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산모의 다채널 심전도 신호로부터 이산여현변환영역에서 특이값 분해를 이용한 태아 심전도 분리 알고리듬

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A New Algorithm for Extracting Fetal ECG from Multi-Channel ECG using Singular Value Decomposition in a Discrete Cosine Transform Domain

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요 약 : 산모의 흉부와 복부로부터 측정된 다채널 심전도에서 태아 심전도를 추출하는 새로운 알고리듬을 제안한다. 산모의 복부 심전도로부터 태아 심전도를 추출하기 위하여, 시간 영역에서 특이값 분해를 근간으로한 방법이 일반적으로 사용되었다. 그러나 이 방법은 산모와 태아의 심전도 벡터 방향이 서로 직교해야 하는 가정과 많은 연산량을 요구하는 단점이 있다. 제안한 알고리듬은 이산연현변환 영역에서 특이값 분해를 이용하여 이러한 단점을 극복한다. 적은 연산량으로 특이값 분해를 하기 위하여 이산여현변환 계수의 특성과 태아 심전도의 주파수 특성에 기초하여 고주파수 성분에 해당하는 이산여현변환 계수를 제거하였다. 또한 산모와 태아의 심전도 벡터 방향에 의한 영향을 덜 받으면서 순수한 태아 심전도를 추출하기 위하여, 산모 복부 심전도에서 산모 심전도가 억압된 새로운 세 개의 채널을 만들고 이들을 다채널 심전도에 추가하였다. 모의 신호와 실제 신호를 이용하여 기존의 시간 영역에서 특이값 분해를 근간으로한 방법과 제안한 알고리듬의 성능을 비교하였다. 제안한 알고리듬은 기존 방법보다 적은 연산량으로 순수한 태아 심전도를 얻을 수 있음을 실험적으로 확인되었다.

Abstract : We propose a new algorithm to extract the fetal electrocardiogram (FECG) from a multi-channel electrocardiogram (ECG) recorded at the chest and abdomen of a pregnant woman. To extract the FECG from the composite abdominal ECG, the classical time-domain method based on singular value decomposition (SVD) has been generally used. However, this method has some disadvantages, such as its high degree of computational complexity and the necessary assumption that vectors between the FECG and the maternal electrocardiogram (MECG) should be orthogonal. The proposed algorithm, which uses SVD in a discrete cosine transform (DCT) domain, compensates for these disadvantages. To perform SVD with lower computational complexity, DCT coefficients corresponding to high-frequency components were eliminated on the basis of the properties of the DCT coefficients and the frequency characteristics of the FECG. Moreover, to extract the pure FECG with little influence of the direction of the vectors between the FECG and MECG, three new channels were made out of the MECG suppressed in the composite abdominal ECG, and the new channels were appended to the original multi-channel ECG. The performance of the proposed algorithm and the classical time-domain method based on SVD were compared using simulated and real data. It was experimentally verified that the proposed algorithm can extract the pure FECG with reduced computational complexity.
Key words : Fetal ECG extraction, Singular value decomposition, Discrete cosine transform

INTRODUCTION

Evaluating the state of health of pregnant women and their fetuses from early pregnancy to delivery is regarded as a matter of great importance of their well-being[1].

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Evaluating the state of the heart of the fetus has great clinical significance in the evaluation of fetal health. In general, methods using ultrasound have been widely used to show the shape of the heart. However, these methods do not easily access electro-physiological information[2].

A method that overcomes this weakness and evaluates the state of health of the fetus is the fetal electrocardiogram (FECG). There are two ways to measure the FECG; one is invasive and the other is

non-invasive. The invasive method measures the FECG from the fetal scalp after electrode leads are inserted into the uterus. However, it is rarely used, except in special circumstances, because it is dangerous and difficult to perform. Therefore, the non-invasive method is usually used.

The non-invasive method also has advantages over the invasive method. One of them is the ease of measuring the FECG, because the leads are simply attached to the mother's abdomen. However, it is difficult to extract the FECG from the composite abdominal electrocardiogram (ECG), because the composite abdominal ECG is composed of the FECG and the maternal electrocardiogram (MECG), and the FECG has a much smaller amplitude than the MECG[3-6].

Several non-invasive methods have been proposed, such as auto-correlation, cross-correlation, adaptive filtering and singular value decomposition (SVD)[2,3,7,8]. SVD has some advantages, such as the need for fewer leads, ease of use in the clinical setting, real-time implementation, and good results[6]. However, this method requires a high degree of computational complexity, and has the limitation that vectors between the ECG and the FECG should be orthogonal. In practical terms, this condition is rarely met, and the results are unsatisfactory when the vectors are not orthogonal[9]. In this paper, the multi-channel ECG was composed of ECGs obtained at the chest and abdomen of a pregnant woman. To perform SVD with low computational complexity, we exploited the frequency characteristics of the FECG and the properties of discrete cosine transform (DCT) coefficients that have most of the block's energy in a few frequency elements. To extract the pure FECG with little influence from the direction of the vectors between the FECG and MECG, we performed SVD in the DCT domain after making new channels with MECG suppressed in the composite abdominal ECG, and appending them to the multi-channel ECG. We applied the proposed algorithm and the classical time-domain method based on SVD to a multi-channel ECG composed of a simulated FECG and the thoracic ECG. Each extracted FECG was compared with the simulated FECG by means of mean square error (MSE) determination. The performance of the two methods was also compared using real data.

PRELIMINARY CONSIDERATIONS

The composite abdominal ECG of a pregnant woman can be represented as a linear combination of the thoracic ECG, the FECG, and noise. In this section, to extract the FECG from the composite abdominal ECG, we review some basic properties of the SVD and the DCT.

A. Basics of the SVD

The SVD of an m×n matrix **A** is given by

$$\mathbf{A} = \mathbf{U}\,\Sigma\,\mathbf{V}^{T} \tag{1}$$

where $\mathbf{U} \in \mathbf{R}^{m\times m}$, $\mathbf{V} \in \mathbf{R}^{n\times n}$. **U** is a left singular vector matrix, and **V** is a right singular vector matrix. The m × n matrix $\Sigma = [\mathrm{diag}\{\sigma_1, \sigma_2, \ldots, \sigma_r\}: \mathbf{0}]$, $r = \min(m,n)$, and $\sigma_1 \geq \sigma_2 \geq, \ldots, \geq \sigma_r \geq 0$, $\sigma_1, \sigma_2, \ldots, \sigma_r$ are the singular values. The set of singular values is called the singular spectrum, and this set is unique for a given **A**. Equation (1) can also be written:

$$\mathbf{A} = \sum_{i=1}^{r} \sigma_i\, \mathbf{u}_i\, \mathbf{v}_i^{T} \tag{2}$$

in which $\mathbf{u}_i$ and $\mathbf{v}_i$ are the ith column vectors of **U** and **V**, respectively. If we set each ECG channel as the row vectors of **A**, the basis vectors for each ECG channel are **v**s, i.e. column vectors of **V**.

B. Basics of the DCT

The DCT of a data sequence $x(n)$, $n = 0, 1, \ldots, (M-1)$ is defined as

$$X(0) = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x(n)$$

$$X(k) = \frac{2}{N} \sum_{n=0}^{N-1} x(n) \cos\frac{(2n+1)k\pi}{2N}, \quad 1 \leq k \leq (N-1) \tag{3}$$

where $X(k)$ is the kth DCT coefficient[10].

The inverse discrete cosine transform (IDCT) is defined as

$$x(n) = \frac{1}{\sqrt{2}} X(0) + \sum_{k=1}^{N-1} X(k) \cos\frac{(2n+1)k\pi}{2N}, \quad 0 \leq n \leq (N-1) \tag{4}$$

The frequency corresponding to this is represented as k in

$$f_s \times \frac{k}{2N} \tag{5}$$

in which f_s is the sampling frequency.

From Equation (4), $X(k)$ represents the coefficient corresponding to each frequency component[10]. Because the DCT coefficients have most of the block's energy in a few frequency elements, the reconstructed signal, which is reconstructed by IDCT with a few coefficients, is very similar to the original signal.

PROPOSED ALGORITHM

A. Outline of the Procedure

The procedure for the proposed algorithm is as follows. 1) Compose the multi-channel ECG from ECGs obtained at the chest and abdomen of the pregnant woman. 2) Perform SVD on the multi-channel ECG with each row has 1000 samples in the time-domain; extract FECG. 3) Perform DCT on the extracted FECG. 4) Save the positions of the coefficients that are below the threshold value in the DCT domain. These positions are used to make new channels in the proposed algorithm. The threshold value will be dealt with in the section "Making new channels". 5) Compose the multi-channel ECG and perform DCT. 6) Eliminate the parts of the DCT coefficients corresponding to high-frequency components on the basis of the properties of the DCT coefficients and the frequency characteristics of the FECG. 7) Make new channels with the MECG suppressed in the composite abdominal ECG and append new channels to the multi-channel ECG. 8) Perform SVD on the multi-channel ECG and IDCT on the results of the SVD. 9) Perform DCT on the extracted FECG and save the locations of the coefficients that are below the threshold value. Figure 1 shows the flow chart of the procedure for the proposed algorithm.

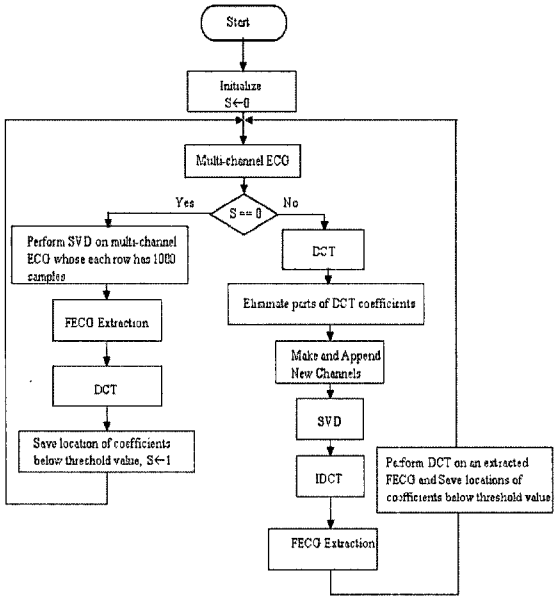


Fig. 1. Flow chart for the proposed algorithm

We next describe the procedures for selecting the DCT coefficients in the DCT domain, for making new channels, and for extracting the FECG in the multi-channel ECG using data from references 11 and 12.

B. Selecting the DCT Coefficients

To determine how much the DCT coefficients will be applied to the proposed algorithm, we take into account not only the frequency bands of the MECG and the FECG, but also the criterion of root mean square error (RMSE). We set the middle number of n_{rmse} and n_{freq} as a critical number, where n_{freq} is the number of DCT coefficients to be truncated by taking into account the frequency bands of the MECG, and n_{rmse} is the number of DCT coefficients to be truncated by taking into account the criterion of RMSE. In this paper, the "critical number" means the number of DCT coefficients that are truncated.

The frequency band of a normal person's ECG is about 0-45 Hz[13]. Generally, the frequency band of the composite abdominal ECG of a pregnant woman is different from that of a normal person's ECG, because the composite abdominal ECG is mixed with the thoracic ECG and the FECG. Figure 2 shows the frequency components of the thoracic ECG and those of the FECG obtained by SVD in the time-domain. The frequency components were obtained using a fast Fourier transform (FFT) algorithm.

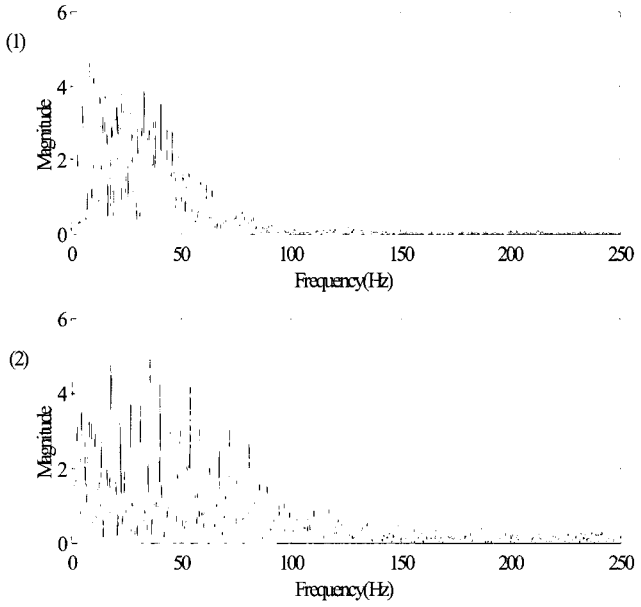


Fig. 2. Distribution of frequency of the composite abdominal ECG(1) and the FECG(2)

From Fig. 2, we can also confirm the fact that the frequency band of the composite abdominal ECG of the pregnant woman is different from that of the normal person's ECG, and that the frequency band of the FECG is wider than that of the thoracic ECG. We set 0-100 Hz as the frequency band that will be applied in the proposed algorithm. The data used to demonstrate the proposed algorithm were acquired at 500 Hz with 2500 samples. When DCT was performed on these data, we calculated from

Equation (5) that the one thousandth DCT coefficient corresponds to about 100 Hz.

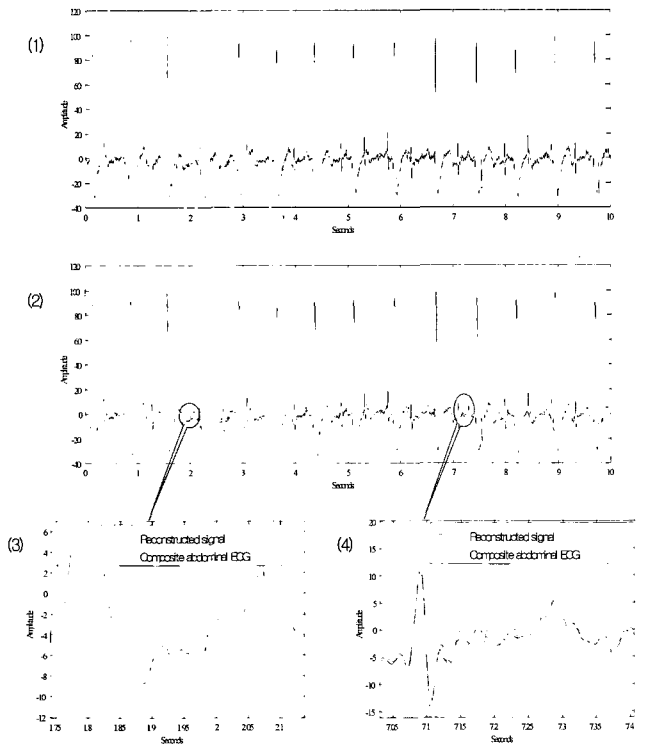


Fig. 3. (1) The composite abdominal ECG. (2) The reconstructed signal after truncating DCT coefficients. (3) Comparison of the two signals, excepting the fetal QRS complex region. (4) Comparison of the two signals in the fetal QRS complex region

The composite abdominal ECG and the signal reconstructed by IDCT with few coefficients when n_{freq} is 1500, are shown in panels (1) and (2) of Fig. 3, respectively. There is a strong similarity between them; the correlation coefficient is 0.998. From panels (3) and (4) of Fig. 3, we observe that the FECG maintains its shape in the reconstructed signal and that the amplitude of the noise is reduced.

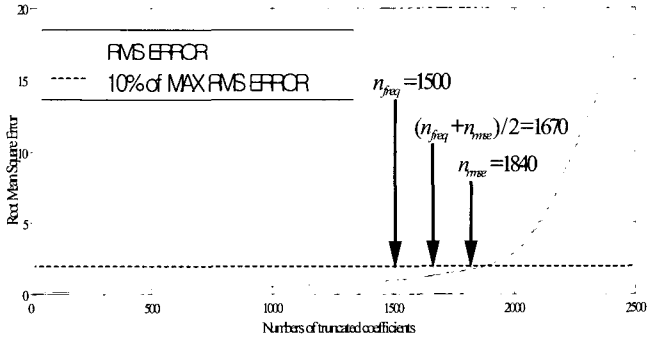


Fig. 4. Selection of the DCT coefficient using the proposed algorithm

To determine by means of RMSE how much the DCT coefficients of each channel are truncated, we show the RMSE of one channel in Fig. 4. There was small increase in the RMSE until the truncated number of DCT coefficients reached approximately 1500. When the RMSE reached 10% of the maximum RMSE, we set the truncated number to n_{rmse}. To determine n_{rmse}, we calculated the RMSE between the reconstructed ECG and the original ECG by sequentially truncating the DCT coefficients from sample 2500 with no zero padded to sample 1000 with 1500 zero padded. From this procedure, we determined n_{rmse} for each channel. If n_{rmse} was less than 1500, we set the n_{rmse} to 1500. After determining all n_{rmse} values, we chose the smallest n_{rmse} value that was greater than 1500, and set it as the n_{rmse} for each channel.

C. Making New Channels

The first step in making new channels was to perform DCT on the FECG. At the beginning of the proposed algorithm, we used the FECG obtained by the classical time-domain method based on SVD. However, in the other cases, we used the FECG obtained by SVD in the DCT domain. The second step was to store the positions of the DCT coefficients less than the inconstant threshold value. The threshold value is 1.5 times the average of the absolute values of the DCT coefficients. The last step was to reduce the amplitude of the DCT coefficients whose positions were stored in the second step, their amplitudes were reduced to 25%. Using this procedure, we obtained new channels with the MECG suppressed in the composite abdominal ECG. Figure 5 shows the DCT coefficients before and after their manipulation in the DCT domain.

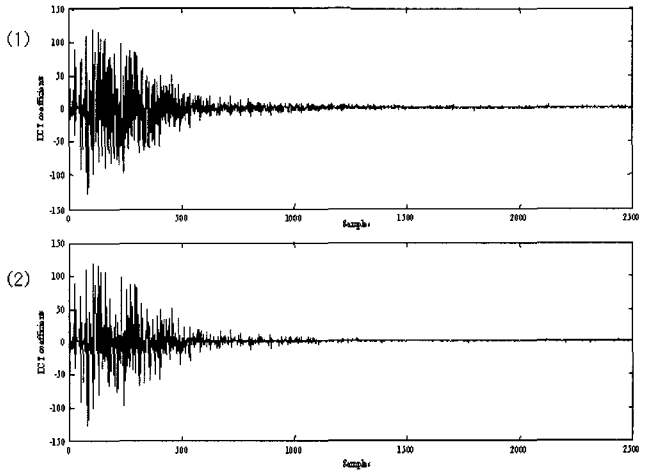


Fig. 5. Before (1) and after (2) manipulation of the DCT coefficients of the composite abdominal ECG

D. Extraction of FECG from the Muti-Channel ECG

An ith channel is composed of the DCT coefficients. It can be expressed as vector $\mathbf{m}_i$.

$$\mathbf{m}_i = (m_i(0) \quad m_i(1) \quad m_i(2) \quad \dots \quad m_i(N-1)) \tag{6}$$

where N is number of the DCT coefficients that will be used in SVD.

A set of $\mathbf{m}_i$ can be expressed by the input matrix **M**.

$$\mathbf{M} = \begin{bmatrix} \mathbf{m}_1 \\ \mathbf{m}_2 \\ \vdots \\ \mathbf{m}_p \end{bmatrix} \tag{7}$$

where p is the number of channels.

Suppose that p signals from the leads are measured and arranged in a vector m(t), called the measurement vector:

$$\mathbf{m(t)} = (m_1(t)\, m_2(t) \dots m_p(t))^T \tag{8}$$

When SVD is performed on the input matrix M, each ECG channel can be represented by the column vectors of V, and an $U\Sigma$, a set of weights, can be used in a linear combination of the ECGs from distinct lead positions. If singular values exist such as $\sigma_1 \geq \sigma_2 \geq, \dots, \geq \sigma_r \geq 0$, M can be represented in a linear combination of the $\mathbf{v}_i$ (i = 0, · ·, r) column vectors of V. Because SVD is performed in the DCT domain, the IDCT should be performed on the DCT coefficients with zero padded to obtain separated time-domain signals.

EVALUATION AND RESULTS

A. Simulated and Real Data, and Comparative Analysis

1) Simulated data. A composite abdominal ECG was made by linear combination of a simulated FECG and a real thoracic MECG. The input matrix was composed of two thoracic MECGs and three abdominal ECGs. The multi-channel ECG, namely the input matrix, was analyzed with the proposed algorithm and the classical time-domain method based on SVD. The performance of each was evaluated and compared.

We determined the search interval for evaluating the residual amount of the MECG in the extracted FECG. Because the duration of the normal QRS is from 0.06 to 0.1 seconds[14], we set ± 20 samples from the R peak position of the MECG as the search interval, corresponding to about 0.08 seconds. The R peak position was obtained from the thoracic MECG. The residual amount of MECG in the extracted FECG was evaluated by summing each MSE between the simulated FECG and the extracted FECG in the search intervals. A simulated FECG is shown in Fig. 6.

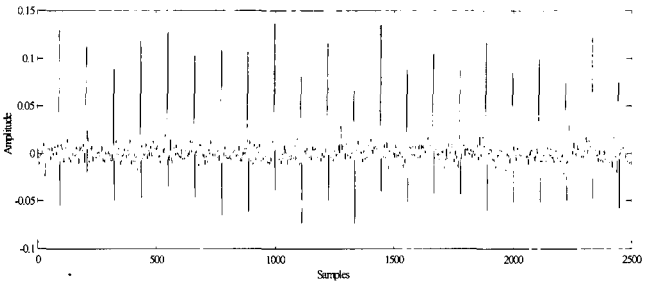


Fig. 6. A simulated FECG

The extracted FECG resulting from the classical time-domain method based on SVD and that from the proposed algorithm are shown in Fig. 7.

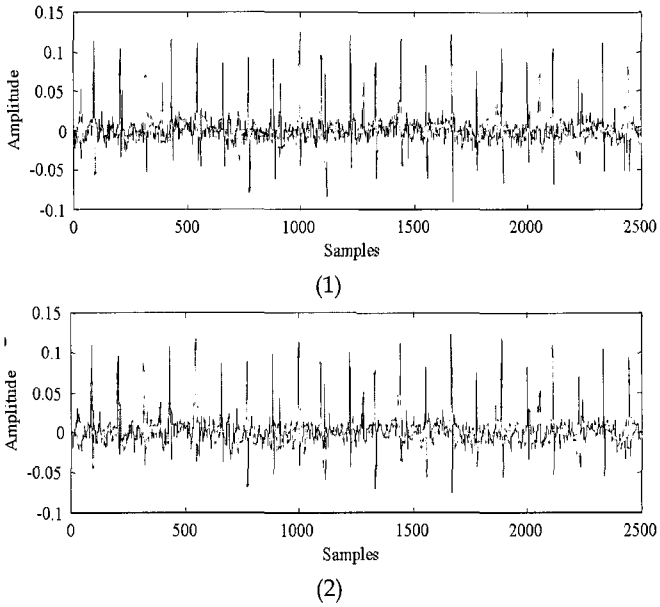


Fig. 7. The extracted FECG using the classical time-domain method based on SVD (1) and the proposed algorithm (2)

The MSE of the classical time-domain method based on SVD and that of the proposed algorithm are shown in Table 1.

Table 1. Comparison of MSEs

	Classical time-domain method based on SVD	Proposed algorithm
MSE	1.0917×10^{-4}	1.1702×10^{-4}

Although the MSE of the proposed algorithm was larger than that of the classical time-domain method based on SVD, this difference was negligible. To properly evaluate their

performance, we must evaluate the residual amount of MECG in the extracted FECG. The residual amounts of MECG in the extracted FECG are shown in Table 2.

Table 2. Comparison of the amounts of residual MECG in the extracted FECGs

	Classical time-domain method based on SVD	Proposed algorithm
Residual amount of MECG	0.0044	0.0035

The residual amount of MECG in the extracted FECG obtained by the classical time-domain method based on SVD was larger than that obtained with the proposed algorithm. We extracted a purer FECG from the composite abdominal ECG using the proposed algorithm.

2) Real data 1. We investigated the application of the proposed algorithm to data from reference 11. The data were obtained from a pregnant woman with a gestational age of 37 weeks. Three abdominal ECGs and two thoracic ECGs were used. Each ECG channel, with 2500 samples, was taken at 500 Hz for 5 seconds. The ECG data are shown in Fig. 8.

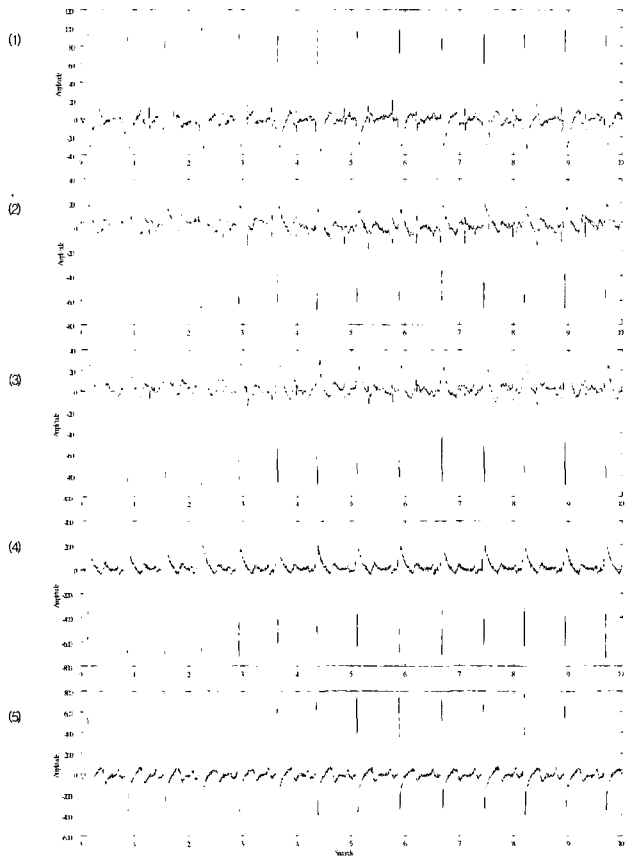


Fig. 8. ECG data for experiment. (1)-(3): composite abdominal ECGs; (4)-(5): thoracic ECGs

According to the proposed procedure, we made an input matrix composed of eight channels, and each channel had 901 samples. Each channel of the input matrix is shown in Fig. 9.

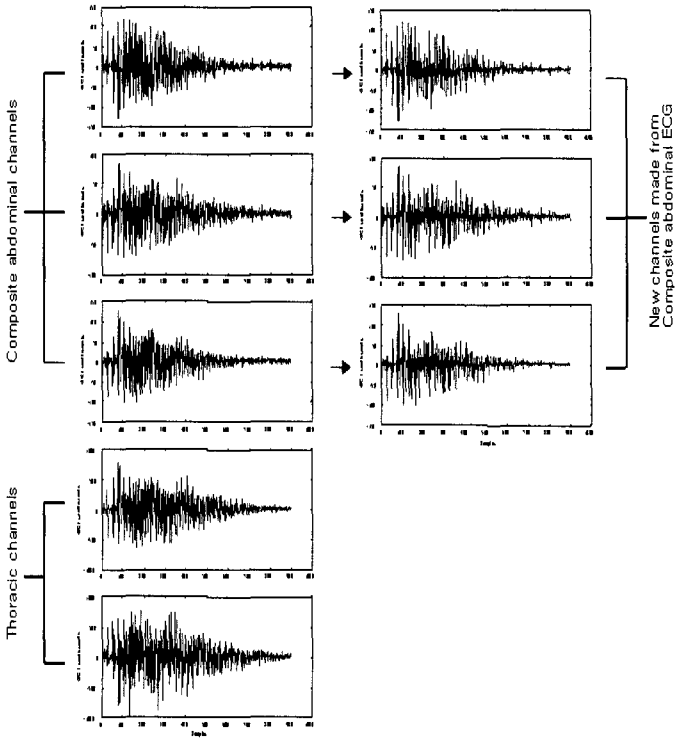
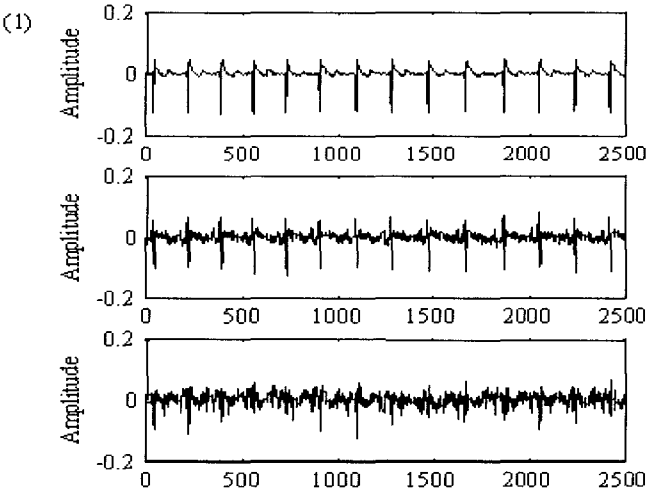


Fig. 9. The DCT coefficients for the channels and the new channels in the input matrix

The results of the classical time-domain method based on SVD and those of the proposed algorithm are shown in Fig. 10 (1) and (2),respectively, in descending order of the magnitude of the singular value.



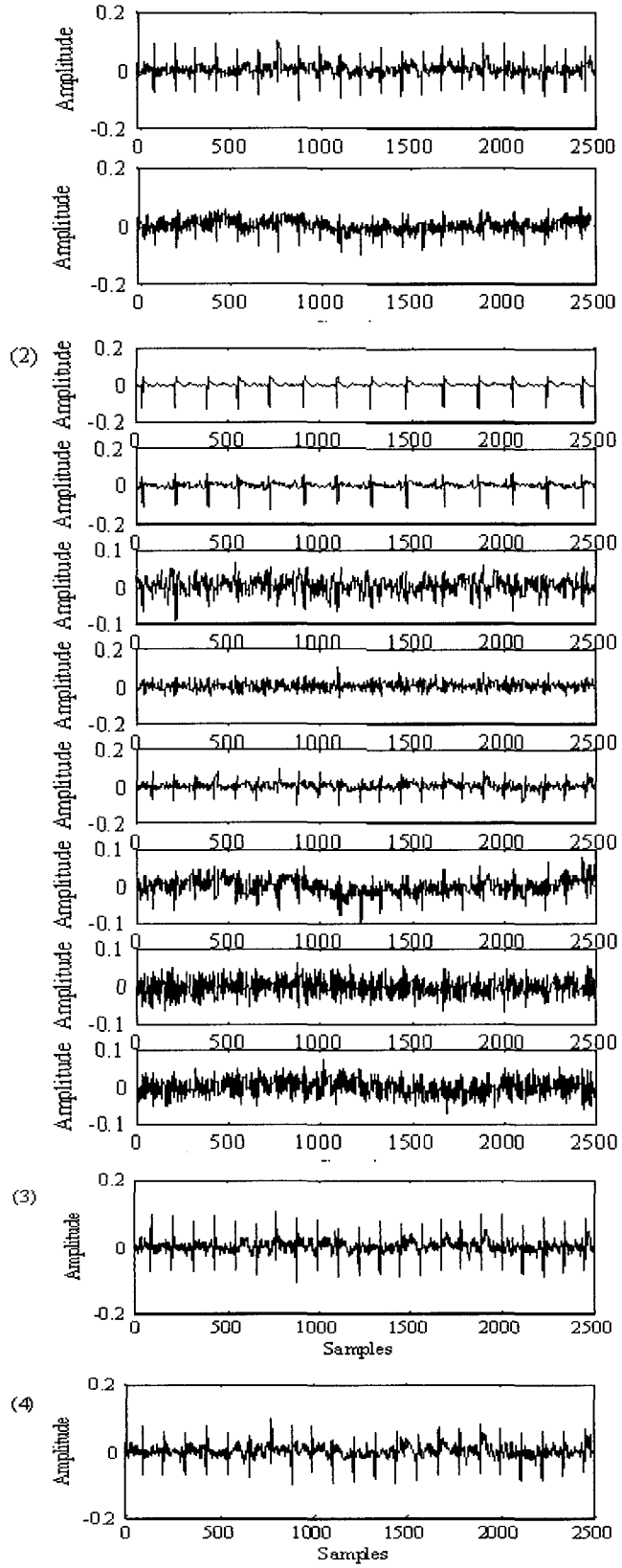


Fig. 10. Results for real data using SVD in the time-domain (1) and the proposed algorithm (2); the extracted FECG using SVD in the time-domain (3) and using the proposed algorithm (4)

The extracted MECG is shown in the first panel of Fig. 10 (1), and although the second panel of Fig. 10 (1) is an extracted MECG, it is contaminated by noise. The extracted FECG is shown in the fourth panel of Fig. 10 (1). Here, the sum of each MSE between the extracted FECG and the thoracic ECG in the search interval was defined as the residual maternal contribution mean square error (RMCMSE). The residual amount of MECG in the extracted FECG, 0.9285, was calculated by subtracting RMCMSE from 1. The results from the proposed algorithm are shown in Fig. 10 (2). Both the first and the second panel of Fig. 10 (2) are extracted MECGs. The extracted FECG is shown in the fifth panel of Fig. 10 (2). The residual amount of MECG in the extracted FECG was 0.9275. Using the proposed algorithm, the residual amount of MECG was 0.12% less than that obtained when the classical time-domain method based on SVD was used.

3) Real data 2. The proposed algorithm and the classical time-domain method based on SVD were applied to data obtained from a pregnant woman with a gestational age of 36 weeks. Three abdominal ECGs and two thoracic ECGs were used. Each ECG channel, with 2500 samples, was taken at 500 Hz for 5 seconds. The ECG data are shown in Fig. 11.

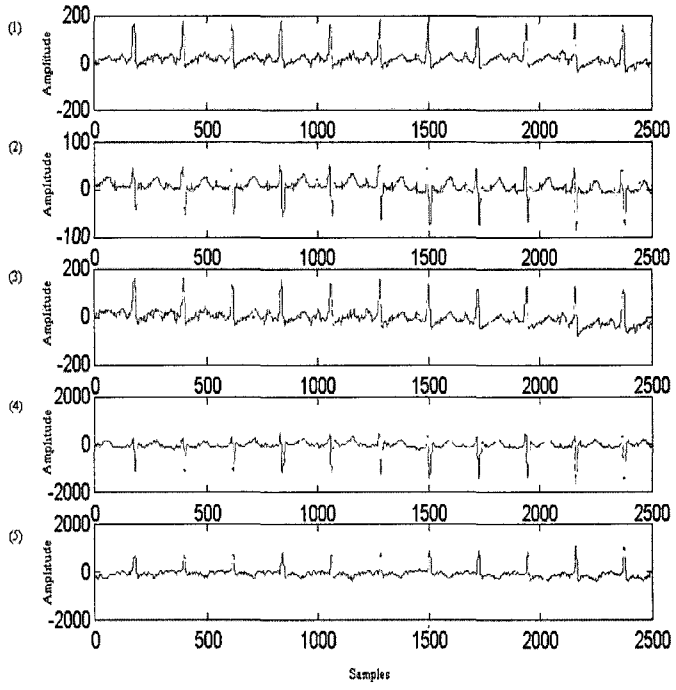
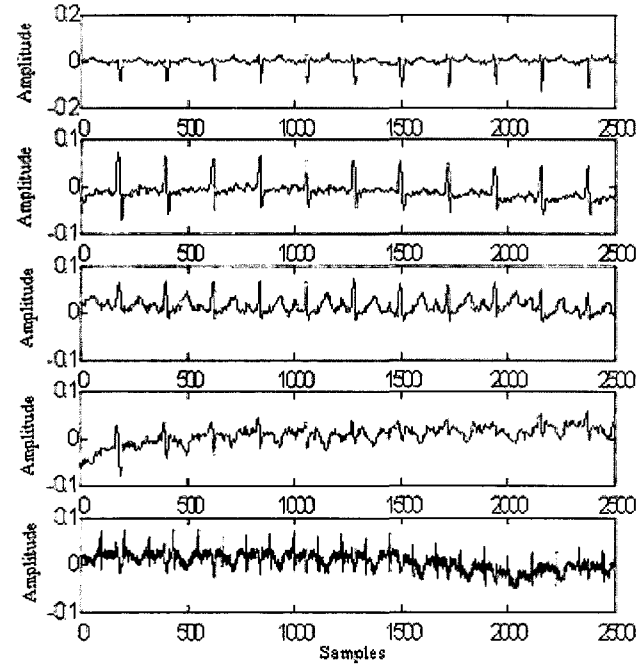
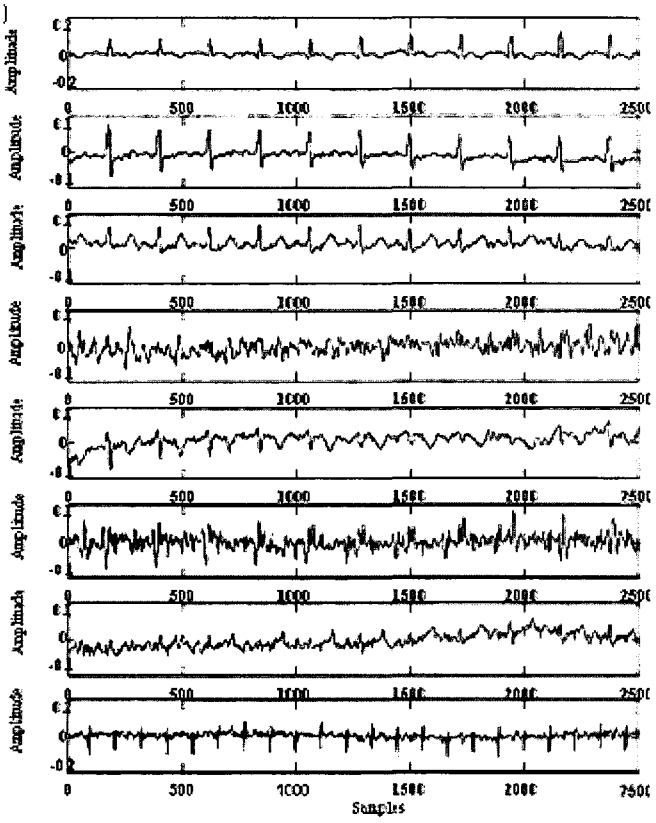


Fig. 11. ECG data for experiment. (1)-(3): composite abdominal ECGs; (4),(5): thoracic ECGs

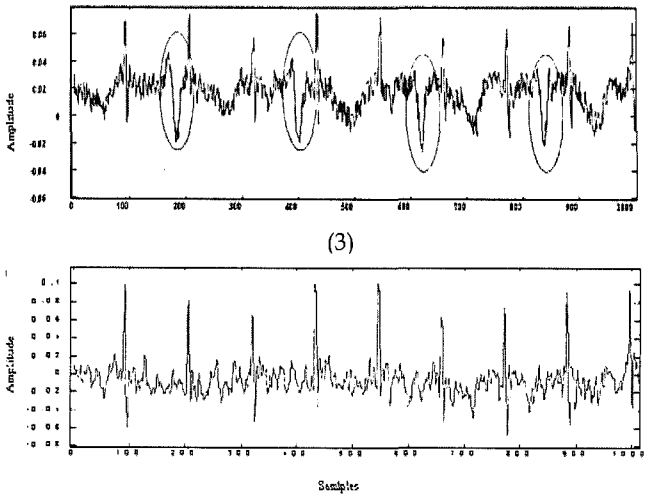
The results of the proposed and classical algorithms are shown in Fig. 12 (1) and (2), respectively, in descending order of the magnitude of the singular value. We show two extracted FECGs (about 1000 samples each) in panels (3) and (4) of Fig. 12.



(1)



(2)



(3)

(4)

Fig. 12. Results for real data using SVD in the time-domain (1), using the proposed algorithm (2); and the extracted FECG using SVD in the time-domain (3) and using the proposed algorithm (4)

The extracted FECG is shown in the fifth panel of Fig. 12 (1). We can ascertain visually that it is mixed with MECG components. The residual amount of MECG in the extracted FECG was 0.917. This result shows that the classical time-domain method based on SVD did not extract the FECG effectively. The results obtained using the proposed algorithm are shown in Fig. 12 (2). Both the first and second panels of Fig. 12 (2) are extracted MECGs. The extracted FECG is shown in the eighth panel of Fig. 12 (2). The residual amount of MECG in the extracted FECG was 0.8520. From a comparison of panels (3) and (4) of Fig. 12, we observe that there is a greater MECG contribution in panel (3). Comparing the residual amounts of MECG in the two extracted FECGs, we observe that the proposed algorithm extracted a purer FECG than did the classical time-domain method based on SVD.

B. Computational Aspects

Figure 13 shows the computational complexity of the SVD according to the increasing length of the column of the input matrix. When the length of the column was reduced to 40%, the computational complexity was reduced to 20%.

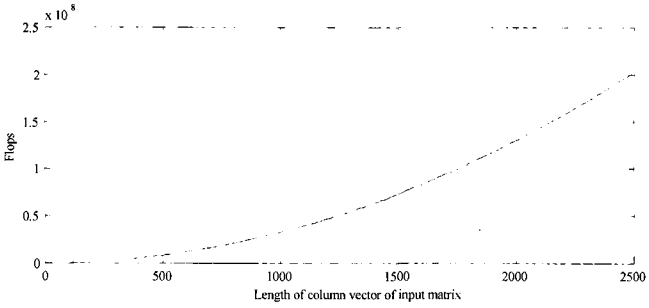


Fig. 13. The computational complexity of the SVD according to the increasing length of the column of the input matrix

The computational complexity of the classical time-domain method based on SVD and that of the proposed algorithm were compared. When the proposed algorithm was applied to the input matrix composed of channels with 2500 samples per channel, the computational complexity was reduced to 28%, including an additional computation due to DCT and IDCT. Here, the computational complexity was evaluated by means of the flop function, counting floating-point operations, in the MATLAB library[8]. The above comparison of computational complexity leads to the conclusion that the proposed algorithm can extract the pure FECG from the composite abdominal ECG with lower computational complexity than can the classical algorithm.

CONCLUSION

Sometimes the extracted FECG obtained by the classical time-domain method based on SVD is unsatisfactory, because it is apt to be influenced by the assumption that vectors between the FECG and MECG should be orthogonal[3,9]. This method also requires a high degree of computational complexity.

In this paper, we propose a new algorithm to extract a purer FECG from a multi-channel ECG, with lower computational complexity, using SVD in the DCT domain.

To perform SVD with lower computational complexity, we eliminated the parts of the DCT coefficients corresponding to high-frequency components, taking into account the properties of the DCT coefficients and the frequency characteristics of the FECG. Experimental results showed that computational complexity was reduced to 28%.

The locations of electrode leads should be chosen such that the maternal subspace and the fetal subspace are orthogonal to each other. If orthogonality is not satisfied due to the stage of pregnancy or the position of the fetus, much of the energy of the FECG is lost, so that some signals will be a mixture of the MECG and FECG[15].

To extract the pure FECG with little influence from the assumption of orthogonality, we introduced three new channels that maintained the FECG components as much as possible and suppressed the MECG in the composite abdominal signal. We then appended new channels to the multi-channel ECG. Because these procedures compensate for the weak energy of the FECG and cause the measurement vector samples to deviate slightly from the direction of the maternal vector, the proposed algorithm can extract a purer FECG and is less affected by the assumption of orthogonaity.

In the experiment with real data 1, comparing the residual amount of MECG in two extracted FECGs, we observed that the extracted FECG obtained using the proposed algorithm had 0.12% less residual MECG than that obtained by the classical time -domain method based on SVD.

In the experiment with real data 2, we observed by visual inspection that the extracted FECG obtained by the classical time-domain method based on SVD had much more residual MECG. The amount of residual MECG in the extracted FECG obtained by the classical time-domain method based on SVD was 7% greater than that obtained when using the proposed algorithm.

In this paper, we have described and experimentally verified that the proposed algorithm can extract a purer FECG with lower computational complexity and with less influence from the assumption of orthogonality. In future studies, we will examine the effects of the new channels on the results when the abdominal ECGs are replaced by the new channels, and will examine the relationship between the new channels and the number of channels. We will also apply the proposed algorithm to more real data.

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