Position difference regularity of corresponding R-wave peaks for maternal ECG components from different abdominal points*

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We collected 343 groups of abdominal electrocardiogram (ECG) data from 78 pregnant women and deleted the channels unable for experts to determine R-wave peaks from them; then, based on these filtered data, the statistics of position difference of corresponding R-wave peaks for different maternal ECG components from different points were studied. The resultant statistics showed the regularity that the position difference of corresponding maternal R-wave peaks between different abdominal points does not exceed the range of 30 ms. The regularity was also proved using the fECG data from MIT–BIH PhysioBank. Additionally, the paper applied the obtained regularity, the range of position differences of the corresponding maternal R-wave peaks, to accomplish the automatic detection of maternal R-wave peaks in the recorded all initial 343 groups of abdominal signals, including the ones with the largest fetal ECG components, and all 55 groups of ECG data from MIT–BIH PhysioBank, achieving the successful separation of the maternal ECGs.

Keywords: fetal electrocardiogram, abdominal ECG, R-wave detection

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1. Introduction

Monitoring the fetal cardiac activity can provide important information for obstetricians to assess the fetal status. Some techniques have been applied to monitor the fetal cardiac activity, such as the PCG (phonocardiogram),[1] MCG (magnetocardiogram),[2–7] ECG (electrocardiogram), etc. ECG technique is regarded as a relatively promising one of them.[8,9]

A recorded abdominal ECG signal of a pregnant woman is considered to be a composite signal as it contains the maternal ECG component, the fetal ECG component, and other noises. Abdominal ECG signals recorded from different abdominal surface points have different signal-to-noise ratios (SNRs). Among all of them, the one with the highest SNR, i.e., with the largest fetal ECG component rather than maternal ECG component, is the most potential one to obtain a clear fetal ECG by means of removing its maternal ECG component from the abdominal ECG signal. However, this method requires the maternal ECG component to be estimated accurately first.[10,11]

One important and effective way to estimate the maternal ECG component is relying on exactly detecting the maternal R-wave peaks.[12,13] As is known to all, an abdominal signal with a larger fetal ECG component is more difficult for detecting the maternal R-wave peaks. Sometimes, the fetal ECG component from some abdominal point is so large that the maternal R-wave peak detection and the maternal component estimation fail to be executed directly. One possible solution to this problem is as follows: (i) select another abdominal signal (recorded synchronously on another abdominal point) with the largest maternal ECG component, rather than the largest fetal component, as a reference signal; (ii) detect the maternal R-wave peaks of the reference signal, which are easier; (iii) return the detected maternal R-wave peak indexes of the reference signal and detect the maternal R-wave peaks of the abdominal signals with larger fetal ECG components, by means of local searching at the positions of the reference signal's maternal R-wave peaks.

In the above idea, for the computer to accomplish the automatic local searching, we need to set up a reasonable local search range. In order to obtain the reasonable value of the searching range, therefore, we must study the regularity of position difference of the corresponding R-wave peaks between different point abdominal signals.

In Section 2, we collected 343 groups of abdominal ECG signal data from 78 pregnant women and ignored the channels from which experts were unable to determine R-wave peaks. In Section 3, based on the filtered data, the statistics of position difference of corresponding R-wave peaks are studied. In Sec-

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tion 4, the studied statistical regularity is validated by using the ECG data from MIT–BIH PhysioBank. In Section 5, making use of the obtained reasonable range value of 30 ms, we accomplish the automatic detection of maternal R-wave peaks in the recorded initial 343 groups of abdominal ECG signals, including the ones with the largest fetal ECG components, and the 55 groups of ECG data from MIT–BIH PhysioBank.

2. Data collecting and filtering

2.1. Data collecting

We designed a data collecting program to obtain abdominal ECG data and conducted the experiment on 78 pregnant women in the Obstetrics Branch of Nanjing General Hospital of Nanjing Military Command. The data collecting system was composed of a standard 12-lead ECG machine and a PC machine. The standard 12-lead ECG machine, made by Nihon Kohden Corporation with the model No. 1350P, was connected to the PC machine with a dedicated USB cable. The ECG machine acted as a data acquisition module, and some parameters of it must be preset; the sample frequency was set to 500 Hz, the cutoff frequency of anti-aliasing filter was set to 75 Hz, and the switches for baseline drift suppression and EMG interference suppression were set on.

We designed three placement schemes for the ten electrodes (see Figs. 1(a)–1(c)). In the three schemes, six electrodes which are originally thoracic electrodes, labeled from C1 to C6, had the fixed positions, located at the six vertices of a hexagon. The hexagon was inscribed in a circumference with the pregnant woman's navel as its center and the radius 10 cm. Among the left four electrodes, which are originally limb electrodes, the electrodes labeled as F and R were also placed at fixed positions, the uterus fundus and pubic respectively, and the other two limb electrodes labeled as L and N were movable, having different positions in the three schemes.

Each group of data recorded by the standard 12-lead ECG machine was composed of eight-channel abdominal ECG signals and the corresponding relationship between each channel and the electrodes was shown in Table 1.

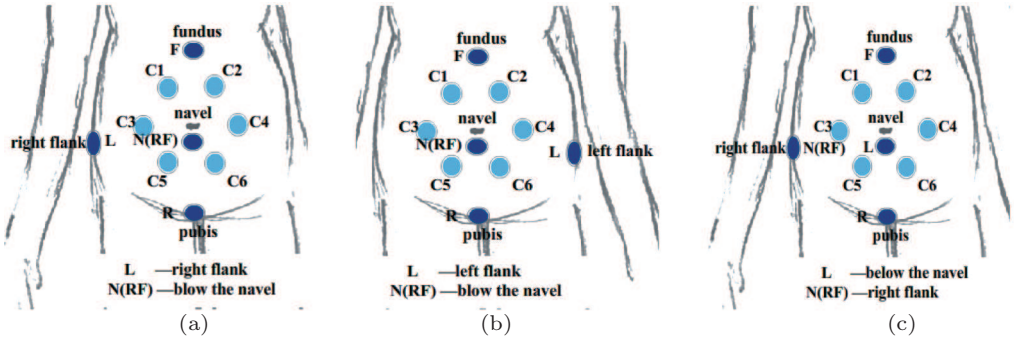


Fig. 1. (color online) Three placement schemes for ten electrodes.

Table 1. The corresponding relationship between eight-channel signals and the ten electrodes.

Channel number	1	2	3	4	5	6	7	8
Corresponding electrodes	L–R	F–R	C1	C2	C3	C4	C5	C6

The experimental steps are as follows: (i) We let the woman lie down on a bed and cleaned her abdominal skin with alcohol and applied saline water at the positions where the electrodes would be pasted in order to remove the grease on the skin and enhance the conductivity of the electrodes; (ii) Placed the ten electrodes according to Fig. 1(a), then recorded 1–2 groups of data with duration of 24 seconds; (iii) Adjusted the positions of the electrodes according to Fig. 1(b) and recorded 1–2 groups of data with duration of 24 seconds; (iv) Adjusted the positions of the electrodes according to Fig. 1(c) and recorded 1–2 groups of data with duration of 24 seconds.

2.2. Data filtering

In our experiment, 343 groups of data had been collected from 78 pregnant women. Since any algorithm for R-wave peak detection must be affected by noises,[14,15] the exact location of the detected R-wave peaks should be confirmed by experts' visual inspection. However, signal to noise ratios of the collected abdominal signals in some channels might be too low and often mixed with severe baseline drift and noises,[16] thus, the confirmation of the R-wave peaks for this kind of abdominal ECG signals was really a difficult task even for the experts, as shown in Fig. 2. In Fig. 2(a), the electrodes might not be pasted firmly and the maternal R waves were not obvious; in Fig. 2(b), after amplification of an R-wave peak, there were multiple local peaks, and even experts could not identify which one to be the real R-wave peak. Therefore, it was necessary for experts to have a visual inspection of the data

waveform first, and delete the signals of some channels in each group of data, which had a poor signal quality, or whose real R-wave peaks were difficult to confirm.

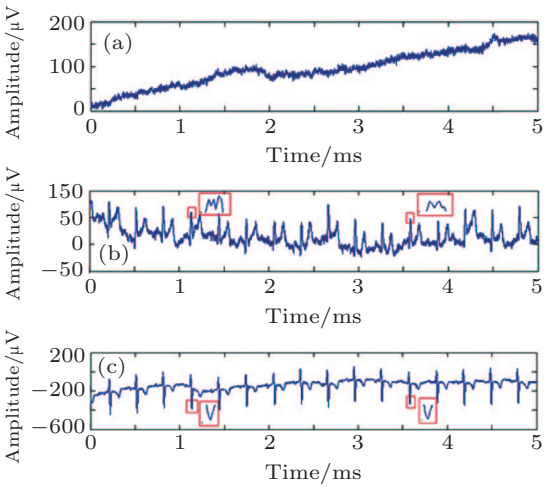


Fig. 2. (color online) Different situations of signal quality. (a) Abnormal abdominal ECG signal to be deleted. (b) Multiple local R-wave peaks abdominal ECG signal to be deleted. (c) Abdominal ECG signal to be retained.

The remaining signals after deletion were relatively clear and stable, with less noise interference, as shown in Fig. 2(c). To study the regularity in data, we sorted the remaining data and established the sample library of pregnant abdominal ECG signals. The specific distribution of the data sorted according to the electrode placement scheme and the channel number was shown in Table 2. Compared with the last electrode placement scheme, the abdominal ECG signals collected by the first two schemes were more stable and had less noise interference.

Table 2. Distribution of the filtered pregnant abdominal ECG signals according to the electrode placement scheme and channel number.

Channel number	1	2	3	4	5	6	7	8
Scheme 1	99	99	17	108	24	105	61	101
Scheme 2	82	93	95	37	83	30	85	39
Scheme 3	5	76	55	75	53	67	52	57

3. Maternal R-wave peak position detection and statistics

We used a fast adaptive R-wave detection algorithm[17–19] to automatically detect the R-wave peak positions of all the data in the established sample library first, as shown in Fig. 3. Although the quality of the filtered data in the sample library is relatively good since we had disregarded some channels' signals of low signal to noise ratio, the automatically detected R-wave peak positions by the computer algorithm were still confirmed or corrected by expert visual inspection again to ensure the accuracy of each detected peak, observing the detected R-wave peak positions one by one with carefulness and patience.

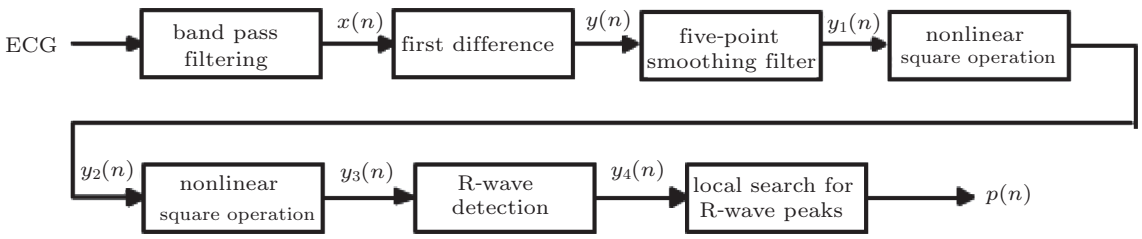


Fig. 3. Flowchart of the adaptive R-wave detection algorithm.

After the detection of the R-wave peak positions, we studied the statistical regularity about the position differences of the corresponding R-wave peaks of different channel signals. Specifically, we took the first 24 detected R-wave peak positions of each channel and analyzed the position differences of the detected corresponding R-wave peaks.

Now, we take the first three R-wave peak positions of one group of data as an example to illustrate the statistical method. As shown in Table 3, the remaining channels of this group are channel 2, channel 3, channel 5, and channel 7 after filtering. The detected positions of the first R-wave peaks of the channel 2, channel 3, channel 5, and channel 7 are 290, 296, 296, and 296 respectively, and the channel 2 has the minimum index number 290. Take the minimum index number 290 as the reference value, i.e., let R be 290 for the first peak; calculate respectively each channel's corresponding value of $D(1)$ according to Eq. (1). The values of $D(1)$ are equivalent to the first peak position differences. Similarly, the peak indexes of $P(2)$ and $P(3)$ can also be used to calculate the corresponding values of $D(2)$ and $D(3)$. All the filtered data, involving 1598 channels, and 38352 R-wave peak positions' difference values in total, were calculated out.

The peak position difference value is defined as

$$D(k) = P(k) - R. \tag{1}$$

Table 3. Schematic table for calculating position difference of each R-wave peak.

Channel number	$P(1)$	$P(2)$	$P(3)$	$D(1)$	$D(2)$	$D(3)$
1						
2	290	623	963	0	0	0
3	296	630	971	6	7	8
4						
5	296	631	971	6	8	8
6						
7	296	630	971	6	7	8
8						

Based on the detected R-wave peak relative positions (i.e., position difference values), we conducted a statistical study. The statistical results of eight-channel signals' peak position difference values are divided into three parts and respectively shown in Figs. 4(a)–4(c), according to three electrode placement schemes. The position difference statistics of R-wave peaks of each channel are illustrated by a broken line in each chart, with the horizontal axis representing the peak position difference time and the vertical axis representing the proportion of the R-wave peaks with the corresponding difference time. From Fig. 4, it can be found that the statistics for different electrode placement schemes are different. However, no matter which scheme is adopted, the position difference value ($D(k)$) always lies in a range of 0–15 dots, which indicates a corresponding time difference range of 0–30 ms.

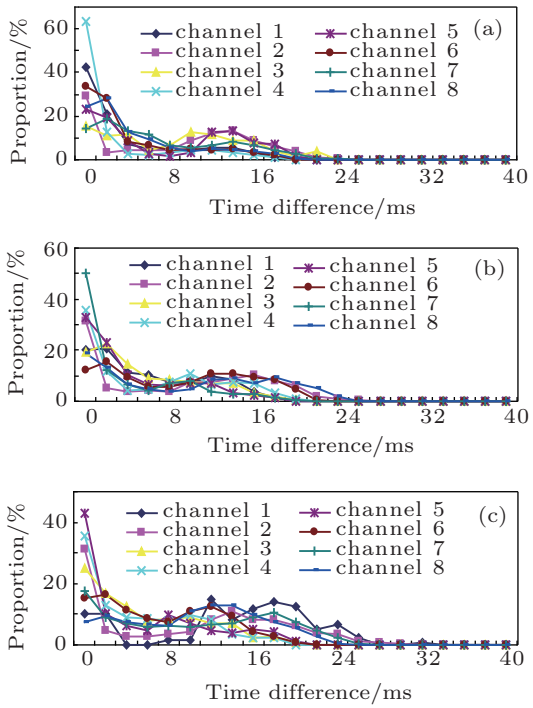


Fig. 4. (color online) Distribution of position differences of corresponding R-wave peaks for different channels under three electrode placement schemes. (a) The first scheme of electrode placement. (b) The second scheme of electrode placement. (c) The third scheme of electrode placement.

Similarly, a statistics for the difference of corresponding RR interval is done and the summary of the result is shown in Fig. 5. Likewise, horizontal axis represents the difference time of RR interval and the vertical axis represents the proportion of the difference time with the corresponding RR interval. From Figs. 5(a)–5(c), we can find that in three different electrode placement schemes, the difference range of RR interval is between 0–4 dots, namely 0–8 ms. The reasons for the difference in the RR interval can be the noise interference and discrimination error, which probably results in 1–2 dots offset per R-wave peak position. Therefore, an RR interval difference between 0–8 ms can be considered as a normal phenomenon.

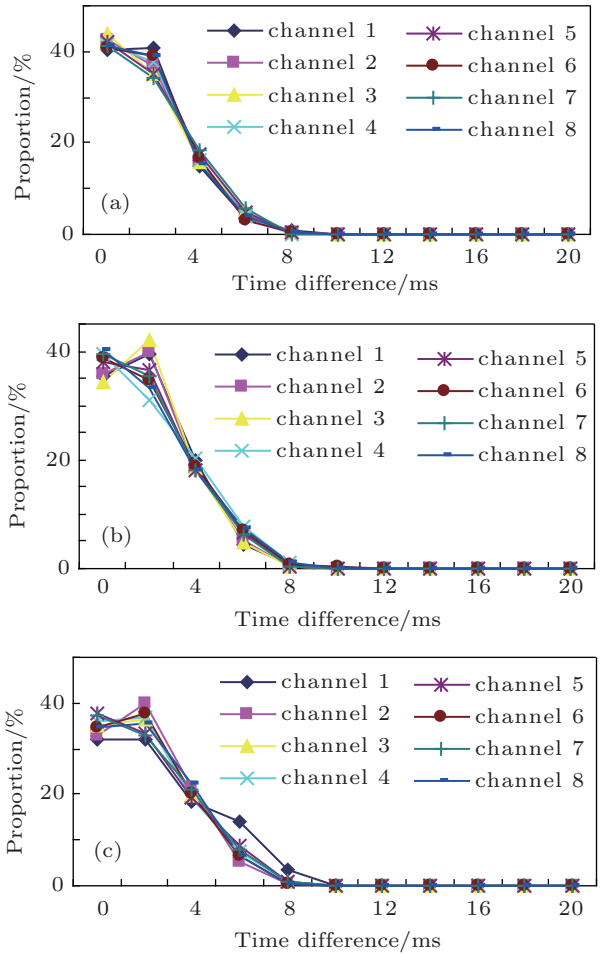


Fig. 5. (color online) Distribution of the differences of corresponding RR intervals for different channels under three electrode placement schemes. (a) The first scheme of the electrode placement. (b) The second scheme of the electrode placement. (c) The third scheme of the electrode placement.

4. Further validation of the statistical regularity

The non-invasive fetal electrocardiogram database from the MIT–BIH PhysioBank has been proven to be useful for testing fECG separation algorithms.[20] This database contains a series of 55 multi-channel abdominal fetal ECG recordings, taken from a single pregnant woman between 21 and 40 weeks of pregnancy. The records have variable durations and were

taken weekly (two or more records were acquired during some weeks). Each record includes 5 or 6 signals from different channels and the sampling frequency is 1 kHz. In order to validate the found regularity in Section 3, we also took this database to do some verification experiments.

We first unified the channel number and data length for each recording, selecting the front five signals with the duration of 0–60 s to study. Then, our statistical method proposed in Section 3 was applied to all of the unified recordings and the result is shown in Fig. 6.

Based on Fig. 6, we can see that the R-wave position difference values $(D(k))$ always lies in the range of 24 dots, which indicates a corresponding time difference range of 24 ms, and the difference range of RR intervals is within eight dots, namely 8 ms. As described in the recording information of the database, in order to improve SNR, the electrode positions were varied (the specific locations of the electrodes were not mentioned in the literature), which may contribute some small variances to our obtained statistical result in Section 3. However, anyway, the resultant range of 30 ms is still applicable to the ECG data coming from the MIT–BIH PhysioBank.

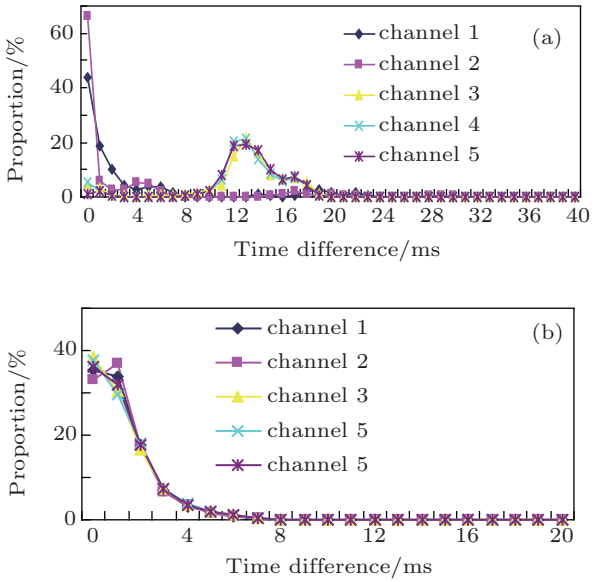


Fig. 6. (color online) Distribution of the differences of corresponding R-wave peaks and RR intervals for different channels. (a) Distribution of position differences of corresponding R-wave peaks. (b) Distribution of position differences of corresponding RR intervals.

5. Automatically detecting maternal R-wave peaks based on the statistics

We selected one group of data, which has obvious fetal ECG components in some channels, as an example. We tried to conduct an automatic maternal R-wave detection for each channel directly with the above mentioned adaptive R-wave detection algorithm shown in Fig. 3; the detected results are shown in Fig. 7, indicating a high detection error rate. Particularly, the signals with larger fetal ECG components over the maternal ECG component, which should have been more promising to separate clear fetal ECG, even had more serious problem in maternal R-wave peak detections. Thus, it's obvious that the conventional R-wave detection algorithm can not be directly used for detecting maternal R-wave peaks when the abdominal ECG signal has a large fetal ECG component.

According to the above study of the regularity, we first select one abdominal ECG signal as a reference signal which is relatively stable and has a smaller fetal ECG component from the eight-channel abdominal ECG signals, such as the channel 7 signal in Fig. 7(a). The maternal R-wave peak positions of the reference signal can be obtained by applying the conventional R-wave detection algorithm, as shown in Fig. 7(b). Then, we can return to the other seven-channel signals and calculate their R-wave peak positions respectively by doing a local search, whose center is the reference signal's R-wave peak positions and search range is 30 ms. As shown in Fig. 7(c), no false detection exists anymore.

Finally, based on the detected maternal R-wave peak positions of the eight-channel signals and the method mentioned in Ref. [12], the clear fetal ECG signals are separated from the abdominal ECG signals, as shown in Fig. 7(d).

We also expanded comparative tests to all 343 groups of original ECG data and the 55 groups of ECG data from MIT–BIH PhysioBank. Firstly, we directly detect the maternal R-wave peaks for each channel signal by using adaptive R-wave detection algorithm mentioned in Section 3, and then made use of the obtained regularity to help to detect R-waves as mentioned above. The results are listed in Tables 4 and 5, respectively. Specifically, the number corresponding to the direct detection or using regularity represents the number of signals with R-wave detection errors for each channel.

Analyzing comparative test results, it is obvious that using the conventional adaptive R-wave detection algorithm directly to detect the maternal R-wave from the abdominal signal will cause a high detection error rate, while if we apply the obtained regularity, the correct detection rates for all the eight channel signals will be greatly increased.

Table 4. Detection result of the comparative test for the 343 groups of ECG data.

	Number of signals with R-wave detection errors							
Channel number	1	2	3	4	5	6	7	8
Direct detection	90	51	123	70	84	72	60	62
Using regularity	4	4	4	4	4	4	4	4

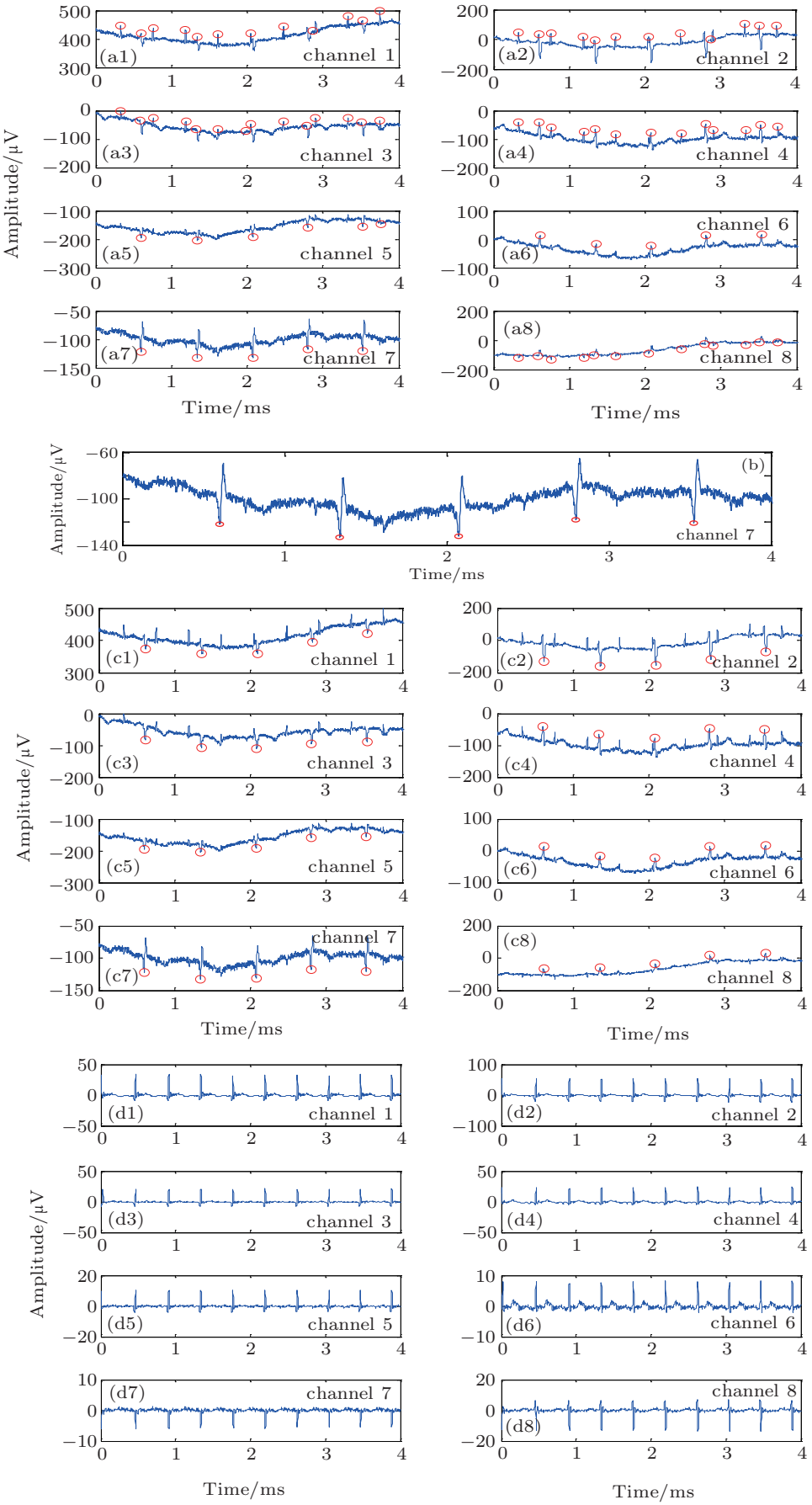


Fig. 7. (color online) Demonstration of the automatic maternal R-wave detection for abdominal ECG signals based on R-wave peak difference regularity. (a1)–(a8) Direct maternal R-wave peak detection for channels 1–8, respectively. (b) Correct direct detection for easy channel signal. (c1)–(c8) Automatic detection based on the proposed method for channels 1–8, respectively. (d1)–(d8) Final fetal ECG separated using this work for channels 1–8, respectively.

Table 5. Detection result of the comparative test for the 55 groups of ECG data from MIT–BIH PhysioBank.

	Number of signals with R-wave detection errors				
Channel number	1	2	3	4	5
Direct detection	2	0	3	8	12
Using regularity	0	0	1	0	1

6. Conclusion

In this paper, the experiment had been conducted to collect the abdominal ECG signals from 78 pregnant women. With the filtered signals, the difference range of corresponding R-wave peak position was studied, and a statistical regularity is discovered that the range of the R-wave peak position will not exceed 30 ms. Based on this regularity, we achieve the goal of automatically detecting the abdominal ECG signal's maternal R-wave peaks and separating the fetal ECG signal.

The merit of our method is that it avoids the complexity of directly detecting maternal R-wave peaks of pregnant abdominal ECG signal which has a large fetal component. Instead, we only need to pick out an easier one with a smaller fetal component from eight-channel signals and make a detection to obtain the R-wave peak indexes, then come back to the remaining seven signals to do a local search in a reasonable range and finally obtain the exact maternal R-wave peak positions of all eight-channel signals. In this way, both the accuracy and the efficiency of the R-wave peak detection are greatly improved.

However, the step picking out an easier signal from eight-channel signals as a reference signal perhaps can be modified. For instance, based on independent component analysis (ICA) or principal component analysis (PCA) of multiple abdominal signals,[21,22] we can construct one signal that has superior SNR for the mother's ECG as a reference signal instead; we can also select a dedicated thorax channel signal as a reference signal.[11,23–25] Such ideas should be further studied in the future work.

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