Applicability of initial optimal maternal and fetal electrocardiogram combination vectors to subsequent recordings*

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A series of experiments are conducted to confirm whether the vectors calculated for an early section of a continuous non-invasive fetal electrocardiogram (fECG) recording can be directly applied to subsequent sections in order to reduce the computation required for real-time monitoring. Our results suggest that it is generally feasible to apply the initial optimal maternal and fetal ECG combination vectors to extract the fECG and maternal ECG in subsequent recorded sections.

Keywords: fetal monitoring, real-time multi-channel recording, independent component analysis (ICA), periodic component analysis

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1. Introduction

Fetal monitoring based on abdominal electrocardiogram (aECG) has attracted people's attention because it is both non-invasive and less sensitive to the electrode position than Doppler based cardiotocography.[1,2] We can extract the fetal electrocardiogram (fECG) and the maternal electrocardiogram (mECG) from aECG to assess the condition of health. Various approaches have been developed to extract weak fECG components, which can be classified into methods based on a single-channel and those based on a multi-channel recording. The single-channel methods include local principal component analysis in pseudo-phase space,[3] model matching,[4] and comb filtering.[5,6] The multi-channel methods include singular value decomposition,[7] spatial filtering,[8,9] multi-channel phase space reconstruction,[10] periodic component analysis (πCA),[11–13] and independent component analysis (ICA).[14–20] The multi-channel methods have more potential to steadily extract fECG and mECG because they contain more information.

The most commonly used multi-channel fECG extraction methods are πCA and ICA. Although they are based on different extraction criteria, both methods construct optimal weight vectors or an unmixed matrix. The multi-channel signals are then converted into the desired components by projecting them onto the vectors or matrix. We denote the M-channel aECG records of length N as $x_i(n)$ $(n = 1,\ldots, N, i = 1,\ldots,M)$, the optimal mECG combination vector (mECV) as $\boldsymbol{W}_{\rm m} = [w_{\rm m1}, w_{\rm m2}, \ldots, w_{{\rm m}M}]$, and the optimal fECG combination vector (fECV) as $\boldsymbol{W}_{\rm f} = [w_{\rm f1}, w_{\rm f2}, \ldots, w_{{\rm f}M}]$. Then, the mECG and fECG can be calculated according to the following equations:

$$\text{mECG} = [w_{\rm m1}, w_{\rm m2}, \cdots, w_{{\rm m}M}] \begin{bmatrix} x_1(n) \\ x_2(n) \\ \vdots \\ x_M(n) \end{bmatrix}, \tag{1}$$

$$\text{fECG} = [w_{\rm f1}, w_{\rm f2}, \cdots, w_{{\rm f}M}] \begin{bmatrix} x_1(n) \\ x_2(n) \\ \vdots \\ x_M(n) \end{bmatrix}. \tag{2}$$

Note that $x_i(n)$ in Eq. (2) can be either aECG or the residual signals after removing the mECG component.

During the perinatal period, when the fetus is growing, the fetus moves more often, and the risk of hypoxia increases, so continuous real-time fetal monitoring is necessary. A general rule for continuous real-time monitoring is that N-point fECG extraction must be finished in $N\times T_{\rm s}$ seconds, where $T_{\rm s}$ is the sampling interval (in seconds). Nevertheless, obtaining $\boldsymbol{W}_{\rm m}$ and $\boldsymbol{W}_{\rm f}$ for the πCA and ICA methods is time-consuming because the optimization problems must be solved and some prerequisite information or other computations are also required. In πCA, the instantaneous fetal heart rate[11,13] or RR interval[12] must first be estimated. In ICA, because of the disorder of the obtained independent components, an exceptional procedure is needed to judge which output is mECG and which is fECG. The calculations involved in these procedures are too huge for real-time extraction to be feasible today. So it is essential to simplify these steps.

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In this paper, we investigate whether the initial optimal $\boldsymbol{W}_{\rm m}$ or $\boldsymbol{W}_{\rm f}$, obtained from the beginning of a monitoring record, can be used to correctly extract the mECG or fECG components from subsequent sections. If they can, then we can reduce the computational time by determining the mECV and fECV at the beginning and then directly apply them to the subsequent sections using Eqs. (1) and (2). To the best of our knowledge, no research has been published regarding the applicability of the initial optimal maternal and fetal ECG combination vectors to the remainder of the recording.

The rest of this paper is arranged as follows. In Section 2, we briefly introduce the database used. We investigate the applicability of the initial optimal mECV in Section 3, and fECV in Section 4. Further discussion and analyses are given in Section 5. Section 6 gives our conclusion and an outlook.

2. Description of data

The database we used for our experiments is the well-known MIT non-invasive fetal electrocardiogram database,[21] which contains 55 multi-channel abdominal fetal ECG records taken from a single subject between the 21st and the 41st gestational weeks. Every record contains 3- or 4-channel abdominal signals, with a synchronized sampling rate of 1 kHz and a duration of 114–2780 s. As an example, the first 10 s aECGs of the recording "ecgca748 (22+1)" are presented in Fig. 1.

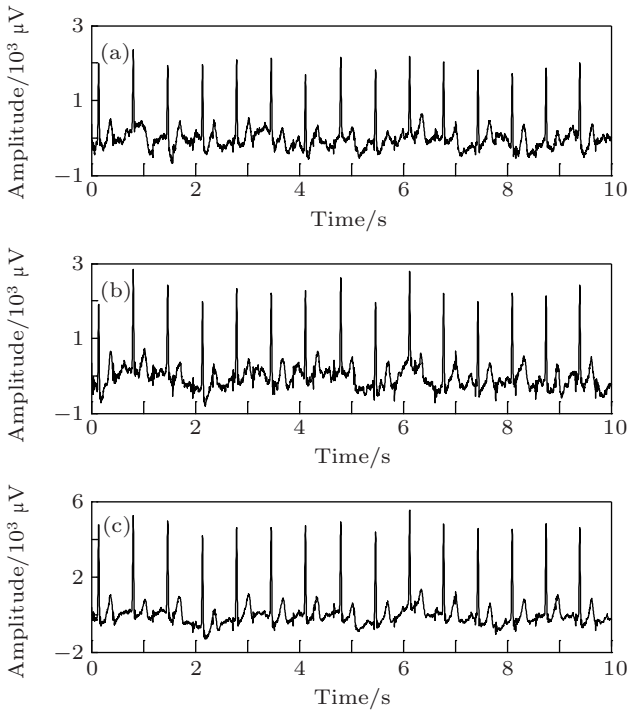


Fig. 1. Abdominal ECGs of the recording "ecgca748 (22+1)" in the MIT database. Panels (a)–(c) show the data of channels 1–3, respectively.

3. Applicability of the initial optimal mECV

3.1. Method

The method used to choose the identification window (IW) and the test windows (TWs) from an aECG record is illustrated in Fig. 2. For simplicity, the IW and the TW have the same length.

As shown in Fig. 2, for an L-second multi-channel record with a sampling rate of $f_{\rm s}$ (in units of Hz), we define the IW as the beginning section with duration $N \times T_{\rm s}$ ($T_{\rm s} = 1/f_{\rm s}$). Next, we obtain a series of TWs by sliding a window of the same duration along the record, with a delay of $D \times T_{\rm s}$. Therefore, the total number of TWs is $K = \lfloor (L - NT_{\rm s})/(DT_{\rm s}) \rfloor$, where $\lfloor\ \rfloor$ denotes that the fractions are rounded down.

We determine the initial optimal mECV (i.e., the mECV for the IW (mECV_IW)) using the method proposed in Ref. [14]. We then apply it to the subsequent TWs, denoted as $\boldsymbol{Z} = [\boldsymbol{Z}_1, \boldsymbol{Z}_2, \ldots, \boldsymbol{Z}_K]^{\rm T}$, to construct the corresponding combination signals $\boldsymbol{Y} = [\boldsymbol{Y}_1, \boldsymbol{Y}_2, \ldots, \boldsymbol{Y}_K]^{\rm T}$, where $\boldsymbol{Y}_i = \boldsymbol{W}_{\rm m}\boldsymbol{Z}_i$, $i = 1, \ldots, K$. We inspect the results to evaluate whether the maternal ECGs in the TWs are successfully extracted, which will demonstrate whether the mECV_IW can be generally applied to the whole recording.

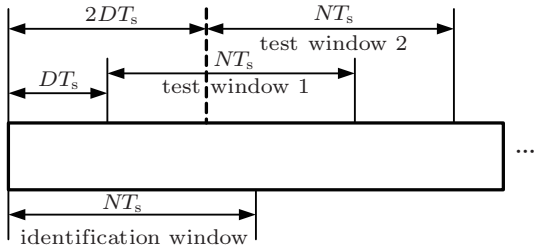


Fig. 2. Splitting the aECG record into the IW and TWs.

3.2. Results for the MIT database

We apply the proposed method to the database described in Section 2. The window length $N \times T_{\rm s}$ and the time delay $D \times T_{\rm s}$ are both 10 s. Some results for "ecgca748" in Fig. 1 are presented in Fig. 3. In this case, the mECV_IW is determined to be $\boldsymbol{W}_{\rm m} = [-0.4748,\ 0.0523,\ -0.8786]$. In Fig. 3, we can see that the mECG component has been successfully extracted. In fact, extractions are successful for all the TWs in this record and the success rate is 100%.

The results for the other 54 recordings in the database are listed in Table 1. As shown in Table 1, the success rates for most recordings are 100%, except for the 10 records presented in bold face.

After carefully examining the failed cases, we find that the original signals contain extensive interferences. These interferences are of the same type. Using recording "ecgca997" as an example, we display the original aECG and the results

from 140–160 s using the mECV_IW in Fig. 4. Large interferences occur simultaneously in all four channels, mainly during 145–155.5 s, which leads to a much higher amplitude. We re-plot two sub-sections, 140s–145 s and 155.5–160 s, in Fig. 5 using an appropriate scale. The combination signals (Figs. 5(e-1) and 5(e-2)) are correct mECG components. This indicates that the abnormal combination results are not caused by an inappropriate W_m, but by the simultaneous large interference in the TWs. Therefore, we reach the conclusion that the mECV_IW is effective for all TWs, except for those contaminated by sudden great interferences.

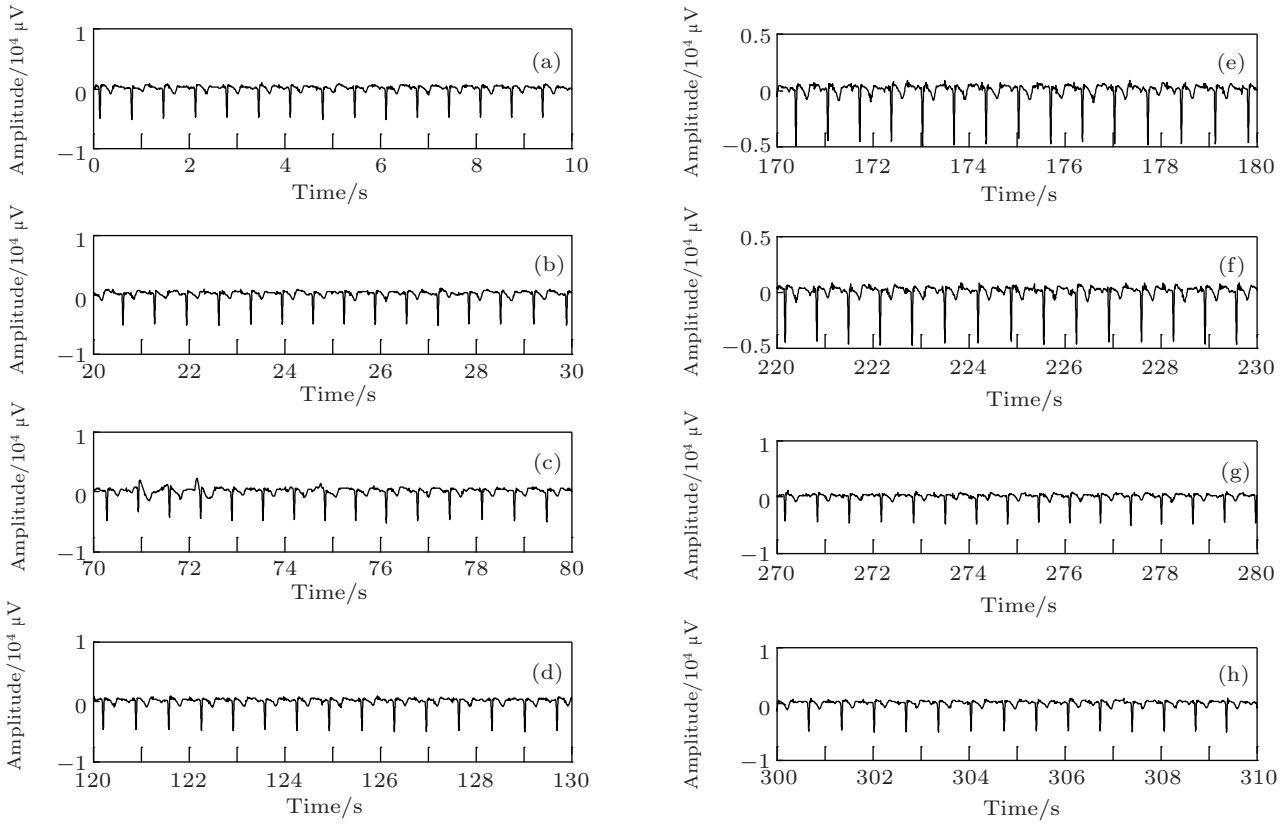


Fig. 3. Extracted mECG when applying mECV_IW to the recording in Fig. 1: (a) the mECG in IW, (b)–(h) the combination results for various TWs.

Table 1. Results when applying mECV_IW to all the recordings. Here L is the total recording length in seconds; K is the total number of TWs; S is the number of TWs in which mECG is successfully combined; and, F is the number of TWs in which the application fails.

Record	L/s	K	$S+F$	Record	L/s	K	$S+F$	Record	L/s	K	$S+F$
ecgca102	270	26	26+0	ecgca880	440	43	43+0	**ecgca896**	**300**	**29**	**27+2**
ecgca154	318	30	30+0	**ecgca571**	**920**	**91**	**89+2**	ecgca595	345	33	33+0
ecgca192	312	30	30+0	**ecgca115**	**730**	**72**	**71+1**	ecgca629	385	37	37+0
ecgca445	185	17	17+0	ecgca252	620	61	61+0	ecgca659	630	62	62+0
ecgca811	330	32	32+0	**ecgca816**	**670**	**66**	**65+1**	ecgca515	820	81	81+0
ecgca876	234	22	22+0	ecgca308	695	68	68+0	ecgca711	840	83	83+0
ecgca900	114	10	10+0	ecgca621	1000	99	99+0	ecgca244	685	67	67+0
ecgca986	360	35	35+0	**ecgca864**	**864**	**85**	**83+2**	ecgca290	1000	99	99+0
ecgca300	144	13	13+0	ecgca127	720	71	71+0	ecgca733	1000	99	99+0
ecgca902	**324**	**31**	**30+1**	ecgca384	500	49	49+0	ecgca585	545	53	53+0
ecgca997	**165**	**15**	**13+2**	**ecgca436**	**580**	**57**	**52+5**	ecgca597	1000	99	99+0
ecgca323	414	40	40+0	ecgca699	335	32	32+0	ecgca886	425	41	41+0
ecgca274	396	38	38+0	ecgca868	220	21	21+0	ecgca444	1000	99	99+0
ecgca649	1000	99	99+0	**ecgca998**	**225**	**21**	**17+4**	ecgca840	320	31	31+0
ecgca848	365	35	35+0	ecgca392	370	36	36+0	ecgca746	835	82	82+0
ecgca826	270	26	26+0	**ecgca416**	**315**	**30**	**29+1**	ecgca771	1000	99	99+0
ecgca368	450	44	44+0	ecgca776	500	49	49+0	ecgca473	200	19	19+0
ecgca410	144	13	13+0	ecgca968	570	56	56+0	ecgca906	1000	99	99+0

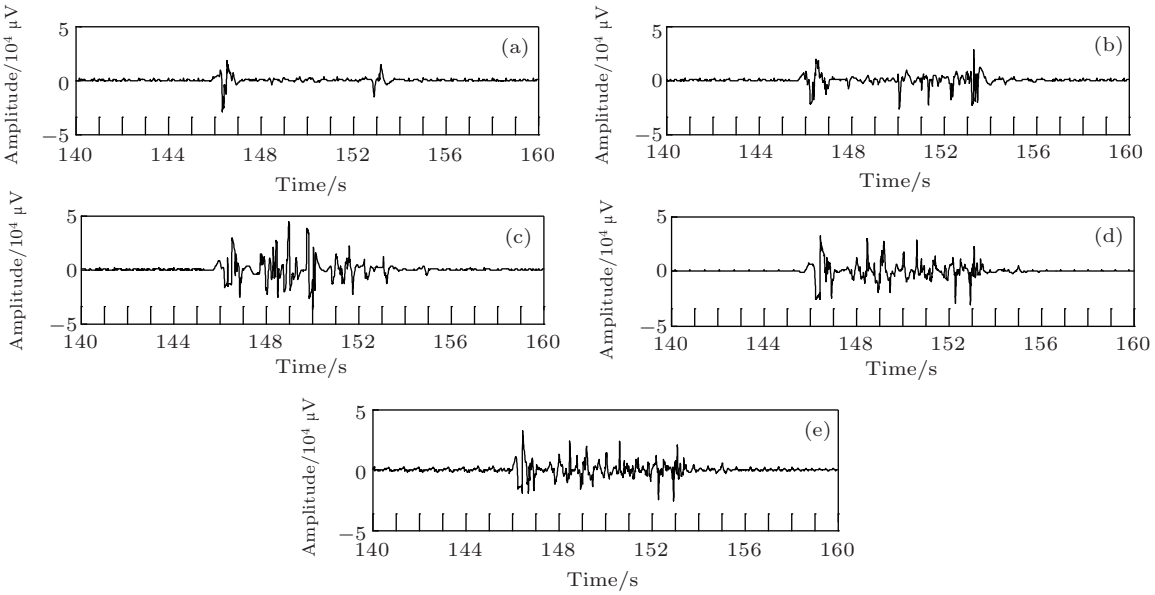


Fig. 4. Original aECGs and the failed combination result for recording "ecgca997 (23+6)": (a)–(d) the original four channel aECGs; and, (e) the combination result.

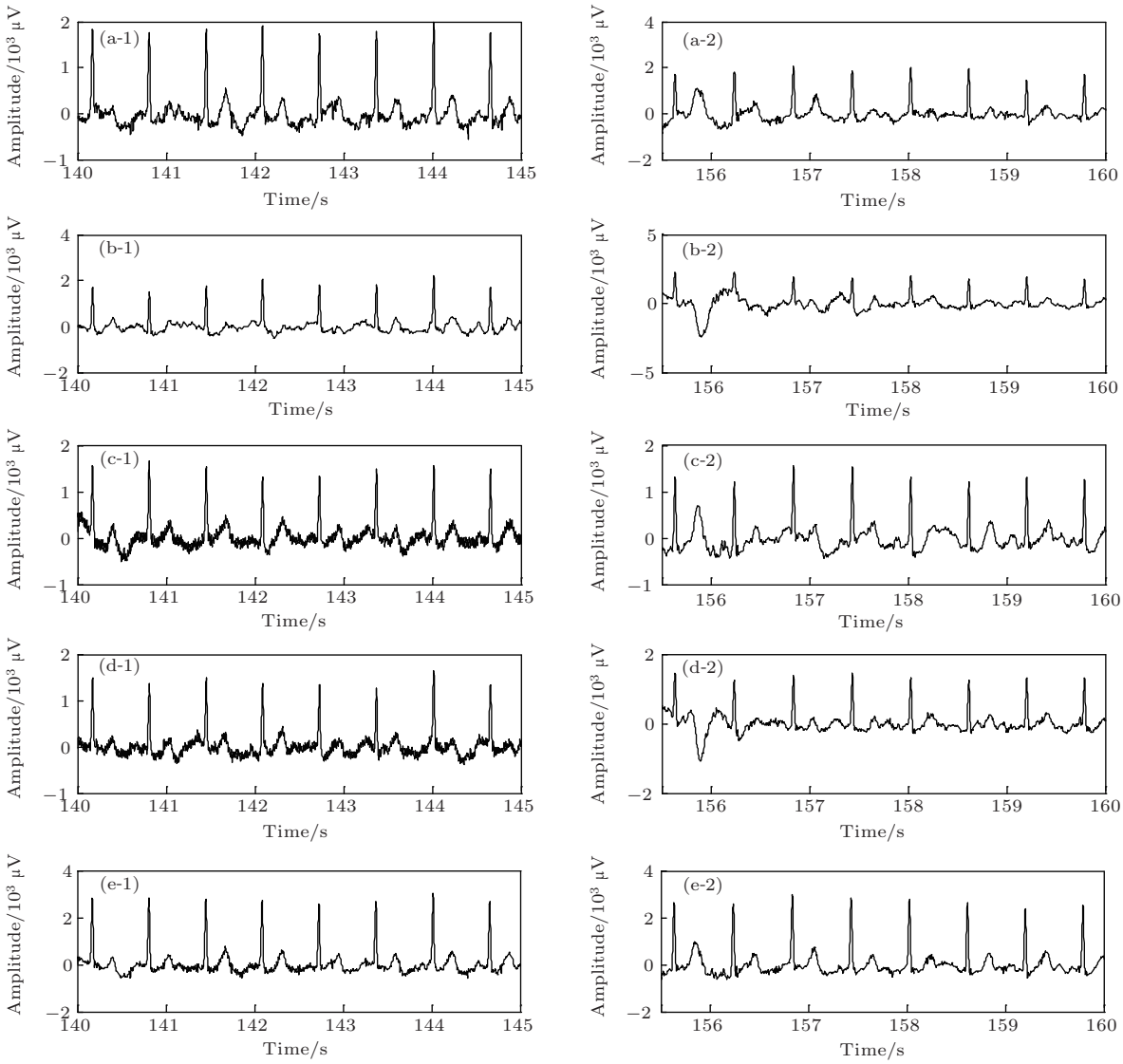


Fig. 5. A closer look at the segments of 140–145 s and 155.5–160 s in Fig. 4(a)–4(e).

4. Applicability of the initial optimal fECV

4.1. Method

The method used to study the applicability of the initial optimal fECV is similar to the method described in Subsection 3.1. The main difference is that preprocessing is required to increase the signal to noise ratio (SNR). That is, the mECG component should be first removed from the original aECG using the method described in Ref. [5].

4.2. Results for the MIT database

In Fig. 6, we use the recording "ecgca748 (22+1)" (from Fig. 1) as an example. We first remove the mECG and then set the first 10 seconds of the residual ECG (rECG) as the IW. The fECV obtained for the IW (fECV_IW) is $\boldsymbol{W}_{\rm f} = [-0.1888, -0.2639, -0.9459]$.

We then apply $\boldsymbol{W}_{\rm f}$ to all of the TWs. Some results are presented in Fig. 7. In Figs. 7(d)–7(h), we can see that the fetal R peaks on the waveforms are quite obvious. We call this the T condition. In Fig. 7(c), the fetal R peaks are not so clear; however, periodic peaks can be clearly seen in its differential result in Fig. 7(i). We call this the DT condition. Cases that do not have periodic peaks at all satisfy the F condition. Among the 30 combination results for the TWs, there are 28 T conditions, 2 DT conditions, and no F conditions. So the success rate of this recording is (T+DT)/K= (28+2)/30=100%.

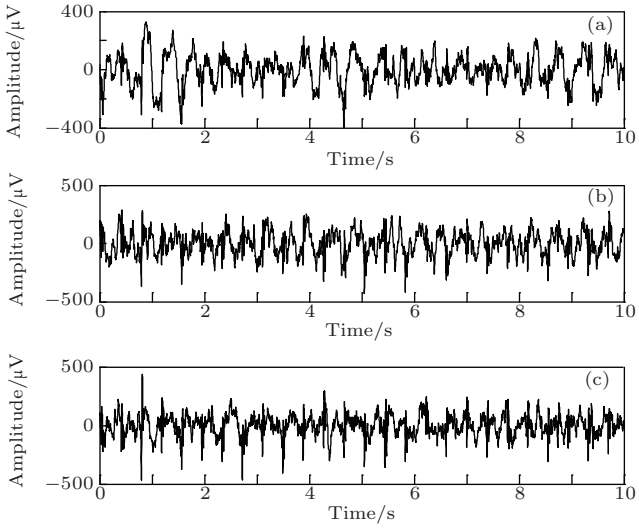


Fig. 6. rECGs after removing the mECG for the recording depicted in Fig. 1.

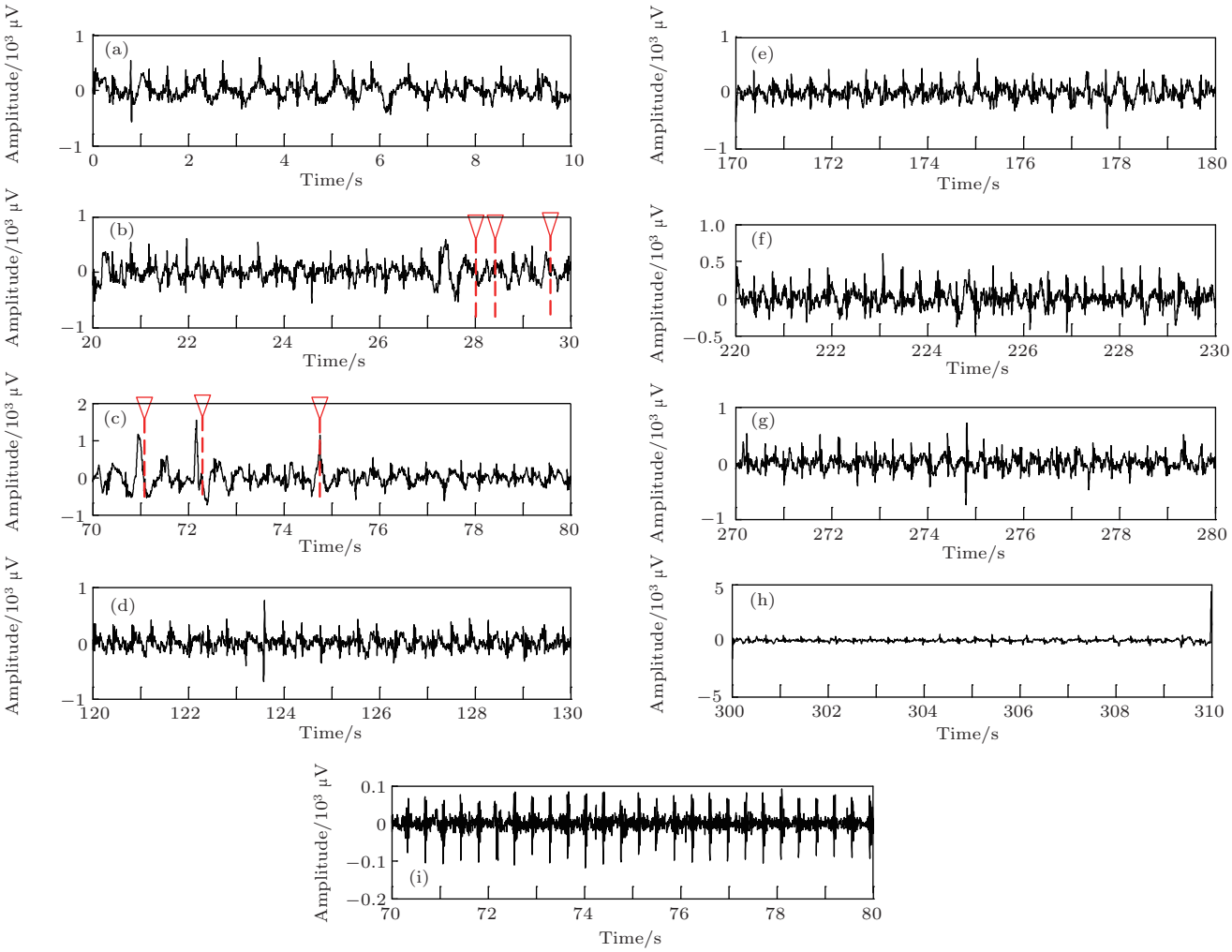


Fig. 7. (color online) fECG extracted by applying fECV_IW to the whole record shown in Fig. 6: (a) combined fECG for IWs, (b)–(h) combination results for various TWs, and (i) the differential result of Fig. 7(c). The red triangles mark potential R peak positions that are illegible.

We repeat the same procedure for the remaining 54 recordings in the database. Note that we fail to obtain the fECVs for 21 recordings because of their low SNRs. This indicates the limitation of ICA in extracting fECG. The results for the other 33 recordings are listed in Table 2. We decide whether the combination result is correct by using two criteria: (i) the R peaks in the combination result, or the corresponding periodic peaks in its difference signal, are clear; and, (ii) the fetal heart rate calculated from a TW combination result is consistent with the reference heart rates that have been calculated in advance.

In Table 2, we can see that the success rates for 9 recordings ("ecgca445", "ecgca881", "ecgca274", "ecgca300", "ecgca826", "ecgca368", "ecgca410", "ecgca886", "ecgca746") are 100%, and the rest are partially successful. There are 28 recordings with success rates higher than 80% (85% of the recordings). We discuss these results further in Section 5.

Table 2. Results when applying fECV_IW to the 33 recordings in the MIT database. Here, L is the total record length in seconds; K is the total number of TWs; T is the number of TWs in which the fECG is successfully combined; DT is the number of TWs in which fECG is successfully combined using the difference; and, F is the number of TWs in which the application fails.

Record	L/s	K	$T/DT/F$ $((T+DT)/K)$	Record	L/s	K	$T/DT/F$ $((T+DT)/K)$	Record	L/s	K	$T/DT/F$ $((T+DT)/K)$
ecgca102 (22+1)	270	26	18/**3**/5 (80.0%)	ecgca848 (24+2)	365	35	32/**2**/1 (97.1%)	ecgca290 (38+0)	1000	99	93/**5**/1 (99.0%)
ecgca154 (22+1)	318	30	25/**4**/1 (96.7%)	ecgca826 (24+2)	270	26	26/**0**/0 (100%)	ecgca733 (38+0)	1000	99	1/**95**/3 (97.0%)
ecgca192 (22+1)	312	30	26/**1**/3 (90%)	ecgca368 (24+2)	450	44	42/**2**/0 (100%)	ecgca585 (38+2)	545	53	5/**32**/16 (69.8%)
ecgca445 (22+1)	185	17	17/**0**/0 (100%)	ecgca410 (24+2)	144	13	0/**13**/0 (100%)	ecgca597 (38+2)	1000	99	38/**52**/9 (91.0%)
ecgca811 (22+1)	330	32	29/**3**/0 (100%)	ecgca571 (25+0)	920	91	82/**7**/2 (97.8%)	ecgca886 (38+2)	425	41	41/**0**/0 (100%)
ecgca876 (22+1)	234	22	12/**4**/6 (72.7%)	ecgca392 (33+4)	370	36	0/**30**/6 (83.3%)	ecgca444 (39+0)	1000	99	54/**44**/1 (99.0%)
ecgca274 (23+6)	396	38	29/**9**/0 (100%)	ecgca416 (33+4)	315	30	0/**26**/4 (86.7%)	ecgca840 (39+0)	320	31	1/**29**/1 (96.8%)
ecgca300 (23+6)	144	13	0/**13**/0 (100%)	ecgca595 (35+6)	345	33	26/**0**/7 (78.8%)	ecgca746 (39+6)	835	82	0/**82**/0 (100%)
ecgca997 (23+6)	165	15	0/**13**/2 (86.7%)	ecgca629 (35+6)	385	37	0/**4**/33 (10.8%)	ecgca771 (39+6)	1000	99	0/**98**/1 (99.0%)
ecgca323 (23+6)	414	40	31/**4**/5 (87.5%)	ecgca659 (35+6)	630	62	37/**19**/6 (90.3%)	ecgca473 (40+2)	200	19	1/**15**/3 (84.2%)
ecgca649 (23+6)	1000	99	73/**22**/4 (96.0%)	ecgca244 (38+0)	685	67	15/**14**/38 (43.3%)	ecgca906 (40+2)	1000	99	2/**91**/6 (93.9%)

5. Discussion

Table 1 shows that we fail to obtain mECG by the mECV_IW for only 21 TWs among 2437 TWs in total for all the 55 recordings in the database. The 21 TWs are contaminated by sudden interferences. The success rate for mECV's applicability is (2437-21)/2437=99.14%, which is quite high.

According to the blind source separation theory,[22] aECG or rECG can be considered as a linear mixture of various independent sources

$$\boldsymbol{X}_{M\times N} = \boldsymbol{A}_{M\times P}\boldsymbol{S}_{P\times N}, \tag{3}$$

where $\boldsymbol{X}_{M\times N}$ represents M-channel aECG or rECG records, $\boldsymbol{A}_{M\times P}$ is the mixing matrix, and $\boldsymbol{S}_{P\times N}$ are the independent P sources. To obtain the independent sources, the unmixed matrix $\boldsymbol{W}_{P\times M}$ that contains $\boldsymbol{W}_{\rm m}$, $\boldsymbol{W}_{\rm f}$, or both can first be determined using FastICA,[14] as described in Subsections 3.1 and 4.1. Then, the sources are reconstructed using

$$\boldsymbol{Y}_{P\times N} = \boldsymbol{W}_{P\times M}\boldsymbol{X}_{M\times N} = \boldsymbol{W}_{P\times M}\boldsymbol{A}_{M\times P}\boldsymbol{S}_{P\times N}, \tag{4}$$

where $\boldsymbol{W}_{P\times M}$ is the estimation of the pseudo-inverse of $\boldsymbol{A}_{M\times P}$, and $\boldsymbol{Y}_{P\times N}$ is the optimal estimation of the sources $\boldsymbol{S}_{P\times N}$.

When the $\boldsymbol{W}_{P\times M}$ determined by one time window of signals is applied to a different window, the $\boldsymbol{A}_{M\times P}$ may have a deviation of $\Delta\boldsymbol{A}_{M\times P}$ and the source signal $\boldsymbol{S}_{P\times N}$ may have an interference or noise component $\Delta\boldsymbol{S}_{P\times N}$. Therefore, equation (4) becomes

$$\begin{aligned}\boldsymbol{Y}_{P\times N} &= \boldsymbol{W}_{P\times M}\boldsymbol{X}_{M\times N}\\ &= \boldsymbol{W}_{P\times M}(\boldsymbol{A}_{M\times P}+\Delta\boldsymbol{A}_{M\times P})(\boldsymbol{S}_{P\times N}+\Delta\boldsymbol{S}_{M\times P})\\ &= \boldsymbol{W}_{P\times M}\boldsymbol{A}_{M\times P}\boldsymbol{S}_{P\times N}+\boldsymbol{W}_{P\times M}(\Delta\boldsymbol{A}_{M\times P}\boldsymbol{S}_{P\times N}\\ &\quad+\boldsymbol{A}_{M\times P}\Delta\boldsymbol{S}_{M\times P}+\Delta\boldsymbol{A}_{M\times P}\Delta\boldsymbol{S}_{M\times P}).\end{aligned} \tag{5}$$

For mECG extraction, equation (5) can be simplified to

$$\begin{aligned}\text{mECG} &= \boldsymbol{W}_{\rm m}\boldsymbol{A}_{M\times P}\boldsymbol{S}_{P\times N}+\boldsymbol{W}_{\rm m}(\Delta\boldsymbol{A}_{M\times P}\boldsymbol{S}_{P\times N}\\ &\quad+\boldsymbol{A}_{M\times P}\Delta\boldsymbol{S}_{M\times P}+\Delta\boldsymbol{A}_{M\times P}\Delta\boldsymbol{S}_{M\times P}).\end{aligned} \tag{6}$$

By comparing Eqs. (6) and (4), we find that when the current $\boldsymbol{W}_{\rm m}$ is applied to a new time window of signals, the mECG estimation will have an error

$$\begin{aligned}\text{error}_{\text{mECG}} &= \boldsymbol{W}_{\rm m}(\Delta\boldsymbol{A}_{M\times P}\boldsymbol{S}_{P\times N}+\boldsymbol{A}_{M\times P}\Delta\boldsymbol{S}_{M\times P}\\ &\quad+\Delta\boldsymbol{A}_{M\times P}\Delta\boldsymbol{S}_{M\times P}).\end{aligned} \tag{7}$$

The factor $\boldsymbol{A}_{M\times P}$ in Eq. (3) depends mainly on the locations of sensors and sources, the geometry of the body, and the conductivity of tissues.[22] In Eq. (7), $\Delta\boldsymbol{A}_{M\times P}$ must be small enough to be neglected for the mECG extraction. This is because during the monitoring of abdominal ECG there is no change of the relative position between the maternal heart and the abdominal electrodes. The mECG source component is much bigger than the interference at most time, so $\Delta\boldsymbol{S}_{M\times P}$ can

also be neglected. Therefore, the error in Eq. (7) is generally small. This is why the mECV_IW successfully extracts the mECG of the TWs at a high success ratio of 99.14%. Of course, $\Delta \boldsymbol{S}_{M\times P}$ (interference) is occasionally strong enough to cause an mECG combination error, as shown in Fig. 4.

The results in Table 2 show that when applying the fECG_IW to the entire recording the success rate is 100% for 10 recordings but less for others, and below 80% in four cases. So why does the success rate decrease when using fECV_IWs?

When extracting the fECG, equation (5) can be simplified to

$$\begin{aligned}\text{fECG} = {} & \boldsymbol{W}_{\text{f}}\boldsymbol{A}_{M\times P}\boldsymbol{S}_{P\times N} + \boldsymbol{W}_{\text{f}}(\Delta\boldsymbol{A}_{M\times P}\boldsymbol{S}_{P\times N} \\ & + \boldsymbol{A}_{M\times P}\Delta\boldsymbol{S}_{M\times P} + \Delta\boldsymbol{A}_{M\times P}\Delta\boldsymbol{S}_{M\times P}). \end{aligned} \tag{8}$$

Comparing this with Eq. (4), we find that when the current $\boldsymbol{W}_{\text{f}}$ is applied to a new window, the fECG estimate will have an error

$$\begin{aligned}\text{error}_{\text{fECG}} = {} & \boldsymbol{W}_{\text{f}}(\Delta\boldsymbol{A}_{M\times P}\boldsymbol{S}_{P\times N} + \boldsymbol{A}_{M\times P}\Delta\boldsymbol{S}_{M\times P} \\ & + \Delta\boldsymbol{A}_{M\times P}\Delta\boldsymbol{S}_{M\times P}). \end{aligned} \tag{9}$$

The fECG combination is less successful for two reasons. First, even after removing the maternal component, the fECG is so weak that various kinds of interferences (such as electrohysterogram, electromyography, or respiration) may have the same or higher magnitude than the fECG. So $\Delta \boldsymbol{S}_{M\times P}$ in Eq. (9) cannot be neglected. Second, $\boldsymbol{A}_{M\times P}$ can change because the fetus is floating in an amniotic fluid and its location can vary. So $\Delta \boldsymbol{A}_{M\times P}$ in Eq. (9) also cannot be neglected.

However, as the gestational age increases, the fetus grows and has less room to move. Consequently, the failure rate of the fECG extraction based on the fECV_IW decreases, as shown in Fig. 8. Conversely, interferences such as electrohysterogram and fetal electromyography occur more frequently with increasing gestational age, which may partly account for an increase in DT conditions, especially after 38 weeks. Of course, the case may be quite different during labor.

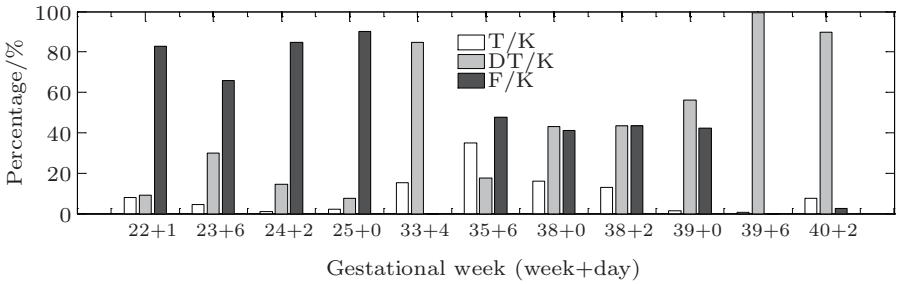


Fig. 8. Success rates for fECV according to the gestational age.

6. Conclusions

Our experiments and investigations have led to the following conclusions. First, when using abdominal electrodes for continuous fetal monitoring, the initial optimal mECV obtained at the beginning of a signal can be used to extract the mECG from the remainder of recordings. That is, the mECV_IW can be directly applied to the entire aECG. Second, the initial optimal fECV can also be used to extract the fECG; however, the success rates are lower because of the complex conditions. The interference affects the fECG more easily due to its lower amplitude. Additionally, the fetus is floating and can change its position. Further study is needed to both increase the applicability of fECV by reducing noise and to apply this technique to a real-time fetal monitoring system.

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