A Novel Extraction Method of Fetal Electrocardiogram From the Composite Abdominal Signal

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***Abstract*—In contrast to the ultrasonic measurement of fetal heart motion, the fetal electrocardiogram (ECG) provides clinically significant information concerning the electrophysiological state of a fetus. In this paper, a novel method for extracting the fetal ECG from abdominal composite signals is proposed. This method consists of the cancellation of the mother's ECG and blind source separation with the reference signal (BSSR). The cancellation of the mother's ECG component was performed by subtracting the linear combination of mutually orthogonal projections of the heart vector. The BSSR is a fixed-point algorithm, the Lagrange function of which includes the higher order cross-correlation between the extracted signal and the reference signal as the cost term rather than a constraint. This realizes the convexity of the Lagrange function in a simple form, which guarantees the convergence of the algorithm. By practical application, the proposed method has been shown to be able to extract the P and T waves in addition to the R wave. The reliability and accuracy of the proposed method was confirmed by comparing the extracted signals with the directly recorded ECG at the second stage of labor. The gestational age-dependency of the physiological parameters of the extracted fetal ECG also coincided well with that of the magnetocardiogram, which proves the clinical applicability of the proposed method.**

***Index Terms*—Blind source separation with reference signal, fetal electrocardiogram, P and T waves.**

I. INTRODUCTION

A FETAL electrocardiogram (ECG) provides clinically significant information concerning the physiological state of a fetus. For example, arrhythmias show the maturity of fetal cardiac activity, and anoxia is known to alter the balance between the electrical polarization and repolarization of heart [10]. Ultrasonic measurements of physical motion of the fetal heart can not provide such electrophysiological information. Nevertheless, the fetal ECG has not been widely used in clinical applications, because there is no low-cost, reliable method to measure the fetal ECG. The magnetocardiogram (MCG) could directly monitor the electrical activity of the fetal heart, which is measured by placing a SQUID probe close to the fetus over the mother's abdomen [11]. However, MCG measurement requires special large equipment [11]. As such, signal processing methods for extracting the fetal ECG signal from the composite abdominal signal have been developed [1], [7]. In particular, independent component analysis (ICA) and blind source separation (BSS) have been applied to this problem [5], [3]. Although most of these methods successfully restore the R wave, the P and T waves are not clearly restored [5]. Fetal arrythmia detection requires P wave extraction. When the P wave is not followed by the R wave, the conduction block can be found. The anoxia distorts the T wave. Taken together, the information of the R wave occurrence alone is not sufficient for the clinical purposes described above. In addition, the application of the proposed methods during the gestational ages of from 24 to 36 weeks, in which the signal-to-noise ratio (SNR) of fetal ECG recording is severely degraded, has not yet been examined [10]. Therefore, a more precise and reliable method of extracting fetal ECG is required.

In this paper, a novel method for extracting the R, P, and T waves of the fetal ECG from the composite abdominal signal is proposed. The proposed method combines cancellation of the mother's ECG signal and the BSS with reference (BSSR). The validity of the proposed method is assessed by practical applications to clinical data. In addition, representative physiological parameters of the extracted fetal ECG are compared with those directly measured by the MCG. Through these applications, the proposed method is shown to provide a novel framework for the reliable and precise extraction of the fetal ECG.

II. USED RECORDINGS

The data used in the present study were obtained by recordings using 14 electrodes, ten of which were placed on the mother's abdomen, including one reference electrode, one of which was placed at the right thoracic position, and three of which were placed on the back, including one ground electrode. Thirty-seven types of data were subjected to the signal processing, where the gestational ages were distributed from

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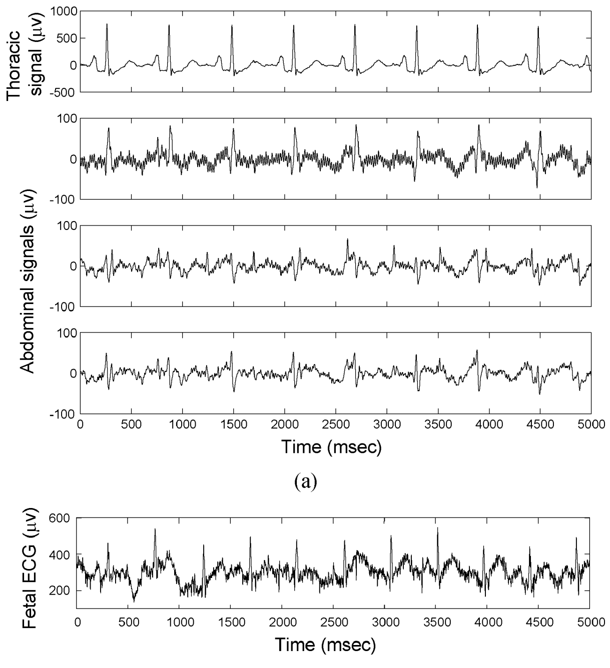


(a)

(b)

Fig. 1. (a) Abdominal signals recorded at the second stage of labor. (b) Direct ECG recorded simultaneously with a scalp electrode from the fetal head.

20 to 41 weeks. These data include a simultaneous recording of the abdominal signal and a direct signal with a scalp electrode that was attached to the fetal head during the second stage of labor. In addition, a signal recorded from a twin's mother at the gestational age of 24 weeks is used for the extraction of the orthogonal projections, which is explained in the next section. Bipolarly recorded data of 12 channels were sampled every 1 ms (1 kHz sampling) with 16-bit resolution and were subject to the bandpass filtering (1–100 Hz, finite impulse response filter).

III. METHODS

A. Method of Canceling the Mother's ECG

Fig. 1 shows the abdominal signal to be analyzed and the direct ECG simultaneously recorded from the fetal head cutaneously with a scalp electrode during the second stage of labor. It is shown that the mother's ECG dominates the fetal ECG with respect to amplitude, and the SNR is not very high in practical situations. A straightforward idea is the direct application of ICA/BSS for extracting the fetal ECG [5], [3]. However, such methods tend to fail in precise extraction, as shown later. Fig. 2 shows the results obtained by directly applying the nonholonomic ICA proposed by Amari [12] to the abdominal signal. One can easily recognize the contamination of the mother's ECG, which is at least partly due to the extreme dominance of the mother's ECG in comparison with the fetal ECG. In order to reduce the effects of the mother's ECG on the extraction, we try to eliminate it from the data recorded from each electrode through preprocessing prior to the BSS-based extraction. An adaptive noise-cancellation (ANC) technique can be used for this purpose. However, the BSS shows better performance than the ANC [7]. Another possibility is the nonlinear projection method (NPM) [8], [9]. Because the NPM uses the trajectory embedded in the higher order dimensional space, its realization requires a huge computational load, which is not suitable for online processing. Therefore, instead of the ANC and NPM, we make use of the electrocardiological knowledge to perform this cancellation.

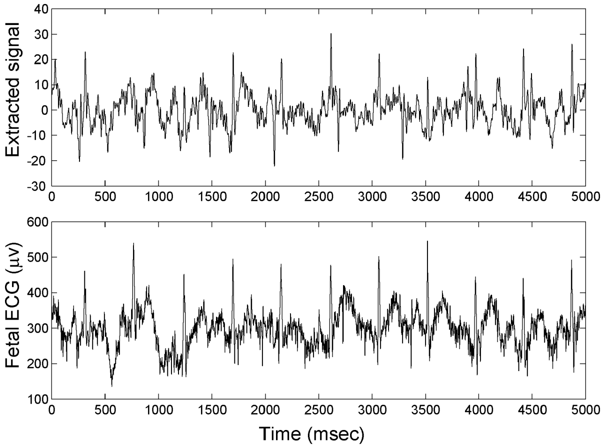


Fig. 2. Extracted signals by the nonholonomic ICA (top) and the direct ECG recorded simultaneously with a scalp electrode from the fetal head (bottom).

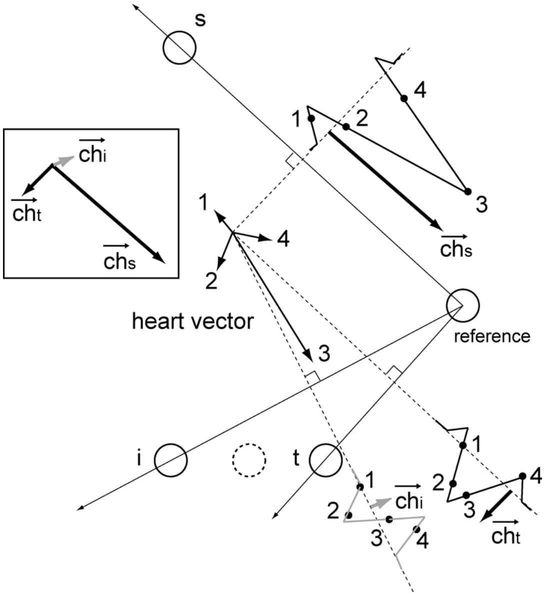


Fig. 3. Projection of the heart vector on a recording axis spanned by electrodes and its reconstruction by the combination of mutually orthogonal projections. In the center, the stroboscopic motion of heart vector is shown schematically. The vector moves in the order of $1, 2, 3, 4, 1, 2, \ldots$. The recording axes are denoted by the lines from the reference to the recording electrodes. The waveforms on the lines perpendicular to the respective axes show the recorded signal. The vector next to the waveform corresponds to that at phase 3. In the enclosed area, the combination of the basis vectors, $\vec{ch}_s$ and $\vec{ch}_t$, can reconstruct the recorded signal vector, $\vec{ch}_i$, shown in grey.

The electrical activities of the heart can construct a vector in the direction of excitation, which is called the heart vector [10]. Therefore, the bipolarly recorded signal in each electrode is a projection of the heart vector on the axis spanned by the reference and the electrode, as shown in Fig. 3. This implies that the projections on the different axes could be used to reconstruct the

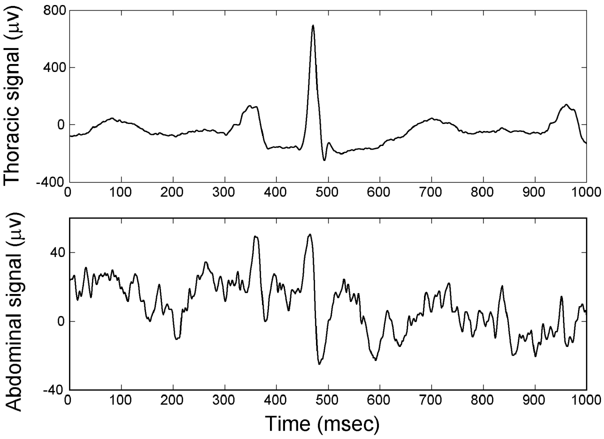


Fig. 4. Selected signals for reconstructing the mother's ECG, which are regarded as linearly independent projections. The top signal is recorded from the thoracic electrode, and the bottom signal is an abdominal signal.

heart vector. Furthermore, each projection can be represented by an appropriate combination of linearly independent projections, which is described as follows:

$$\vec{ch_j}(m) = a_j \cdot \vec{ch_s}(m) + b_j \cdot \vec{ch_t}(m) \quad m = 1, \ldots, M \quad (1)$$

where $\vec{ch_j}(m)$ denotes the signal vector projected on j-th channel of the electrode at time m, $\vec{ch_s}(m)$ and $\vec{ch_t}(m)$ denote the selected pair of projections on the electrodes s and t ($j, s, t \in [1, \ldots, 12]$), respectively, and a_j and b_j are weight coefficients. Furthermore, if the vectors $\vec{ch_s}$ and $\vec{ch_t}$ are mutually orthogonal, then (1) is reduced to give the amplitude of the signal recorded in each electrode, i.e., no further geometric knowledge of the electrode arrangement is required. Consequently, we have

$$\begin{cases} ch_j(m)\cos\theta &= a_j \cdot ch_s(m) \\ ch_j(m)\sin\theta &= b_j \cdot ch_t(m) \end{cases} \quad (2)$$

where θ is the angle between $\vec{ch_j}$ and $\vec{ch_s}$. For our purpose, the exact values of $\cos\theta$ and $\sin\theta$ do not need to be estimated. Instead, only the coefficient linearly relating ch_s or ch_t to ch_j needs to be found. Practically speaking, a_j and b_j are estimated together with $\cos\theta$ and $\sin\theta$ by solving the over-determined (2) in a least squares error sense, where $M \gg 2$. In the present study, 50 consecutive samples ($M = 50$) covering an R wave are used for the estimation. The averaged estimates over five R waves are used for the reconstruction of projections on each electrode. Subtracting the estimated projection from the recorded signal in each electrode is expected to cancel the mother's ECG, provided that the mother's ECG is sufficiently larger than the fetal ECG.

Fig. 4 shows the selected pair of signals, which are approximately mutually orthogonal. Fig. 5 shows the results of cancellation of the mother's ECG. The almost complete disappearance of the mother's ECG indicates that the cancellation procedure works as a preprocessing for the application of ICA/BSS.

B. Blind Source Separation With Reference

The P and T waves and their relation to the R wave could provide clinically significant information concerning the condition of fetal heart [10]. However, previous signal processing methods used to extract the fetal ECG did not seriously consider the detection of the component waves, except for the R wave. Moreover, they can not be used to determine the type of projection of the separated signal [5], [7]. In other words, only the occurrence of the heartbeat has been a target for extraction.

Here, we propose a novel method that can be used to extract the P and T waves in addition to the R wave and can distinguish the extracted projection of the fetal heart vector. Prior to the following extraction, it is supposed that the mother's ECG is cancelled and the data are prewhitened, i.e., the covariance matrix of the data is diagonalized [13]. The method is formulated as follows, which is a BSS with reference, referred to hereinafter as BSSR [2]. Let us consider the situation in which n source signals $\boldsymbol{s} = (s_1, s_2, \ldots, s_n)$ are observed as $\boldsymbol{x} = (x_1, x_2, \ldots, x_m)$ through a linear and immediate mixture

$$\boldsymbol{x} = A\boldsymbol{s} \quad (3)$$

where A denotes the full rank mixing matrix of $m \times n$. The present purpose is to estimate A and $\boldsymbol{s}$. Here, the estimation of individual source signals is considered separately

$$y = \boldsymbol{w}^T \boldsymbol{x} \quad (4)$$

where y and $\boldsymbol{w}$ denote the estimates of a source signal and the corresponding row vector of the estimated inverse of A, respectively. In addition, T denotes a transpose. Here, note that out of m observations only a few sources need to be recovered. These sources are the fetal ECGs, which consist of approximately periodic sequence of pulse-like events. In this sense, the situation is not a completely blind situation. In order to aid the estimation, an artificial or observable signal is referred to that is closely related to the source signal to be recovered. Next, we consider the estimation of y, which is highly correlated with the reference signal r under the constraint $\|\boldsymbol{w}\| = 1$. This is realized by maximizing the Lagrangian

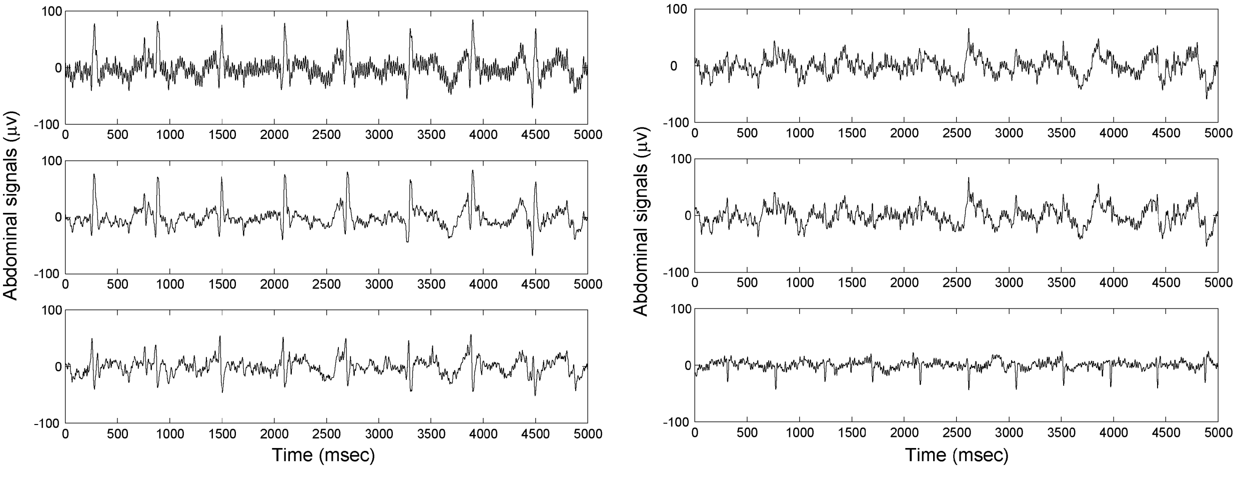
$$L(\boldsymbol{w}) = \frac{1}{2n} E[y^{2n} r^{2n}] - \frac{\lambda}{2}(\boldsymbol{w}^T \boldsymbol{w} - 1) \quad (5)$$

where $E[\,]$ denotes an expectation, and λ is a Lagrange multiplier. We can easily obtain λ, which gives the extrema of $L(\boldsymbol{w})$, as follows. Since $\partial L(\boldsymbol{w})/\partial \boldsymbol{w} = 0$ is satisfied at an extremum, we have

$$\lambda \boldsymbol{w} = E[y^{2n-1} r^{2n} \boldsymbol{x}]. \quad (6)$$

Next, λ is determined by multiplying both sides of (6) by $\boldsymbol{w}^T$ as follows:

$$\lambda = E[y^{2n} r^{2n}]. \quad (7)$$



(a) (b)

Fig. 5. Results of cancellation of the mother's ECG. (a) Signals subject to cancellation. (b) Results of cancellation.

Substituting this into (6), we have

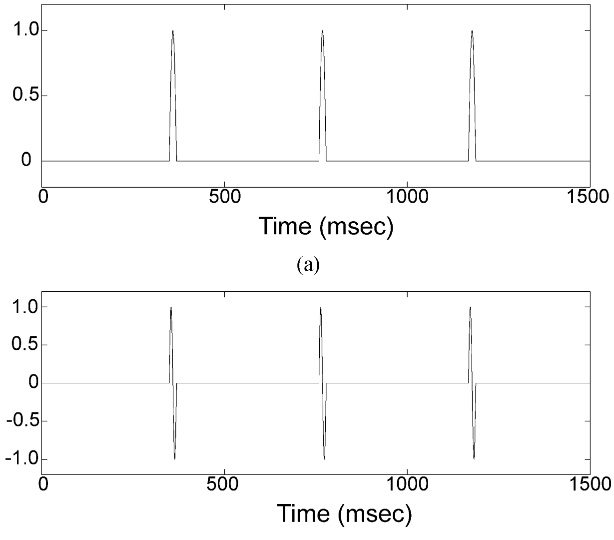
$$\boldsymbol{w} = \frac{E[y^{2n-1}r^{2n}\boldsymbol{x}]}{E[y^{2n}r^{2n}]}. \tag{8}$$

The following interations give the solutions:

$$\begin{aligned} \boldsymbol{w}_{k+1} &= \frac{E[y_k^{2n-1}r^{2n}\boldsymbol{x}]}{E[y_k^{2n}r^{2n}]} \\ y_{k+1} &= \boldsymbol{w}_{k+1}^T\boldsymbol{x}. \end{aligned} \tag{9}$$

Considering the fact that all the concerned signals $\boldsymbol{x}, r$, and y are highly concentrated events along the time axis, the exponent n makes the correlations more sensitive to the temporal concentrations of the estimated events. Here, we use $n = 2$, because this is the minimum order by which to produce the higher order moment and realize the convex Lagrange function.

Empirically, in our case, the reference signal does not have to closely mimic the signal to be estimated. Here, an almost periodic sequence of temporally concentrated waveforms shaped by (10), shown at the bottom of the page, where t denotes the time in terms of ms and t_p, indicates the peak position of the reference event. Fig. 6 shows the respective reference signals, which are selected depending on the polarity of the projection to be extracted. Note that they are mutually orthogonal. We assume that an ultrasonic Doppler signal emitted by the fetal heartbeat could be used for the reference.



(a) (b)

Fig. 6. Reference signals. (a) Unipolar reference signal. (b) Bipolar reference signal.

The practical estimation is performed as follows. The initial value of $\boldsymbol{w}$ is given as a vector, the entries of which randomly take values of ± 1. This is only for the algorithm to start with no strong preference. The extraction is performed segment-wise, where one segment is 5 s (5000 points). The expectation is realized by the temporal integration in the respective segment. In most cases, $\boldsymbol{w}_n$ almost converges within 10 iterations. Therefore, the iteration is usually stopped at 20 times. In summary, the extraction proceeds as follows: 1) cancellation of the mother's ECG; 2) prewhitening; 3) solution of (9) in order to extract the fetal ECG.

$$\begin{cases} \cos\left(\frac{\pi(t-t_p)}{30}\right), & \text{for extracting unipolar projection} \\ \sin\left(\frac{2\pi(t-t_p)}{30}\right), & \text{for extracting bipolar projection } -15\ \text{ms} \le t - t_p \le 15\ \text{ms} \end{cases} \tag{10}$$

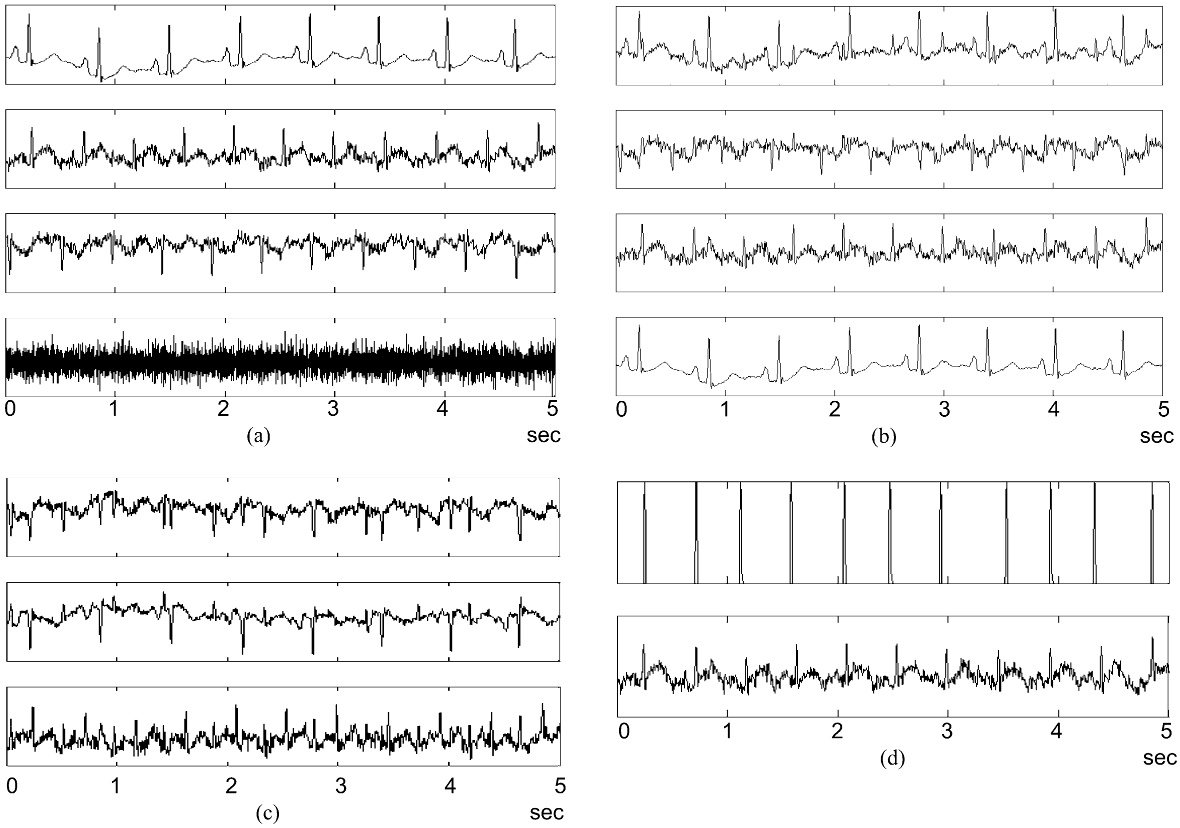


Fig. 7. Simulation results of separation of fetal ECG signal. The scale of the vertical axis is arbitrary. (a) Source signals (from top to bottom): mother's ECG, fetal ECG, 200-ms-displaced and inverted fetal ECG, and EMG signal modeled by the fifth-order autoregressive process. (b) Mixed signals. (c) Separated signals by the nonholonomic ICA algorithm. (d) Reference signal (top) and separated fetal ECG signal (bottom).

IV. RESULTS

In order to assess the ability of the BSSR, extraction is performed for artificially composed signals. Fig. 7(a) shows the source signals that consist of the mother ECG signal, the fetal ECG, a 200-ms-displaced and inverted version of the fetal ECG, and noise mimicking electromyogram (EMG) activity. The time resolution of these signals is 1 ms. A fifth-order autoregressive model is used for simulating the EMG activity, the parameters (from the first to the fifth) of which are (-0.926, -0.853, -0.668, -0.407, and -0.221). Fig. 7(b) shows the mixed signals obtained by an appropriate random mixing matrix. Note that the probability distribution cannot distinguish the two fetal ECG signals. This situation is similar to the case of twins. The nonholonomic ICA algorithm fails to extract the fetal ECG signal, as shown in Fig. 7(c). In contrast, the BSSR successfully extracts the fetal ECG thanks to the reference signal, as shown in Fig. 7(d). By this simulation, the BSSR appears to work well, even in the case in which the observation contains source signals that share similar probabilistic features.

Fig. 8 shows the results of extraction, in which, after canceling the mother's ECG, the nonholonomic ICA and BSSR are applied to the actual composite data at the second stage of labor, as shown in Fig. 1. In the application of BSSR, the occurrence timing of the reference event is set to coincide with the fetal ECG recorded directly with the scalp electrode on the fetal head. Actually, in order to achieve more realistic conditions, the occurrence timing of the reference event is forced to stochastically fluctuate around the peak timing of the R wave of the fetal ECG with a uniform distribution ranging from ± 20 ms. Compared with the directly recorded signal, the nonholonomic ICA sometimes fails to extract the P and T waves, which are successfully extracted by the BSSR. The performances of these two extraction methods are more explicit in the averaged waveforms, as shown in Fig. 9(a)–(c), where 100 extracted waveforms are averaged synchronously centering around the R wave peak. The P and T waves of the directly recorded signal can clearly be seen. Although blurred in the extracted signals, the BSSR extracts the representative waves more distinctly than the nonholonomic ICA. This tendency is indicated in a more quantitative manner by the correlation coefficient between the direct recording and the extracted results: 0.56 ± 0.11 for the BSSR and 0.30 ± 0.089 for the nonholonomic ICA, which is statistically significant (the number of beats is 130, $p < 0.01$).

In the previous section, we stated that the extraction performance by the BSSR does not significantly depend on how closely the reference mimics the source signal to be estimated. When the distribution width governing the occurrence of the reference event is varied as 0 ms, ± 10 ms, ± 20 ms, ± 30 ms, ± 40 ms, and ± 50 ms centering around the R wave occurrence timing, the correlation coefficients are 0.58 ± 0.11, 0.58 ± 0.11, 0.56 ± 0.11, 0.50 ± 0.12, 0.57 ± 0.11, and 0.46 ± 0.14, respectively. Nevertheless, this does not imply that an increased discrepancy between the timings of the reference and fetal R waves severely distorts the extracted waveform, but that the relative variation in the amplitudes causes the deterioration in the

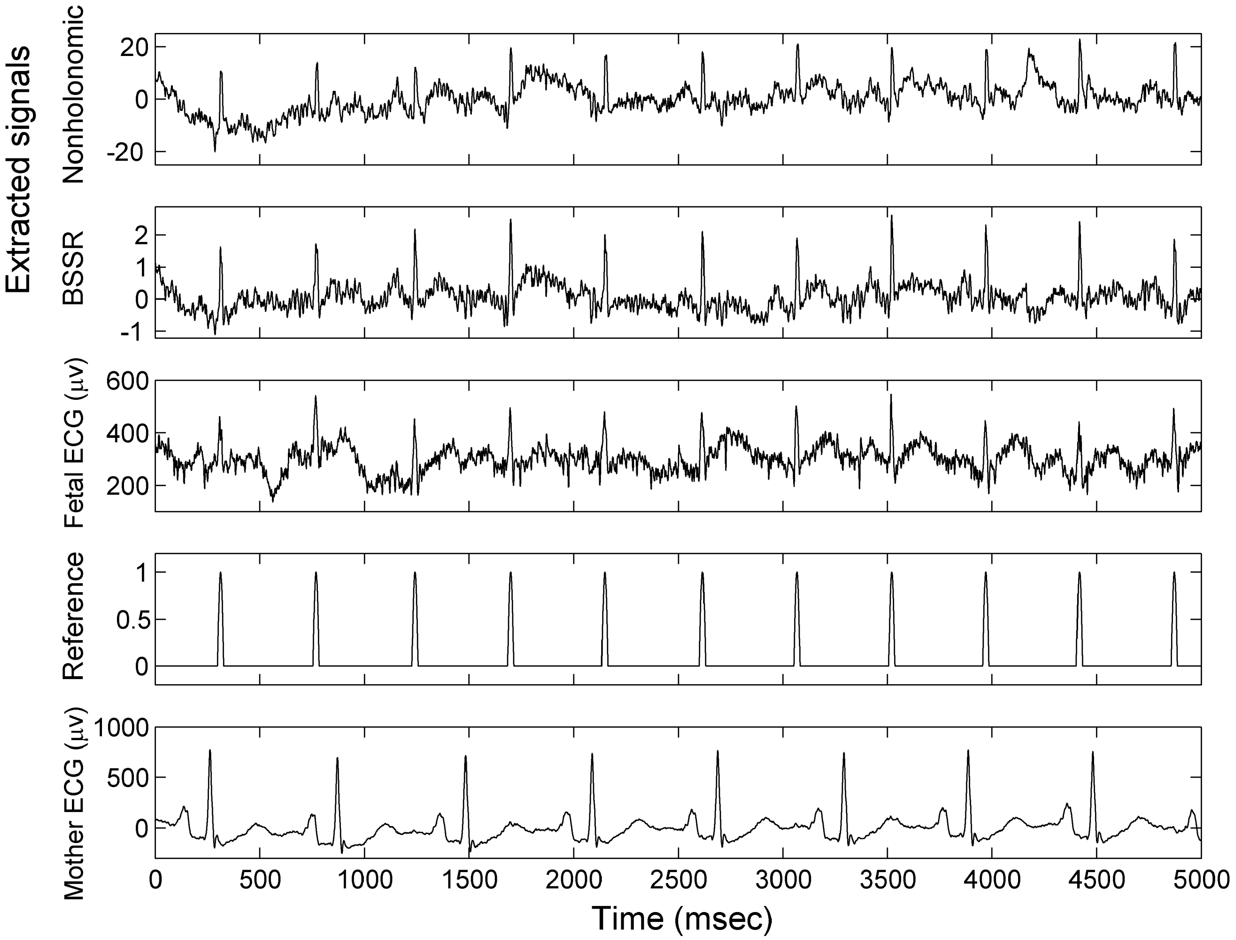


Fig. 8. Results of extraction obtained by applying the BSSR to the actual composite data shown in Fig. 1. The traces are (from top to bottom) the extracted signals by the nonholonomic ICA and the BSSR, the directly recorded ECG, the reference signal, and the mother's ECG.

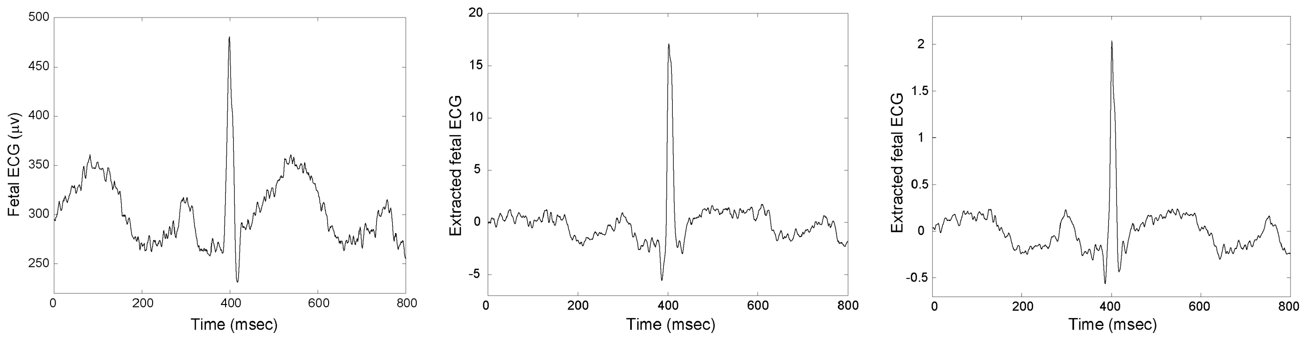
correlations. These results demonstrate the robustness of the extraction with respect to the discrepancy between the reference and the actual ECG.

The heart vector is expanding/contracting while rotating in three dimensional space during the heart period. Electrodes around the origin of the vector pick up various projections of the heart vector. Among which, the mutually orthogonal projections are regarded as different sources in the framework of BSS. Here, using the unipolar and bipolar references in (10), the mutually orthogonal projections are extracted, and the results for one of the twin fetuses are shown in Fig. 10. These waveforms are averaged over 250 beats. The analyzed signals were recorded from the mother of the twins at the gestational age of 24 weeks, which slightly degrades the performance of extraction, as is recognized from the indistinct T waves. Nevertheless, as shown in this figure, both projections of the P and R waves are successfully extracted.

In order to assess the reliability and accuracy of the proposed method, the gestational age-dependency of the physiological parameters of the extracted ECG is compared with that of the fetal MCG [11] because the MCG is a direct noninvasive way to measure the fetal ECG-related signal. The MCG data are taken from the fetal cardiogram database, which consists of the averaged feature parameters measured by different institutes around the world. Fig. 11 shows the gestational age-dependency of the physiological parameters of the extracted ECG of 37 subjects, whose gestational ages are distributed from 20 to 41 weeks. Naturally, the fetal ECGs are not known in these 37 data before labor. The R wave occurrence timings are roughly obtained by the preliminary separation with the reference, the events of which are periodically placed at appropriate intervals along the time axis. The respective physiological parameters are obtained from the averaged waveform of the extracted ECG (number of beats: 100). The estimated regression coefficients are given together with the MCG data in Table I. Although there exist large variances in both results (see the plots for the database [11]), the coefficients of the extracted ECG coincide approximately with those of the MCG. This result confirms the reliability and accuracy of the BSSR applied in practical situations.

V. DISCUSSION

In the present paper, a novel method for extracting the fetal ECG from abdominal composite signals was proposed. The proposed method consists of the cancellation of the mother's ECG and the BSS with the reference signal. Based on the physiological knowledge, the mother's ECG component in each electrode was reconstructed by combining mutually orthogonal projections of the heart vector and was then cancelled by subtraction. Subsequently, the extraction of the fetal ECG was realized by the newly developed BSS referring to the signal related to



(a)

(b)

(c)

Fig. 9. Averaged directly recorded and extracted ECGs synchronously centered around the peak timing of the R wave. (a) Directly recorded ECG. (b) Extracted ECG by the nonholonomic ICA. (c) Extracted ECG by the BSSR.

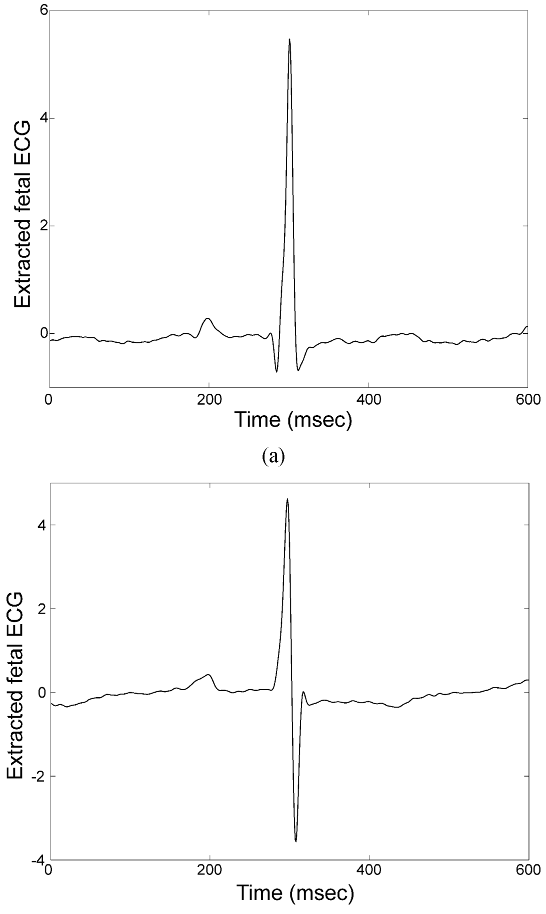
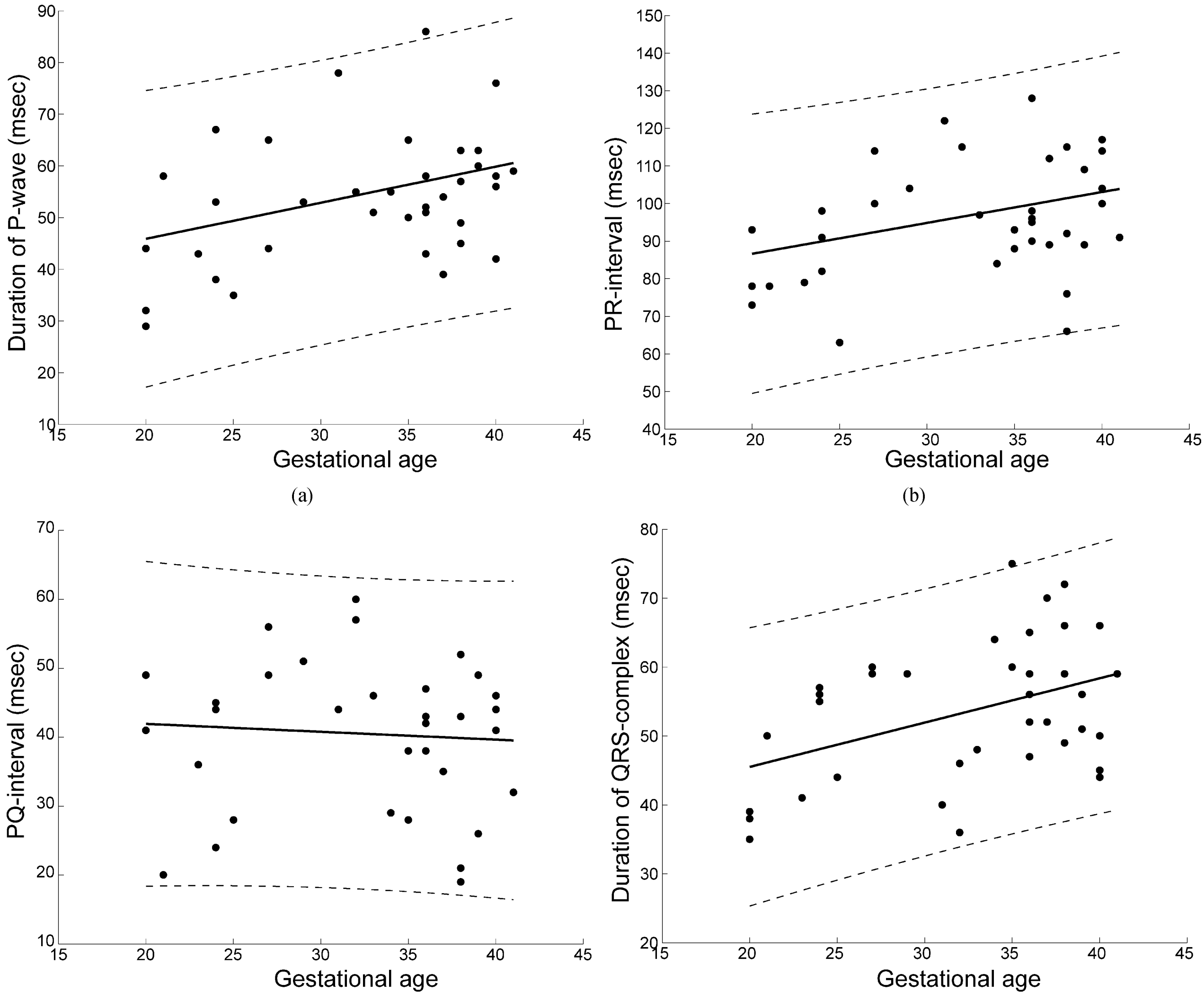


Fig. 10. Extracted projections of the heart vector using the mutually orthogonal reference signals shown in Fig. 6. (a) Extracted waveform with the unipolar reference averaged over 250 beats. (b) Extracted waveform with the bipolar reference averaged over 250 beats.

the fetal ECG (BSSR). The BSSR is designed to recover the signal that maximizes its correlation with the reference. The BSSR successfully extracted the source signal from the simulated composite signal, which indicates the applicability of the proposed algorithm. In practical application, the proposed method was shown to be able to extract the P and T waves in addition to the R wave. The reliability and accuracy of the proposed method was confirmed by comparing the extracted signals with the directly recorded fetal ECG from the head. The gestational age-dependency of the physiological parameters of the extracted fetal ECG also coincide well with that of the MCG, which demonstrates the clinical applicability of the proposed method. Actually, preliminary applications show that the BSSR works well for finding the pathological states: damped P waves in the premature ventricular contraction and interruption of P wave generation in the premature A-V nodal contraction (the results are omitted here).

Thus far, various BSSRs have been proposed [4], [6], [2]. A straightforward construction of BSSR is that depends on the framework of the Wiener filter, in which the square error between the separated signal and reference is minimized [4]. There are variations in the utilization of the framework. In the Fast ICA with reference, the solution is iteratively searched starting with the Wiener weight, but the reference is not referred to in every iteration step [4]. Provided that a reference close to a signal to be extracted is available and there is an algorithm that enables a continuous reference, the framework of the Wiener filter could be a powerful tool. Another type of fixed-point algorithm is also proposed based on the Lagrange function including the correlation with the reference as a constraint [6], [2]. Although in these algorithms the reference information is referred to in every iteration step, the Lagrange function becomes more complex in order to guarantee its convexity [6]. Instead of a cross-correlation, other probabilistic measures, such as a Kullback-Leibler divergence, could be used to quantify the distance between the extracted signal and the reference. However, because, at least in our case, the deterministic signal is used for the reference, this substitution is not considered to be essential. If the BSSR is generalized, such a probabilistic measure may be useful. This will be considered theoretically in a future study.

In contrast to previously proposed algorithms, in the algorithm proposed herein, we include the higher order cross-correlation between the extracted signal and the reference in the cost function itself. This simple composition of the Lagrange function enables the method to use the reference in every iteration step. Considering that the signals to be extracted and the reference are temporally concentrated signals, the higher even-order cross-correlation between these signals is expected



(a) (b) (c) (d)

Fig. 11. Gestational age-dependency of the physiological parameters of the extracted ECG. The solid and dotted lines indicate the regression lines and 95% reliable intervals, respectively. (a) Duration of P wave. (b) Interval between P and R waves (PR interval). (c) Interval between P and Q waves (PQ interval). (d) Duration of QRS complex.

TABLE I
REGRESSION COEFFICIENTS OF THE FEATURE PARAMETERS OF THE EXTRACTED FETAL ECG TOGETHER WITH THOSE OF MCG [11]

	Regression Coefficients	
	extracted fetal ECG (ms/week)	fetal MCG (ms/week)
P wave duration	0.90	0.85
QRS duration	0.63	0.80
PR interval	0.67	0.70
PQ interval	-0.13	-0.10

to be convex. In addition, provided that the reference is a deterministic signal, the cross-correlation depends mainly on the statistics of y. Hyvärinen reported the third-order convergence of the Fast ICA, which uses the same framework of a fixed- point method based on the fourth-order moment of y, the kurtosis, as in the present study [14]. Taken together, the convergence of the proposed BSSR algorithm is at least practically guaranteed, which is supported by the result that, at most, 20 iterations are sufficient for convergence in the present applications.

In the clinical application, the proposed method may suffer from noise in each measurement channel. Provided that the noise is a stationary, temporally white, zero-mean random process that is independent of the source signals and is also spatially white, prewhitening could cancel the noise effects under the condition that the number of measurement channels is sufficiently large compared with the number of source signals [15]. Under the same statistical noise condition, the framework of the factor analysis is also applicable [16]. Twelve channels in the present measurement set-up is considered to be sufficiently large compared with the number of ECG signals to be recovered. Nevertheless, because the ECG is measured through low-impedance channels, the EMG, rather than the noise measured individually in each electrode, is the major disturbance. Such EMG activity could be separated in the BSSR, as the EMG is expected to be shared simultaneously by a number of electrodes. Another possible disturbance is a time-varying mixture, which is expected to be caused by a change in the spatial relationship between the fetus and the mother. Under this condition, a finer time resolution of parameter evolution than is currently used, 5 s, may be required for reliable extraction. The ultrasonic Doppler signal as a reference is expected to be available for timing the parameter evolution of the BSSR.

The proposed method is designed for online processing in clinical situations. By introducing the reference, the output channel for the extracted signal is arbitrarily selected in contrast with the uncertainty in a standard ICA/BSS. In addition, the simple realization of the proposed method allows the extraction of various kinds of projections of the fetal ECG. Although, compared to standard ECG recording, a greater number of electrodes are required and the reference signal has to be taken from some other source, such as an ultrasonic Doppler signal, the proposed method has some degree of clinical significance, despite the above requirements, which could be reduced by further improvements in the algorithm and the measurement method.

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