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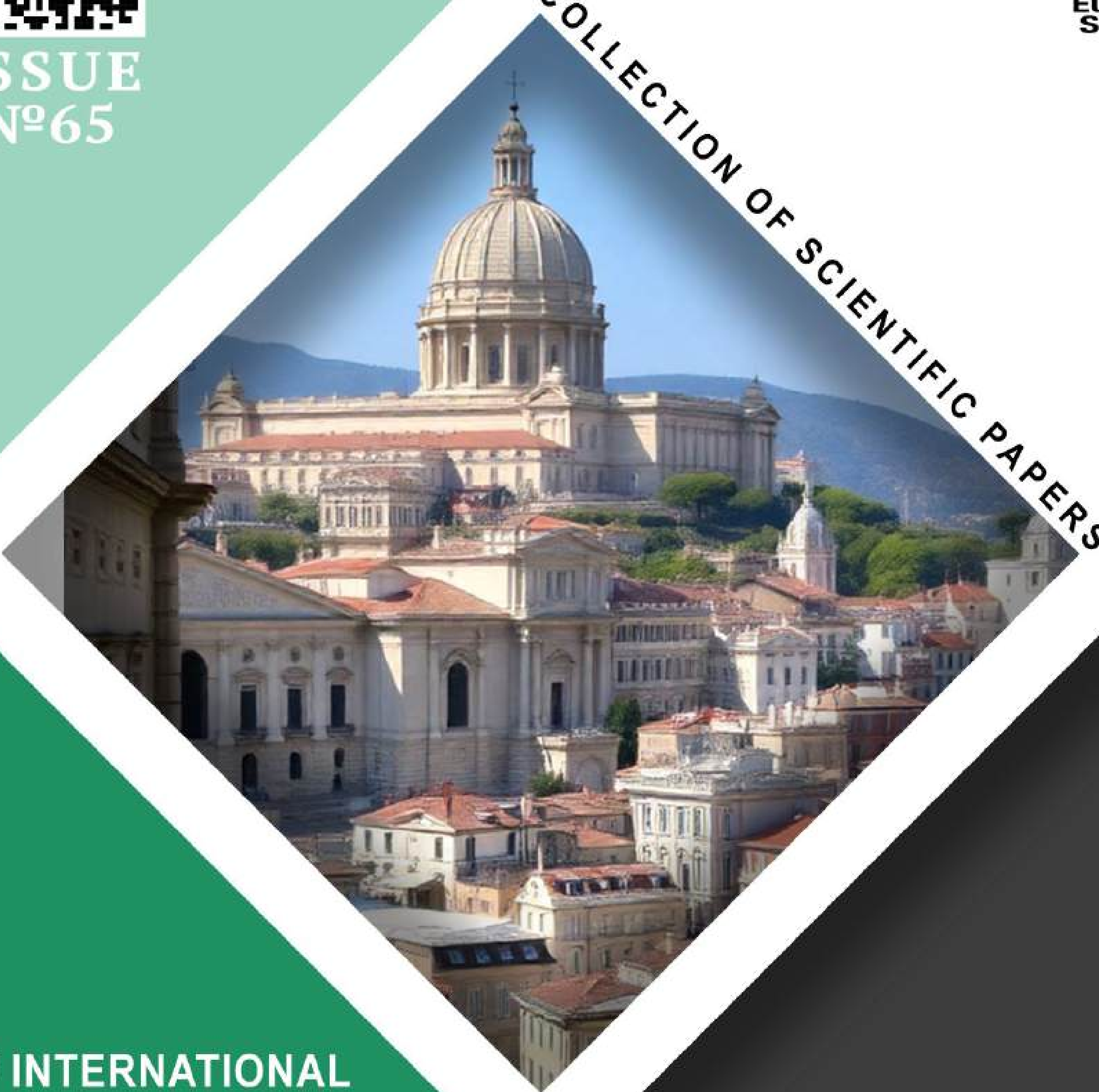
ISSUE №65

COLLECTION OF SCIENTIFIC PAPERS

EUROPEAN OPEN SCIENCE SPACE



4TH INTERNATIONAL SCIENTIFIC AND PRACTICAL CONFERENCE

SCIENTIFIC INNOVATION: THEORETICAL INSIGHTS AND PRACTICAL IMPACTS

DECEMBER 8-10, 2025, NAPLES, ITALY

UDC 01.1

Collection of Scientific Papers with the Proceedings of the 4th International Scientific and Practical Conference «Scientific Innovation: Theoretical Insights and Practical Impacts» (December 8-10, 2025, Naples, Italy). European Open Science Space, 2025. 507 p.

ISBN 979-8-89704-952-3 (series)
DOI 10.70286/EOSS-08.12.2025

The conference is included in the Academic Research Index ReserchBib International catalog of scientific conferences.

The conference is registered in the database of scientific and technical events of UkrISTEI to be held on the territory of Ukraine (Certificate №572 dated 16.06.2025).

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ISBN 979-8-89704-952-3

METHOD FOR ASSESSING THE PRESENCE OF FETAL HEART ACTIVITY BASED ON TEMPLATE SUBTRACTION AND WAVELET ANALYSIS

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Noninvasive analysis of the abdominal ECG signal (aECG) is one of the most promising methods for fetal monitoring in late pregnancy. The main problems of this approach are the low amplitude of the fetal electrocardiogram (fECG), significant overlap of the maternal ECG signal (mECG), motor and electromyographic artifacts [1]. As a result, the separation of fetal cardiac activity becomes more difficult, and traditional filtering approaches often prove to be insufficiently robust at low signal-to-noise ratios [2, 3, 4].

One effective solution is multi-stage signal processing using wavelet analysis, which provides simultaneous temporal and frequency localization of fetal QRS complexes, which have a significantly higher frequency than maternal ones [5, 6].

The developed method of detecting fetal cardiac activity is based on the sequential transformation of the abdominal ECG signal in order to suppress the dominant maternal ECG and amplify the high-frequency components characteristic of fetal QRS complexes. The initial signal x(t) entering the system input is described by the mixed source model:

$$x(t) = m(t) + f(t) + n(t), \tag{1}$$

where $m(t)$ – maternal ECG signal, $f(t)$ – fetal component, a $n(t)$ – noise and motion artifacts.

For digital processing, the corresponding representation is used in the form:

$$x[n] = m[n] + f[n] + n[n], \tag{2}$$

Since the maternal component has a much larger amplitude, the primary task is to form the most accurate mECG template and its subsequent subtraction. For this, the signal is pre-filtered in the range of 0.5-70 Hz, which ensures the suppression of low-frequency artifacts and high-frequency technical noise. After filtering, the maternal R-peaks are detected according to the principle of the modified Pan–Tompkins algorithm; the obtained moments t_k are used to construct the averaged maternal template:

$$T(\tau) = \frac{1}{K}\sum_{k=1}^{K} m(t_k + \tau), \tag{3}$$

which allows to reproduce the characteristic morphology of the mother's QRS complex. Since the amplitude of individual cardiac cycles can vary, the template is scaled individually for each complex by the factor:

$$\hat{m}[n] = \alpha_k T[n - n_k], \tag{4}$$

which ensures that the shape of the template matches the specific cardiac cycle.

After scaling, the template subtraction is performed:

$$y[n] = x[n] - \hat{m}[n], \tag{5}$$

as a result, the maternal component is largely suppressed, and the fetal QRS complexes, on the contrary, become relatively more pronounced. However, even after this stage, the signal may contain residual high-frequency mECG fragments, noise and artifacts. Therefore, the next step is to amplify the frequency range characteristic of the fetal ECG (20-70 Hz), which further improves the separation between residual maternal activity and fetal complexes.

At this stage, a signal is formed that is suitable for analysis by multiscale methods, so a wavelet transform is applied. For this, an orthonormal Daubech basis (db4/db6) is used, which corresponds well to the morphology of QRS complexes. Continuous or discrete wavelet transform [7-9]:

$$W(j,k) = \sum_n y[n]\psi_{j,k}(n), \tag{6}$$

allows to distinguish structures localized in time and frequency, concentrated in the vicinity of sharp changes characteristic of fetal cardiac complexes. To increase the reliability of detection, a multiscale indicator is formed:

$$I[k] = |W_3(k)W_4(k)|, \tag{7}$$

which simultaneously takes into account information from several scales, which allows to suppress noise and enhance consistent components of the fECG.

In order to separate reliable fetal complexes from noise peaks, an adaptive threshold is used:

$$\theta = \mu_I + \lambda\sigma_I, \tag{8}$$

where μ_I та σ_I – indicator statistics in the working interval. Positions of points in which:

$$I[k] > \theta, \tag{9}$$

interpreted as candidates for fetal R-peaks. The final check is based on the physiological regularity of the intervals between peaks, which should correspond to the fetal heart rate range:

$$120 \le HR_f \le 180 \text{ beats/min}, \tag{10}$$

If the sequence of R-peaks satisfies the regularity conditions, the system forms a conclusion about the presence of reliable fetal cardiac activity.

Thus, the proposed method provides a smooth transition from filtering and template-based mECG silencing to wavelet-oriented detection of fetal complexes, combining several complementary stages into a single holistic algorithm.

A fragment of the abdominal ECG signal before processing is shown in Fig. 1.

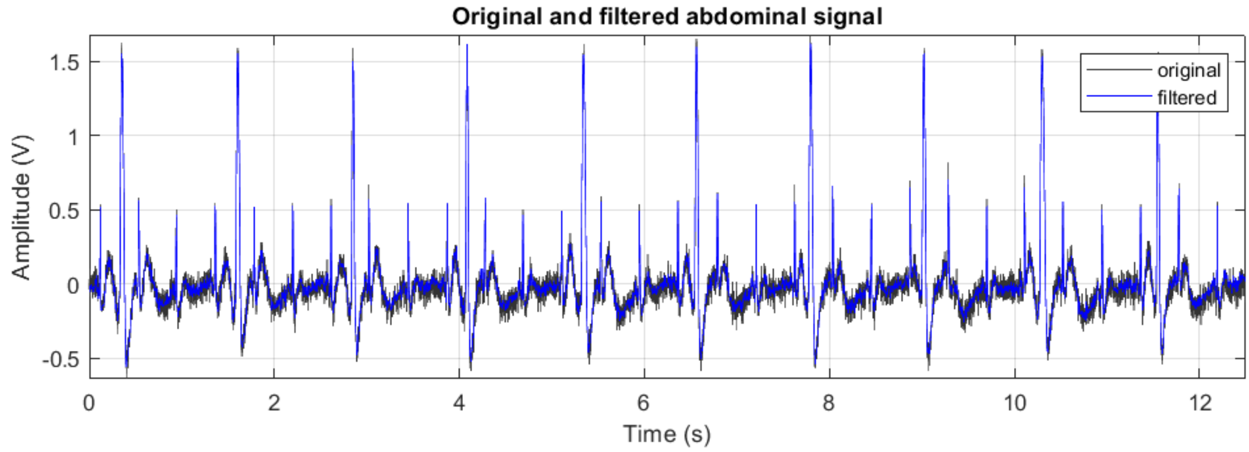

Fig. 1. Abdominal ECG signal before filtering and filtered

The fragment demonstrates the dominance of mECG and low visibility of fetal complexes.

The signal after template subtraction is shown in Fig. 2

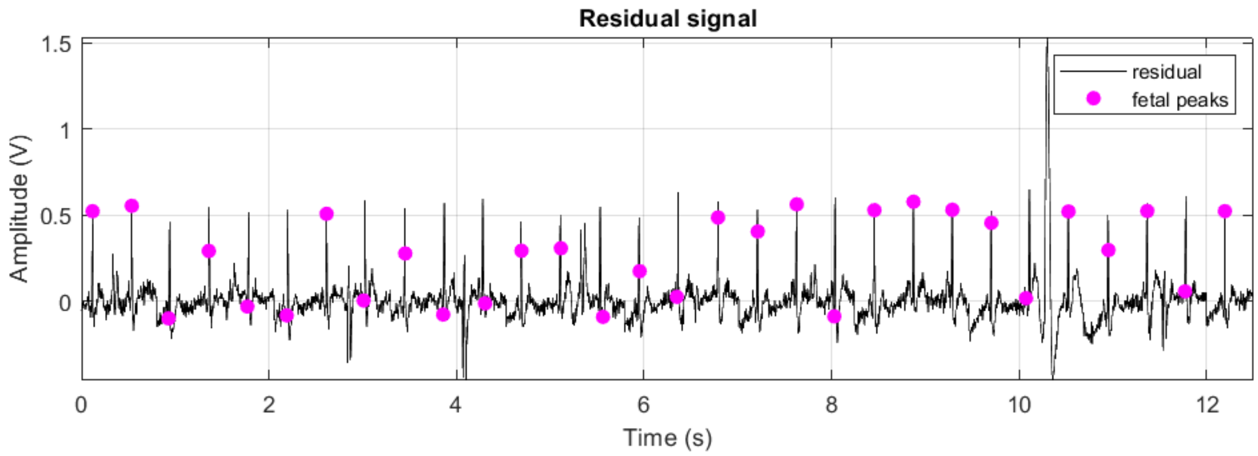

Fig. 2. Signal after removal of the parent template

It is noticeable that high-frequency fetal QRS complexes become more pronounced.

The wavelet indicator (VWT) of the fetal ECG signal is shown in Fig. 3.

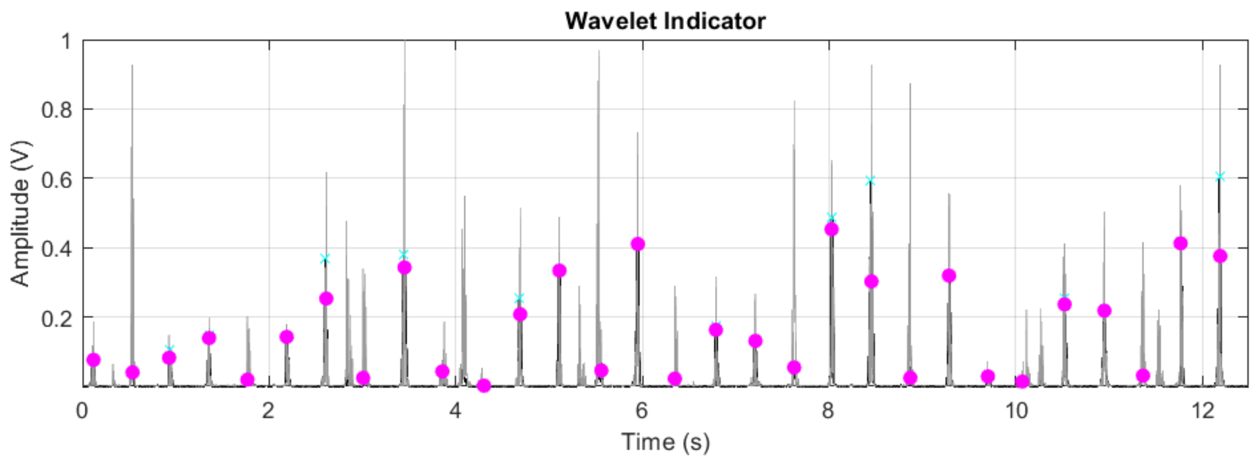

Fig. 3. Multi-scale fECG detection indicator

The indicator peaks in Fig. 3 correspond to the positions of the fetal R-peaks.

Fig. 4 shows the set of fetal complexes obtained after a full processing cascade, including filtering, adaptive maternal complex removal, fetal range amplification, and fetal peak detection.

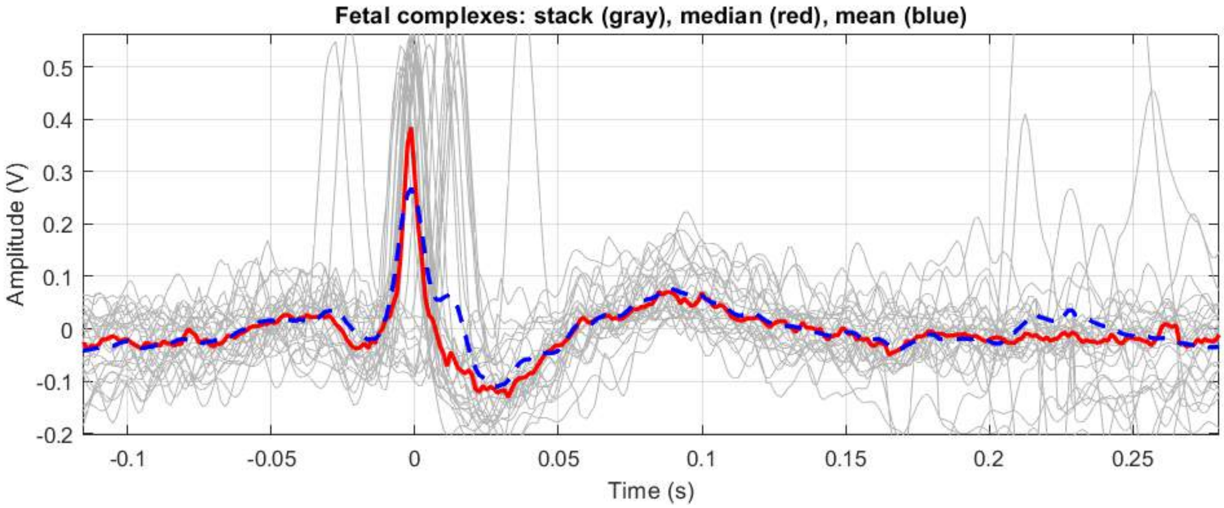

Fig. 4. Fetal complexes: stack (gray), median (red), mean (blue)

The data in Fig. 4 demonstrate the clear presence of fetal cardiac activity: the processed abdominal ECG clearly reproduces a characteristic and stable fetal QRS complex, which scientifically confirms the presence of a fetal ECG signal in the recording.

The algorithm correctly determined the presence of regular fetal activity with an average frequency: HRf=145 beats/min.

The work developed a method for automated detection of fetal cardiac activity in abdominal ECG recordings based on template removal of the maternal ECG, amplification of the fetal frequency band, multiscale wavelet processing and adaptive thresholding with physiological verification of RR intervals.

The proposed method demonstrates high noise immunity and allows you to accurately determine the presence of fECG even at a low signal level.

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ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ПРОМИСЛОВИХ СИСТЕМ ЗА ДОПОМОГОЮ ПРОГРАМОВАНИХ ЛОГІЧНИХ КОНТРОЛЕРІВ

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Однією з ключових технологій, яка відіграє важливу роль в автоматизації виробничих процесів, є програмовані логічні контролери (ПЛК). ПЛК представляє собою спеціалізований пристрій, який призначений для контролю та керування різноманітними процесами [1].