference maternal ECG, whereas 24 unipolar channels were used on the abdomen, in order to have the highest possible SNR on the abdominal signals in terms of common-mode signal rejection. Among the unipolar channels, only three of them, clearly indicated in Fig. 4, were selected to give rise to three abdominal differential leads digitally, such as 1–2 to obtain a horizontal lead, 2–3 to obtain a vertical lead and 1–3 to obtain an oblique lead.

In order to obtain the fECG, among the various methods available for the extraction of the fECG from non-invasive recordings, we chose to exploit a high-performance multireference QR-decomposition with back-substitution recursive least-squares (QRD-RLS) adaptive filter, available from the authors of [8], given its numerical stability and good performance [9]. Compared to other techniques, such as blind source separation [10,11], adaptive filters are real-time algorithms to extract the fECG from a reduced number of abdominal electrodes, which can be useful for wearable systems [12] and real-time embedded platforms [11]. The three thoracic leads were used as reference signals in order to produce a good representation of the maternal ECG on the abdomen. The forgetting factor $\lambda$ was set to 0.999 while the number of filter coefficients was set to 20, in accordance with previous studies [13]. Considering that the recording device adopted for the raw data collection was DC-coupled, all the leads were pre-processed to reduce the baseline wandering artefact in order to facilitate the QRD-RLS adaptive filter processing. In fact, such an artefact appears in different forms in the various leads and cannot be reduced by the application of the adaptive filter. Pre-processing consisted of a high-pass linear-phase equiripple finite impulse response filter with a cut-off frequency of 1 Hz. Compared with the current guidelines that would impose a 0.67 Hz limit for the cut-off frequency of ECG signals [14], some studies on non-invasive fECG proved that a higher cut-off frequency of the high-pass filter allows achieving better results, still preserving the low-frequency components of the ECG, mainly related to P and T and to the ST segments [13].

The whole processing chain used to extract the fECG is presented in Fig. 5.

The annotation of the foetal QRS complexes (Real_FECG_n_ann) was performed manually and validated by the cardiologist with the help of a simultaneous cardiac foetal pulsed-wave Doppler signal recorded during the procedure, thus providing a mechanical reference for the electrophys-
Fig. 5. Schematic representation of the whole processing chain for fECG extraction. Three thoracic leads along with each abdominal trace are pre-processed with a high-pass filter with a cut-off frequency of 1 Hz and passed to the QRD-RLS adaptive filter for fECG extraction. Red dots mark the foetal QRS complexes.

Fig. 6. Example of raw abdominal traces (upper plots) and the corresponding extracted foetal ECG signals (lower plots). From the left to the right: horizontal, vertical and oblique leads. Red markers indicate the manually-annotated foetal R peaks.

iological signal. Despite the low signal-to-noise ratio of some real traces, the presence of three different simultaneous abdominal leads (horizontal, vertical and oblique) helps the R peaks annotation, enabling the identification of clear foetal R peaks at least in one good-quality trace. The annotation procedure was verified before and after the fECG extraction process to provide the most accurate indication of the foetal QRS complexes.

Some examples of the extracted fECG are shown in Fig. 6. From this inspection, it emerged that some extracted fECG channels were unreadable, from a clinical perspective. In order to use
Table 4
The abdominal leads chosen for the study [1] and included in the real dataset.

| SIGNAL          | fecg channel 1  | FECG CHANNEL 2 |
|-----------------|-----------------|----------------|
| Real_FECG_1     | horizontal      | oblique        |
| Real_FECG_2     | horizontal      | oblique        |
| Real_FECG_3     | horizontal      | oblique        |
| Real_FECG_4     | horizontal      | vertical       |
| Real_FECG_5     | horizontal      | vertical       |
| Real_FECG_6     | horizontal      | oblique        |
| Real_FECG_7     | vertical        | oblique        |
| Real_FECG_8     | horizontal      | oblique        |
| Real_FECG_9     | horizontal      | oblique        |
| Real_FECG_10    | horizontal      | oblique        |
| Real_FECG_11    | horizontal      | oblique        |
| Real_FECG_12    | horizontal      | oblique        |
| Real_FECG_13    | horizontal      | vertical       |
| Real_FECG_14    | horizontal      | oblique        |
| Real_FECG_15    | vertical        | oblique        |
| Real_FECG_16    | vertical        | oblique        |
| Real_FECG_17    | vertical        | oblique        |
| Real_FECG_18    | vertical        | oblique        |
| Real_FECG_19    | horizontal      | oblique        |
| Real_FECG_20    | vertical        | oblique        |
| Real_FECG_21    | vertical        | oblique        |

Fig. 7. Main different foetal heartbeat morphologies from the real dataset. Specifically, the represented foetal QRS complexes were obtained by synchronized averaging of the highly correlated beats (Pearson’s correlation coefficient > 0.6) after wavelet post-processing exploiting Stationary Wavelet Transform with 7-level decomposition and Han et al. threshold [1].

Along with the real fECG dataset, the raw thoracic maternal ECG differential leads, the three abdominal recordings and the fECG signals extracted by the method presented above were included in a separate file (Real_Traces_n) for those scientists interested in applying and benchmarking different fECG extraction algorithms before the post-processing stage.
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

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Supplementary Materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.dib.2020.106399.

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