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Reconstruction of Fetal Vector Electrocardiogram from Maternal Abdominal Signals under Fetus Body Rotations

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Abstract—**Fetal electrocardiogram (fECG) and its vector form (fVECG) could provide significant clinical information concerning physiological conditions of a fetus. So far various independent component analysis (ICA)-based methods for extracting fECG from maternal abdominal signals have been proposed. Because full extraction of component waves such as P, Q, R, S, and T, is difficult to be realized under noisy and nonstationary situations, the fVECG is further hard to be reconstructed, where different projections of the fetal heart vector are required. In order to reconstruct fVECG, we proposed a novel method for synthesizing different projections of the heart vector, making good use of the fetus movement. This method consists of ICA, estimation of rotation angles of fetus, and synthesis of projections of the heart vector. Through applications to the synthetic and actual data, our method is shown to precisely estimate rotation angle of the fetus and to successfully reconstruct the fVECG.**

I. INTRODUCTION

A FETAL electrocardiogram (ECG) provides clinically significant information concerning physiological states of a fetus. For example, arrhythmias show immaturity of fetal cardiac activity, and anoxia is known to alter the balance between electrical polarization and repolarization of the heart [1]. Its vector form, vector ECG, could add novel information of multi-dimensional trajectory of heart vector which might be a unified form of spatio-temporal electrical excitation and relaxation processes of the heart muscle [2]. The fetal ECG has not yet been popularly used in the clinical situations, because there is no low cost and reliable method to measure the fetal ECG. The magnetocardiogram (MCG) could directly monitor electrical activity of the fetal heart, which is measured by placing a SQUID probe close to the fetus over the mother's abdomen [2]. However, the MCG measurement needs the special large scale equipment [2]. Instead, the signal processing methods extracting the fetal ECG signal from the composite abdominal signal have been developed. Especially, an independent component analysis (ICA) and blind source separation (BSS) have been applied to this problem [4],[5]. However, the performance of these methods severely suffers from contamination of noise including the maternal ECG and the abdominal electromyogram (EMG) activity. Basically, ECG can be regarded as a projection of the heart vector onto the recording surface spanned by the recording sites. Therefore, exactly speaking, the source signals under extraction are no more independent with each other, instead strongly correlated. In this case, an ordinary ICA extracts mutually orthogonal signals whose number is up to the space dimension, e.g., three in the case of ECG. Such orthogonal components are sufficient to construct the fVECG, provided that the component ECG waves are precisely extracted. However, under noisy and nonstationary situations, one cannot get all the possible orthogonal signals up to the number of the space dimension, and some of component waves are mostly missing. In this case, reconstruction of fVECG could not be realized.

In this paper, we propose a novel method for reconstructing fVECG under noisy and nonstationary situations. Original idea of ours is that even if only a single projection of the heart vector is separated, movement of the fetus could serve for recovering the missing projections. Based on this idea, we develop a method for quantitative estimation of fetus movement and synthesis of missing projections so as to reconstruct the fVECG. The method is applied to the synthetic data generated by using the model heart vector [6] and the actual maternal abdominal signals. Through these applications, it is shown that our method can quantitatively estimate the fetus movement, and reconstruct the fVECG with sufficient exactness.

II. ESTIMATION OF HEART VECTOR PROJECTIONS UNDER NOISY AND NONSTATIONARY SITUATIONS

A. Incomplete separation of fECG under noisy and nonstationary situations

Provided that the heart vector is a good approximation of spatiotemporal polarization and depolarization dynamics of the heart muscle, ICA extracts the mutually orthogonal projections (basis projections) of the vector, where the possible number of such projections is equal to the spatial dimension, i.e., three in the case of fECG. Because reconstruction of the fVECG is the purpose of our study, it is sufficient for us to extract these three projection signals. However, actually one or two projections are lost due to the noise contamination such as maternal ECG, EMG, and

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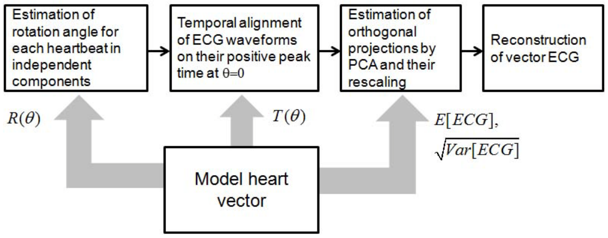


Fig. 1. Procedure for reconstructing fVECG after the fastICA application to the maternal abdominal signals. The model heart vector [6] and its projections provide basis of estimations.

nonstationary disturbances such as fetus body movement. In addition, the component PQRST waves are not always fully separated.

B. Estimation of Heart Vector Projections under Rotation of Fetus Body

Under noisy and nonstationary situations, all the orthogonal basis projections of heart vector may not be extracted by ICA. However, provided that a fetus body moves while recording, different projections of heart vector are expected to be obtained. That is, if the relationship between the position of fetus body and extracted projection is known, the orthogonal basis projections could be synthesized from the obtained projections. The condition that the movement could be confined to rotation around the head-to-tail axis makes this idea more feasible. Actually, this condition is empirically valid for gestation period beyond around 32 weeks [1].

The reconstruction method of fVECG is depicted in Fig.1, which consists of the following steps. (i) After appropriate digital filtering, the fastICA is operated on the maternal abdominal signals, which is omitted from Fig.1. (ii) After an independent component (IC) channel containing the fECG is found by the autocorrelation technique, the rotation angle of the fetus body for every heartbeat in that channel is estimated by referring to $R(\theta)$:

$$R(\theta) = \frac{u_\theta(\tau_{\max}(\theta))}{u_\theta(\tau_{\max}(\theta)) - u_\theta(\tau_{\min}(\theta))}, \qquad (1)$$

where u_θ is a normalized model ECG [6] with rotation angle θ, and $\tau_{\max}$ and $\tau_{\min}$ denote timings of positive and negative peaks within a heartbeat interval, respectively. Figure 2 shows $R(\theta)$, $\tau_{\max}$, and $\tau_{\min}$ obtained from a projected waveform of the model heart vector. $R(\theta)$ is used in an inverse way from the estimate $\hat{R}$ (=positive peak value/peak-to-peak value) to θ, which is a one to one mapping by additional reference to the temporal order of the positive and negative peaks, θ_{np} or θ_{pn}. The projection angle is defined as shown in Fig.3. (iii) Every heartbeat is aligned in time with the others at the positive peak time of its ECGx projection (θ=0). This is done according to T(θ):

$$T(\theta) = \frac{\tau_{\max}(\theta) - \tau_{\max}(0)}{\tau_{\max}(\theta) - \tau_{\min}(\theta)}. \qquad (2)$$

In practice, the temporal position of each heartbeat interval is adjusted so that $\hat{\tau}_{\max}(0) = \hat{\tau}_{\max} - T(\hat{\theta}) \bullet (\hat{\tau}_{\max} - \hat{\tau}_{\min})$ becomes identical, where $\hat{\tau}_{\max}$ and $\hat{\tau}_{\min}$ are estimated positive and negative peak times of actual ECG, respectively, and $\hat{\theta}$ is an estimate of rotation angle. (iv) Principal component analysis (PCA) is operated on thus temporally aligned ECG waveforms segmented with an averaged heartbeat interval. PCA provides the ECG waveforms of most effective projections that synthesize the ECG waveforms under concern. The rotation angles for the principal components of ECG waveform are indentified by following the same procedure as (ii). Then, their original amplitudes are recovered by the following scaling.

$$\overrightarrow{ECG_{\theta_i}} = \overrightarrow{\hat{u}_{\theta_i}} \sqrt{V[ECG_{\theta_i}]} + E[ECG_{\theta_i}] \; (i = 1, 2), \qquad (3)$$

where $\overrightarrow{ECG_\theta}$ denotes the projection of model ECG waveform at θ, and $\overrightarrow{\hat{u}_\theta}$ denotes the principal component of ECG waveform at θ. V and E denote variance and mean, respectively. Finally, solving an inverse transformation gives

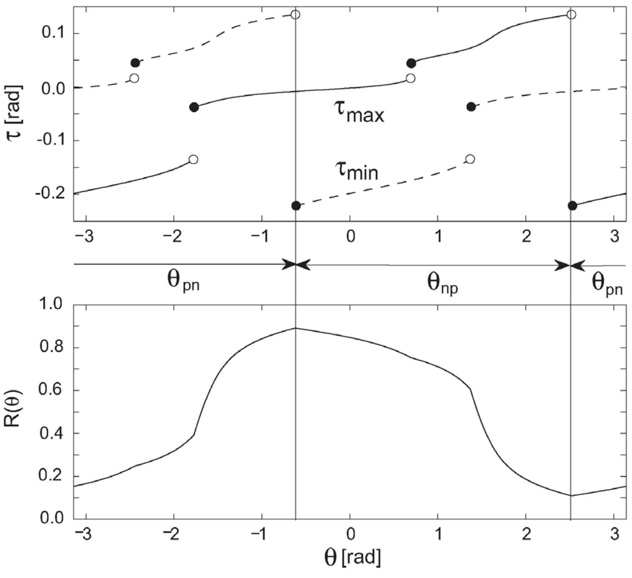


Fig.2 Positive and negative peak timings (top) and R(θ) (bottom) whose definition is given in the text. θ_{np} is for the waveform in which the negative peak precedes the positive, and θ_{np} for the opposite.

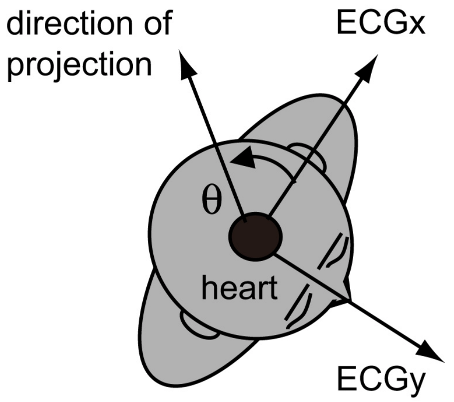
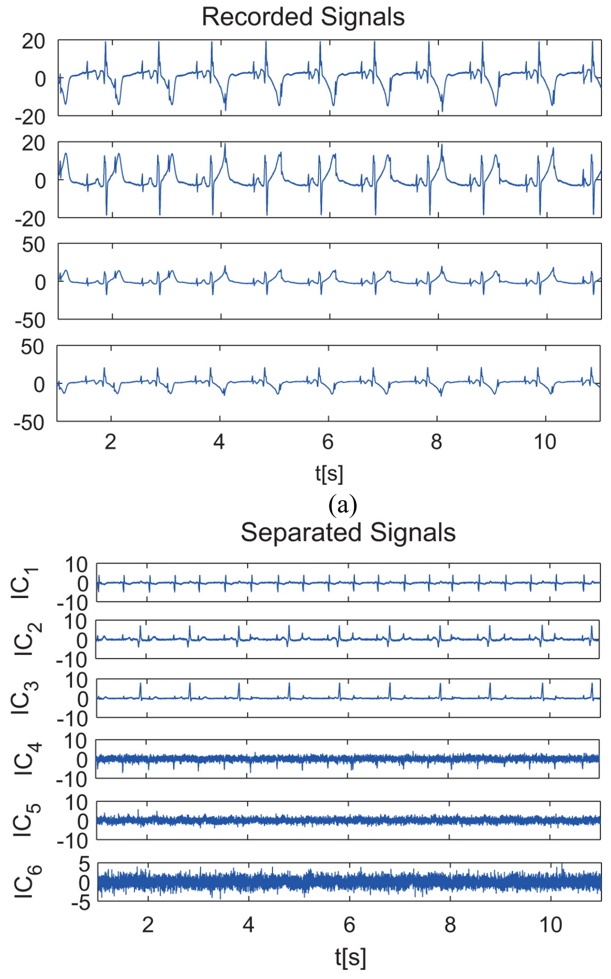


Fig.3 Coordinates of projection of heart vector whose origin is located in the center of the fetus body. ECGx and ECGy are the basis projections.

the basis projections, $\overrightarrow{E\hat{C}G_x}$ and $\overrightarrow{E\hat{C}G_y}$, whereby the fVECG is reconstructed. Here, we are confined to the two dimensional fVECG.

III. APPLICATION RESULTS

The proposed method is applied to twelve channel synthetic time series of heartbeat signal with rotation of fetus body, where each ECG event is made by projecting the model heart vector in reference to the rotation angle at the moment of heartbeat. Sampling rate is 1kHz. White Gaussian noise and 3rd order power of Gaussian noise are added in each recording channel. The heartbeat intervals of mother and fetus are given by randomly following Gaussian distribution around mean intervals of 1s and 500ms, respectively. The rotation angle is given by an integration of Brownian motion. The synthetic time series and rotation angle are shown in Figs.4(a) and 5(a). Separated ICs are shown in Fig.4(b), where the autocorrelation found only one IC contained the fECG. Figure 5(b) shows the resulting behavior of quantities calculated from the waveforms extracted by applying the fastICA on the synthetic data. Based on these calculations, the rotation angle is estimated as shown in Fig.5(a), where the estimated and real values are closely matched. Based on the estimated rotation angle, the basis projections of the heart vector and fVECG are reconstructed as shown in Fig.6. The reconstruction is satisfactory except for scaling, which suggests the validity of the method proposed here. In addition, the method is applied to the actual maternal abdominal signals (12 recording channels, sampling rate 1kHz, gestation age:34 weeks). In Figs.7(a) and (b), four abdominal signals and four ICs are shown, where only one IC contained fECG. There are abrupt jumps in the trace of $\tau_{\max} - \tau_{\min}$, which is due to discontinuity in the relationship between the temporal order of peak times and rotation angle shown in Fig.2. As shown in Fig.7(c), the estimated rotation angle shows fluctuations rather than a distinct trend of rotation. Actually these fluctuations might include those of ECG waveforms, fetal movements deviating from the coaxial rotations, and changes in the maternal physiological situations. In Fig.8, the reconstructed basis projections include P wave in addition to R wave, and the fVECG exhibits a plausible trajectory.



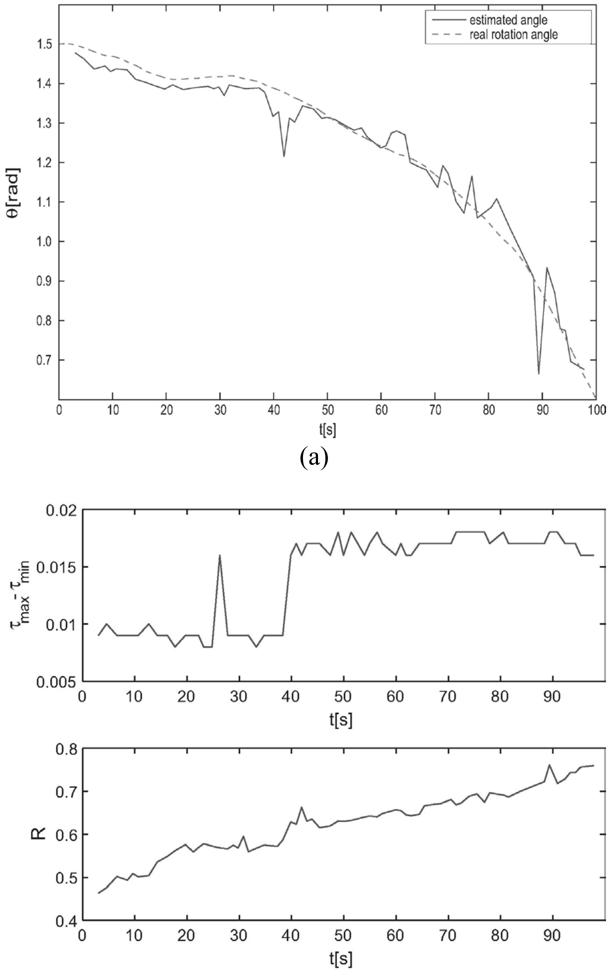
(a)

(b)

Fig.4 (a) Four out of twelve synthetic signals composed of projections of the model heart vector with body rotation and noise. (b) Six out of twelve separated signals by the fastICA . Vertical axes are arbitrary scale.

IV. CONCLUSION

Ideally, ICA extracts uncorrelated projections of the heart



(a)

(b)

Fig.5(a) Generated rotation angle (thick line) and its estimate (dotted line). (b) top: estimate of $\tau_{\max} - \tau_{\min}$, bottom: estimate of R.

vector up to the order of the spatial dimension. However, noise and nonstationarity could disturb full extraction of the basis projections of the heart vector. In this study, we proposed the method to reconstruct the fVECG with the basis projections of the heart vector synthesized by utilizing fetal movements. Applications to the synthetic and actual data suggested ability of the proposed method. In addition to further applications, more stable estimation and applicability to pathological situations will be future subjects.

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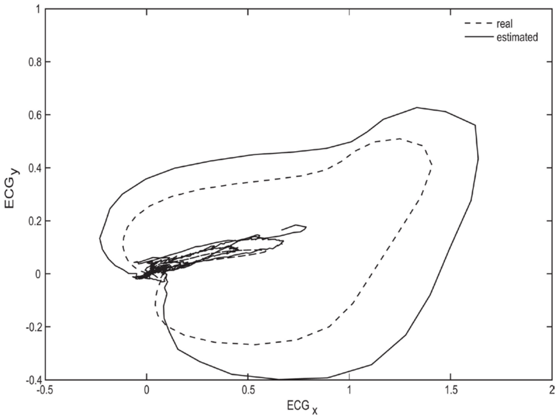
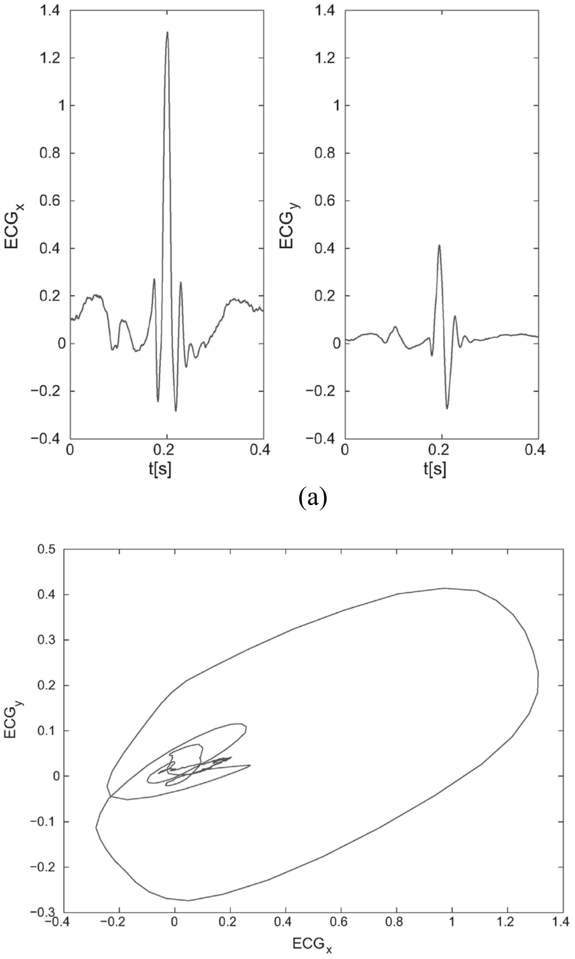


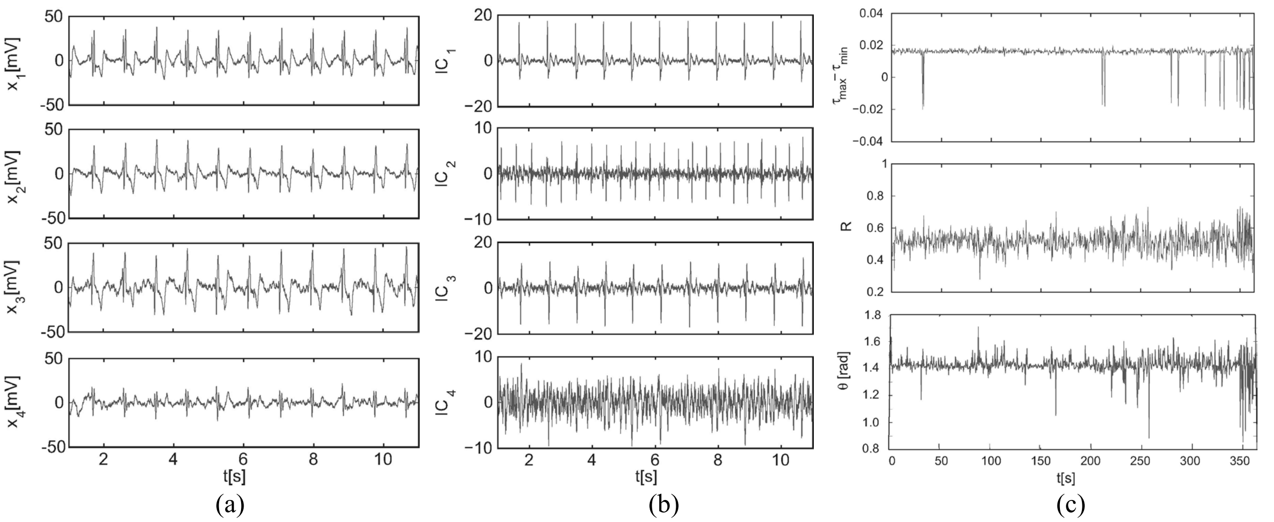
Fig.6 Original fVECG and the reconstructed fVECG.



(a)

(b)

Fig.8(a) Estimated basis projections of the heart vector, ECGx and ECGy, for the data shown in Fig.7. (b) Reconstructed fVECG.



(a) (b) (c)

Fig.7 (a) Four signals out of twelve maternal abdominal signals (gestation age:34weeks). (b) Four ICs out of twelve ICs. Vertical axes are arbitrary scale. (c) upper: estimate of $\tau_{\max}-\tau_{\min}$, mid: estimate of R, bottom: estimate of rotation angle θ.