Identification of Abdominal ECG Lead Location Over Fetal Development for Non-invasive Single Channel W-NETR Fetal ECG Extractor

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Abstract

Recent research has focused on noninvasive techniques for capturing fetal ECGs (fECGs) using abdominal electrodes. These existing systems typically rely on a sophisticated and high number of abdominal ECG leads. The recently proposed W-NETR method addresses easy and real-time usability utilizing only a single non-invasive abdominal ECG lead using a deep learning approach. Despite its accuracy, its performance is influenced by precise lead placement, affecting its practical implementation. This study explores the optimal abdominal ECG lead placement for precise fECG extraction in early (20-22 weeks) and late (37-40 weeks) gestational periods. Using an 11-lead prototype by Atom Medical Co, we identify the best lead on the upper abdomen in the early stage and on the lower abdomen in the late stage, with a right back-placed reference electrode. We found that the single-leaded W-NETR pipeline not only accurately reconstructs fECG but also surpasses ground truth through enhanced noise filtration when optimal lead placement is used. This discovery opens avenues for implementing such lightweight models in future real-life fECG extractors, leveraging its computational efficiency and high performance.

1. Introduction

Monitoring maternal and fetal ECGs is essential for assessing both the mother's and baby's health during pregnancy [1]. Recent studies focus on noninvasive fetal ECG (fECG) extraction using abdominal electrodes. However, clinical systems rely on multiple leads, such as the 11-lead system proposed by Doshi et al. [2].

Efforts have been made to simplify this process by using algorithms that extract fECG from a single abdominal lead [3]. Although these methods show promise, performance is sensitive to lead placement. In our previous study [3], transformer-based deep learning was used for single-lead extraction, demonstrating high accuracy on datasets like ADFECGDB [4] and PCDB [5], which performed poorly though certain leads in these datasets.

This study aims to determine the optimal abdominal lead placement for accurate single-channel fECG extraction, which may vary with fetal development. We analyzed data from an 11-lead system during gestational weeks 20-22 and 37-40, using our W-NETR pipeline [3] to extract fECG signals. We compared these to ground truth signals using the Structural Similarity Index (SSIM) [6] to identify the best lead placement for each stage of pregnancy.

2. Methodology

Figure 1 illustrates the system designed to identify the optimal abdominal ECG lead location throughout fetal development in the mother's womb. A prototype fetal ECG monitor, manufactured by Atom Medical Co (Tokyo, Japan), is utilized to collect data using 11 abdominal ECG leads. Subsequently, these data are fed into a pre-trained W-NETR pipeline, as proposed in [3], to extract 11 fECG signals. The SSIM metric is then employed to assess the best fECG reconstruction among the 11, indicating the most effective abdominal lead location with respect to the recorded gestational week.

2.1. Dataset

Sixteen pregnant women participated in the study, with data collected during gestational weeks 20-22 and 37-40 over 10 minutes in clinic rooms. Each had eleven custom-made gold electrodes with silver chloride gel placed on the abdomen, a reference electrode on the back, and one on the chest for maternal ECG. The configuration was consistent across participants for precise lead position analysis.

A prototype fetal ECG monitor (Atom Medical Co, Japan) was used. Real-time fetal ECG extraction involved canceling maternal ECG signals, followed by blind source separation with reference [7], using projections of the heart vector to isolate fetal ECG R waves. For more details on this method, see [2].

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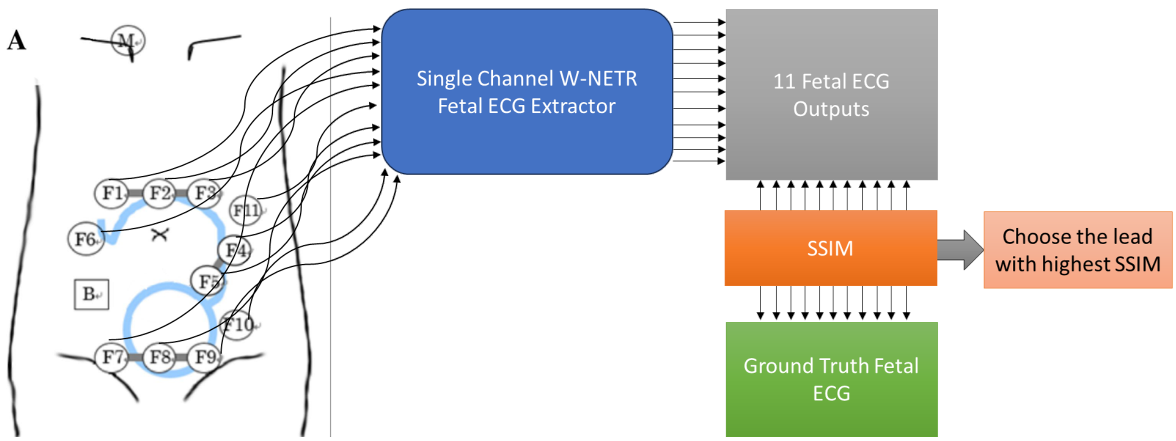

Figure 1. The presented system aims to pinpoint the optimal abdominal ECG lead location throughout fetal development in the mother's womb. A prototype fetal ECG monitor, manufactured by Atom Medical Co (Tokyo, Japan), is employed to gather data using 11 abdominal ECG leads. Subsequently, these data are input into a pre-trained W-NETR pipeline to extract 11 fECG signals. Afterward, the SSIM metric is used to evaluate the best fECG reconstruction among the 11, indicating the best abdominal lead location with respect to the recorded gestational week.

2.2. Train W-NETR

Before utilizing the data collected from the 11 leads, we initially trained the state-of-the-art single fECG extractor, the W-NETR pipeline proposed in [3], on the synthetic PhysioNet's FECGSYN dataset [8]. Subsequently, we fine-tuned the pipeline using only 20% of the collected real data through the 11-ECG lead system. The fine-tuning process employed the identical training parameters outlined in the original W-NETR publication (refer to [3] for detailed information). Leveraging the automatic maternal ECG feature cancellation capability of the W-NETR architecture, we incorporated the collected maternal ECG data during the training process to enhance the performance of fECG signal reconstruction. Given that the W-NETR pipeline employs a single-leaded approach, we organized the data such that each dataset with 11 abdominal leads corresponds to the same fECG ground truth for every data sample. Following the completion of the training process, the remaining 80% of the real collected data was utilized to extract 11 fECG signals, each corresponding to the 11 abdominal ECG leads collected for individual data samples in the inference mode.

2.3. SSIM - Evaluation Metrics

After extracting the 11 fECG reconstructions for each individual sample in the dataset, we categorize the data based on the respective gestational week during which it was collected, resulting in seven distinct data groups covering gestational weeks between 20-22 and 37-40. Subsequently, we systematically assess the quality of the 11 fECG reconstructions within each data group for every data sample by employing the Structural Similarity Index (SSIM) [6, 9]. The SSIM serves as a metric indicating the structural similarity between the extracted signal and the provided fECG ground truth, evaluating the extraction method's ability to preserve details of the fetal ECG data.

The SSIM is defined as:

$$\mathrm{SSIM} = \frac{(2\mu_{\mathrm{x}}\mu_{\hat{\mathrm{x}}} + \mathrm{c}_1)(2\sigma_{\mathrm{x}\hat{\mathrm{x}}} + \mathrm{c}_2)}{(\mu_{\mathrm{x}}^2 + \mu_{\hat{\mathrm{x}}}^2 + \mathrm{c}_1) + (\sigma_{\mathrm{x}}^2 + \sigma_{\hat{\mathrm{x}}}^2 + \mathrm{c}_2)}, \qquad (1)$$

where $\mu_x, \mu_{\hat{x}}, \sigma_x^2, \sigma_{\hat{x}}^2$, and $\sigma_{x\hat{x}}$ represent the mean, variance, and covariance of the ground truth signal $\mathbf{x}$ and the extracted signal $\hat{\mathbf{x}}$. Additionally, c_1 and c_2 are constants related to the dynamic range of the data. SSIM values range between [0,1], with a higher value indicating superior extraction performance.

This approach enables us to pinpoint the abdominal lead location that yields a higher number of samples with the highest SSIMs within each of the seven data groups corresponding to the respective gestational week. Ultimately, we achieve our goal to determine the abdominal lead location that produces the best fECG reconstructions relative to fetal development in the womb.

3. Results

Table 1 displays the mean reconstructed SSIM for all corresponding 11 abdominal ECG leads across gestational week periods ranging from 20-22 to 37-40. The highest mean SSIM is highlighted in blue, indicating the optimal lead number for each gestational week in the table. Lead number 2 exhibits the highest mean SSIM in weeks 20, 21, and 22, while lead 8 attains the highest mean SSIM in

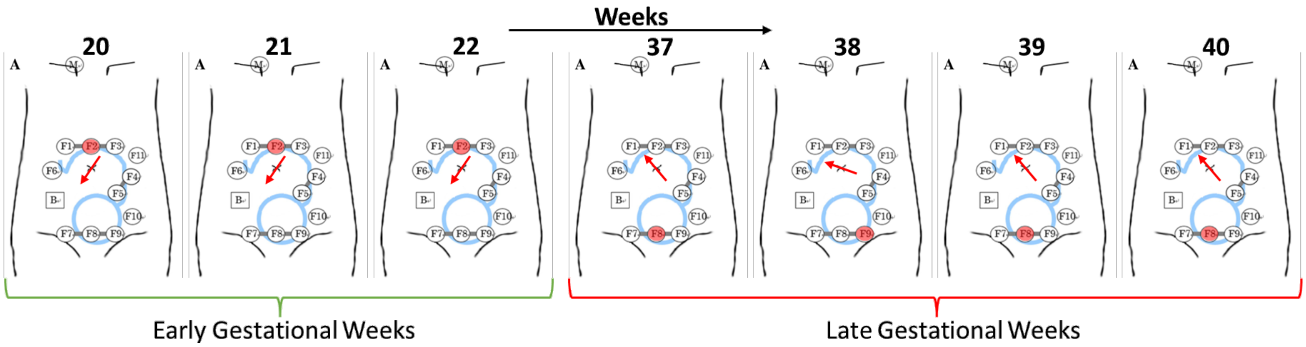

Figure 2. Visualization of the optimal abdominal ECG lead location for precise fECG extraction across the selected gestational weeks. The red arrow represents the two-dimensional vector direction aimed at enhancing extraction, taking into account that the reference lead (marked as "B") is situated on the mother's back.

Table 1. The mean reconstructed SSIM is depicted for all corresponding 11 abdominal ECG leads across gestational week periods spanning from 20-22 and 37-40. The highest mean SSIM is highlighted in blue indicating the best lead number for each gestational week.

	Early Gestational			Late Gestational			
Lead #	20	21	22	37	38	39	40
1	0.68	0.7	0.71	0.8	0.79	0.79	0.81
2	**0.71**	**0.74**	**0.74**	0.81	0.81	0.82	0.81
3	0.69	0.72	0.73	0.83	0.8	0.83	0.82
4	0.32	0.35	0.35	0.74	0.75	0.76	0.75
5	0.31	0.34	0.36	0.72	0.72	0.74	0.75
6	0.34	0.37	0.36	0.71	0.72	0.71	0.74
7	0.64	0.68	0.67	0.91	0.92	0.89	0.93
8	0.66	0.7	0.7	**0.93**	0.92	**0.94**	**0.96**
9	0.6	0.62	0.65	0.92	**0.95**	0.93	0.93
10	0.4	0.45	0.44	0.88	0.89	0.9	0.88
11	0.41	0.48	0.47	0.83	0.84	0.82	0.81

weeks 37, 39, and 40. In the 38th gestational week, the highest SSIM is observed with lead 9. These findings are visually represented in Figure 2, which illustrates the best abdominal ECG lead location for accurate fECG extraction throughout the chosen gestational weeks. Additionally, it reveals the generally superior two-dimensional vector direction for improved extraction, considering that the reference lead (annotated as "B") is positioned on the mother's back.

These results show that in early gestation (20-22 weeks), the best lead placement is in the upper abdomen, while in later stages, it shifts to the lower abdomen. Figure 3 shows fECG reconstruction using lead 2 (upper abdomen) and lead 8 (lower abdomen) in weeks 20, 37, and 40. In early pregnancy, lead 2 slightly outperforms lead 8 (SSIM 0.72 vs. 0.68), but in later weeks, lead 2 misses fECG peaks and makes false detections. Lead 8, however, accurately reconstructs the fECG. Despite minimal differences early on, placing the lead in the lower abdomen ensures good extraction quality throughout pregnancy.

4. Discussion and Conclusions

To enhance the practicality of the lightweight single-leaded fECG non-invasive extractor in real-life scenarios, we investigated the optimal abdominal ECG lead location and its correlation with fetal development to achieve superior fECG reconstructions. Our study focused on two distinct gestational periods: an early stage spanning weeks 20-22 and a late stage covering weeks 37-40. The results unequivocally reveal that the best abdominal ECG lead location differs between these periods, being situated in the upper part of the abdomen during the early stage and shifting to the lower part in the late stage, with reference electrodes positioned on the mother's back as depicted in Figure 1.

This conclusion was drawn from utilizing the 11-lead prototype fetal ECG monitor manufactured by Atom Medical Co (Tokyo, Japan), as proposed in patent WO/2007/029485 [7], which covers nearly all conceivable point locations on the mother's abdomen. These findings align with existing knowledge indicating that the fetal position remains upright until the late stages of pregnancy, with the head descending in preparation for delivery [10] which affect the fECG vector direction. The efficiency of the single-lead deep learning-based system W-NETR in fECG extraction is evident when using the optimal abdominal ECG lead, as demonstrated in Figure 3. The figure illustrates the successful reconstruction of the fECG signal by W-NETR, with lead 2 in the early stage and lead 8 in the late stage of pregnancy. Notably, W-NETR not only reconstructs the fECG accurately but also surpasses the ground

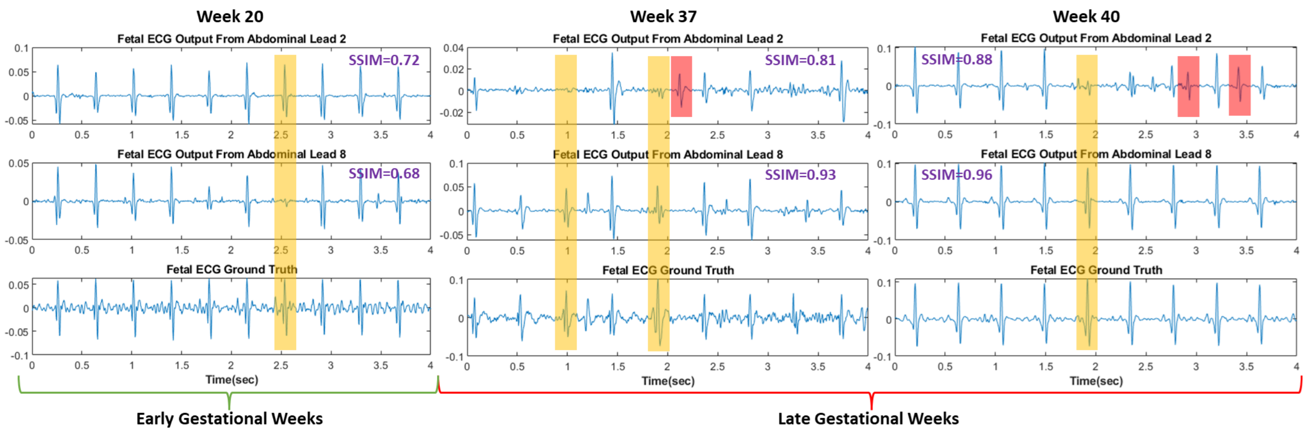

Figure 3. Illustrations of fECG reconstruction utilizing the single-leaded W-NTER pipeline with the upper abdomen lead 2 (top) and the lower abdomen lead 8 (middle), alongside the provided fECG ground truth (bottom). The figure showcases examples from an early gestational week (week 20) and late gestational weeks (week 37 and 40). The yellow rectangles highlight examples of missing fECG peaks in the reconstructions, while the red rectangles indicate false detections of fECG peaks.

truth by effectively filtering out contaminant noise in all cases, particularly noticeable in the week 20 example in the figure. As a result, these findings create opportunities for the implementation of lightweight single-leaded models, such as W-NETR, in future real-life fECG extractor systems, capitalizing on their computational efficiency and high reconstruction performance.

In our future work, we will expand the study to include gestational weeks 20 to 41 and increase subject numbers for validation. We also plan to extend validation to other single-lead systems beyond the W-NETR, enhancing the reliability of implementing these efficient systems in real-life devices.

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