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A Fetal ECG Signal Monitoring System Using Digital Signal Processor

(디지탈 신호처리기를 사용한 태아심전도 신호 추출 시스템)

朴榮喆,* 曺秉模,* 金南鉉,** 金源麒,** 朴相曦,*** 尹大熙*

(Young Cheul Park, Byoung Mo Cho, Nam Hyun Kim, Won Ki Kim, Sang Hui Park, and Dae Hee Youn)

要 約

본 논문에서는 TI사의 TMS32020 디지탈 신호처리기를 사용하여 다중 채널 적응 잡음제거기로 구현되는 실시간 태아 심전도 추출시스템을 구성하고 그 성능을 분석하였다. 산모의 복부에 부착된 전극으로부터 얻은 심전도 신호와 가슴에 부착된 세개의 전극에서 얻은 세 종류의 심전도 신호는 다중 채널 필터의 기대 입력과 기준 입력들로 각각 사용된다. 다중 채널 필터의 출력이 복부 심전도에 섞여 있는 산모의 심전도 성분과 같은 모양을 갖도록 LMS 알고리듬을 사용하여 필터 계수들을 조정해 나가며 복부 심전도에서 필터의 출력을 빼면 향상된 태아 심전도를 얻게되고 이 신호는 파형 표시기로 나타나게 된다. 디지탈 신호처리 알고리듬과 구성된 시스템에 사용된 파라메타들의 성능을 분석하기 위하여 off-line의 경우와 함께 on-line 실험 결과들이 제시되었다.

Abstract

This paper describes the implementation of a real time fetal ECG monitoring system in which an adaptive multi-channel noise canceller is realized using the Texas Instruments TMS32020 programmable digital signal processor. An ECG signal from the electrode placed on the mother's abdomen and three ECGs from those on the chest are applied as the desired signal and the reference inputs, respectively, of the multi-channel filter. The coefficients of the filter are updated using the LMS algorithm such that the output of the multi-channel filter copies the maternal ECG embedded in the abdominal ECG. The enhanced fetal ECG is obtained by subtracting the filter output from the abdominal ECG, and the difference signal is recorded.

Both off-line and on-line experimental results are presented to verify the effectiveness of the parameters for the digital signal processing algorithms and the prototype system.

*正會員, 延世大學校 電子工學科

(Dept. of Elec. Eng., Yonsei Univ.)

**正會員, 延世大學校 醫用工學科

(Dept. of Medical Eng., Yonsei Univ.)

***正會員, 延世大學校 電氣工學科

(Dept. of Electrical Eng., Yonsei Univ.)

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I. Introduction

Even though the clinical value of the fetal electrocardiogram (ECG) has been reported by many authors[1-3], only the fetal heart rate is widely used due to the lack of a simple, compact, and inexpensive monitoring system which can record the fetal QRS complex without artifact added in the process of eliminating the mother's

QRS complex. Problems encountered in determining the fetal ECG from electrodes placed on the abdomen of the mother are the dependency of the signals on different placements of the electrodes artifact and EMG (electromyogram) interference due to mother's movement, and most serioulsy, relatively small amplitude of the fetal ECG compared with that of the mother's.

Several deterministic methods have been developed for improving the quality of the fetal ECGs from the electrodes attached to the mother's abdomen[4-7]. These techniques detect the presence of the mother's ECG sensed by the electrode on the chest, use the information to find the mother's QRS complex embedded in the ECG from the abdominal lead and remove the mother's QRS complex from the abdominal recording. A main shortcoming of such a method is that any fetal QRS complexes obscured by the mother's are also eliminated.

As an effort to overcome the above problem, statistical approaches have been proposed[8,9]. They use an adaptive multi-channel noise canceller which estimates the mother's QRS complex embedded in the abdominal ECG as a weighted sum of chest ECG's and subtracts the estimated mother's QRS complex from the abdominal ECG to yield an enhanced fetal ECG.

Real time realization of the statistical methods needs processors which can perform digital signal processing algorithms requiring heavy computations. Also, a simple, compact, but inexpensive fetal ECG monitoring system is essential for it to be adopted as an actual clinical value. These requirements can now be met using high-speed digital signal processors[10].

The prototype fetal ECG monitoring system described in this paper realizes the adaptive multichannel noise cancellation algorithm using a Texas Instruments TMS32020 programmable digital signal processor[11]. It has been shown[9] that the method in[9] performs better than that in[8], if accurate positions of successive mother's QRS complexes can be detected. However, precise alignment of the mother's QRS complex is a difficult task and incorrect detection of the positions of the maternal QRS complexes degrades the performance of the method. Thus, the fetal ECG enhancement system presented in this paper adopts the algorithm in[8], after slight modifications are made.

For experimental purpose, the desired signal containing both maternal and fetal QRS complexes is obtained from the abdominal lead (AL in Fig. 1) and the reference signals containing only the mother's ECG complex are collected from 3 chest leads (CL-I, CL-II, and CL-III in Fig. 1). Here, suction type electrodes are used to gain baseline stability.

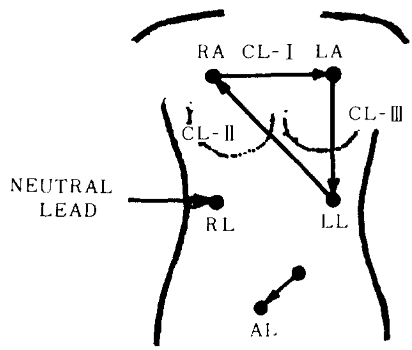

Fig.1. Positions of electrodes for ECG data collection.

The signals from 4 leads are applied to the analog signal processing unit which includes filters and amplifiers. Then the pre-processed signals are sampled at the rate of 250 Hz and with the resolution of 12 bits. The sampled signals are processed by the DSP unit which consists of (1) 4 identical bandpass filters with the lower and the upper cutoff frequencies of 3 Hz and 45 Hz, respectively; and (2) and adaptive multi-channel filter to yield an enhanced fetal ECG signal, which is displalyed/recorded on general ECG monitor/recorder. The complete system consists of analog pre/post-processor, A/D and D/A converters, DSP (Digital Signal Processing) unit, and display (or recording) unit as depicted in Fig. 2.

In the next section, digital signal processing algorithms are summarized. In Section 3, the hardwares and softwares of the DSP unit are described. After presenting experimental results in Section 4, conclusions are drawn in Section 5.

II. Digital Signal Processing Algorithms

Figure 3 shows the signal model and the schematic diagram of the DSP unit. Here, $F_i(z)$

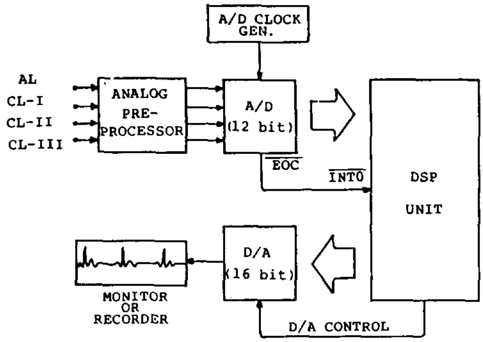

Fig.2. Block diagram of the fetal ECG monitoring system.

denotes the transfer function of the system relating the mother's ECG $\tilde{m}_a(k)$ from the abdominal lead and the mother's ECG $\tilde{m}_i(k)$ from the i-th chest lead; $\tilde{b}(k)$ is the fetal ECG from the abdominal lead; and $\tilde{n}_a(k)$ and $\tilde{n}_i(k)$, i=1,2,3, represent interferences such as EMG, 60 Hz sinusoid, and system noise embedded in the abdominal and the i-th chest sensor output signals, respectively. From Fig. 3, the signals applied to the DSP unit can be summarized as

$$\tilde{x}_a(k)=\tilde{b}(k)+\tilde{m}_a(k)+\tilde{n}(k)$$

and

$$\tilde{x}_i(k)=\tilde{m}_i(k)+\tilde{n}_i(k), \qquad i=1,2,3 \qquad (1)$$

Related to the signals in (1), it is reasonable to make the following assumptions;

1) The fetal QRS complex is not sensed by the chest electrodes.
2) The fetal ECG and the mother's ECG are uncorrelated.
3) The interferences at different electrodes may be partly correlated.

The signals in(1) are passed through the FIR bandpass filters with the same coefficients to reduce the levels of the interferences. That is

$$x_i(k)=\sum_{j=0}^{40} h(j)\,\tilde{x}_i(k-j), \qquad i=a,1,2,3 \quad (2a)$$

where

$$h(j)=h(40-j), \qquad 0\leq j\leq 19 \qquad (2b)$$

The coefficients of the bandpass filter are designed such that the lower and the upper cutoff frequencies are given by 3 Hz and 45 Hz, respectively.

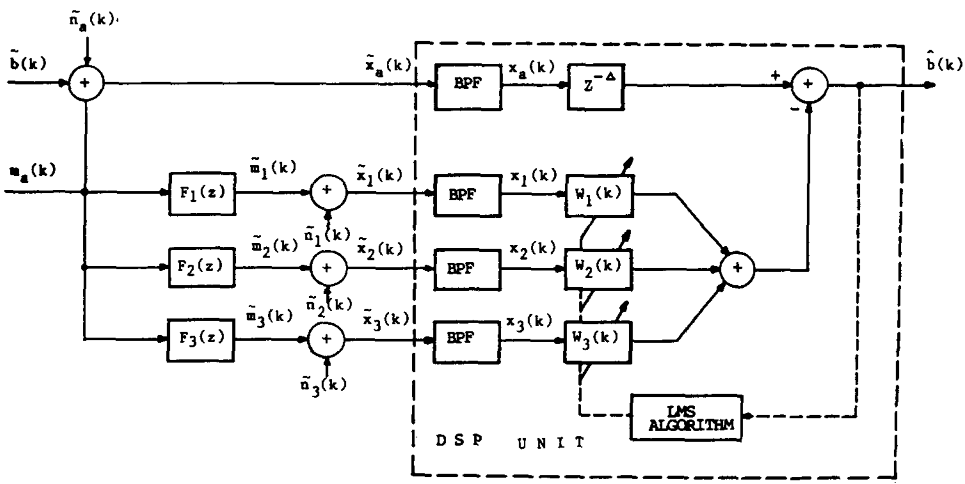

Fig.3. The signal model and the schematic diagram of the DSP unit.

Also, since the impulse response function of the bandpass filter is symmetric, no phase distortion occurs and the filtering operation in (2a) can be performed using 20 multiplications. The output signals of the bandpass filter can be expressed as

$$x_a(k) = b(k) + m_a(k) + n_a(k)$$

and

$$x_i(k) = m_i(k) + n_i(k), \qquad i=1,2,3 \qquad (3)$$

where b(k), $m_i(k)$, and $n_i(k)$ are the bandpass filtered version of $\tilde{b}(k)$, $\tilde{m}_i(k)$, and $\tilde{n}_i(k)$, respectively.

Now, the problem is to generate a replica of $m_a(k)$ as a weighted sum of $x_i(k\text{-}n)$ and subtract it from $x_a(k)$ to yield an enhanced fetal ECG $\hat{b}(k)$. That is

$$\hat{b}(k) = x_a(k-\Delta) - \sum_{i=1}^{3} W_i'(k) X_i(k) \qquad (4a)$$

where

$$W_i(k) = [w_{i0}(k)\ w_{i1}(k) \cdots w_{iN-1}(k)]', \; i=1,2,3 \qquad (4b)$$

and

$$X_i(k) = [x_i(k)\ x_i(k-1) \cdots x_i(k-N+1)]', \quad i=1,2,3 \qquad (4c)$$

are the weight vectors and the reference input vectors, respectively, for the i-th chest ECG and the prime denotes matrix transpose. Since the fetal ECG b(k) is uncorrelated with the maternal ECG's while $m_a(k)$ and $m_i(k)$, i=1,2,3 are correlated, the enhanced fetal QRS complex can be obtained by minimizing the mean squared value of $\hat{b}(k)$ if the relevant signals are stationary[8]. However, to account for nonstationarity of the signals, the weight vectors should be updated in a recursive way. A simple but efficient algorithm is the LMS algorithm[8] which can be summarized as

$$W_i(k+1) = W_i(k) + \frac{\alpha}{\sigma_i^2(k)} \hat{b}(k) X_i(k), \quad i=1,2,3 \qquad (5a)$$

where

$$\sigma_i^2(k) = \beta\, \sigma_i^2(k-1) + (1-\beta) x_i^2(k), \quad 0<\beta<1 \; (5b)$$

In (5a) and (5b), $\sigma_i^2(k)$ is the variance estimate of $x_i(k)$ and β is the smoothing parameter controlling the convergence speed of the algorithm and the mean squared value of $\hat{b}(k)$. In (5a), the loop gain α is normalized by $\sigma_i^2(k)$ to improve the convergence speed of the adaptive algorithm[12].

III. Implementation Using A Digital Signal Processor

Hardware

The hardware configuration of the DSP unit and the A/D and D/A converters is shown in Fig. 4. The pre-processed 4-channel analog signals are multiplexed and sampled sequentially at the rate of 250 Hz per channel (i.e., 1 KHz sampling rate for the A/D converter). After a data conversion is completed, the $\overline{\text{EOC}}$ (End of Conversion) signal is sent to the $\overline{\text{INT}}$ 0 pin of the TMS32020 and the programs defined by the interrupt service routine are executed. Our choice of the TMS 32020 operating at 20 MHz as the CPU requires that the program and data memories have a maximum access time of 70 ns or faster. Memories with slower access times would require memory wait states to be inserted, drastically reducing the speed of the processor. The DSP unit uses 4K words of static RAM, 2K words of which are mounted on battery back-up socket. Also, as depicted in Fig. 5, the prototype system was designed to be interfaced to the MC68000

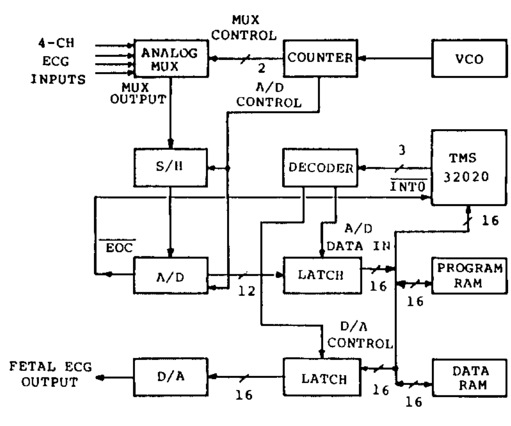

Fig.4. Hardware configuration of the DSP unit and the A/D and D/A.

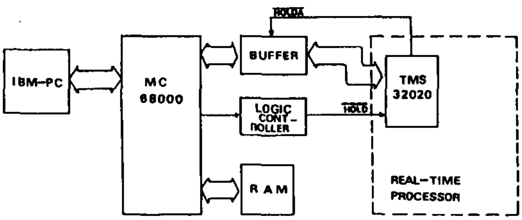

Fig.5. Prototype system interfaced with MC 68000 and IBM-PC.

ECB (Educational Computer Board)[13] connected to the IBM-PC through the RS-232C and interfaced with the DSP unit. Using the MC68000 ECB, the programs generated by the IBM-PC can be downloaded and the datas stored in the data RAM can be checked by the IBM-PC. Such a configuration made it easy to modify programs and to check the performances of the DSP algorithms in the real time environment.

Software

The flowchart in Fig. 6 summarizes the software realizing the DSP algorithms. The FIR bandpass filter coefficients are stored in the on-chip memory block B0 and past input sample values and intermediate data are stored in the on-chip memory block B1. With the TMS32020 instruction cycle of 200 nsec and the signal sampling rate of 250 Hz, there are 20,000 instruction cycles per sample period. Using the simulator on the IBM-PC, it was checked that only 51.3% of the total processing capacity of the TMS32020 was used and the code for fetal ECG monitoring occupies about 1.2K words program memroy.

IV. Experimental Results

Off-Line Experiments

Parameters required to realize the digital signal processing algorithms were chosen after processing a variety of clinic ECG signals in off-line environments. The results are

$$\alpha = 1-\beta, \qquad \beta = 1-2^{-8}$$
$$\Delta = (N-1)/2, \qquad N = 41$$

In the process of deciding parameters, the shapes of the resulting enhanced fetal ECG's were carefully examined even though the mean squared value of $\hat{b}(k)$ was used as a reference.

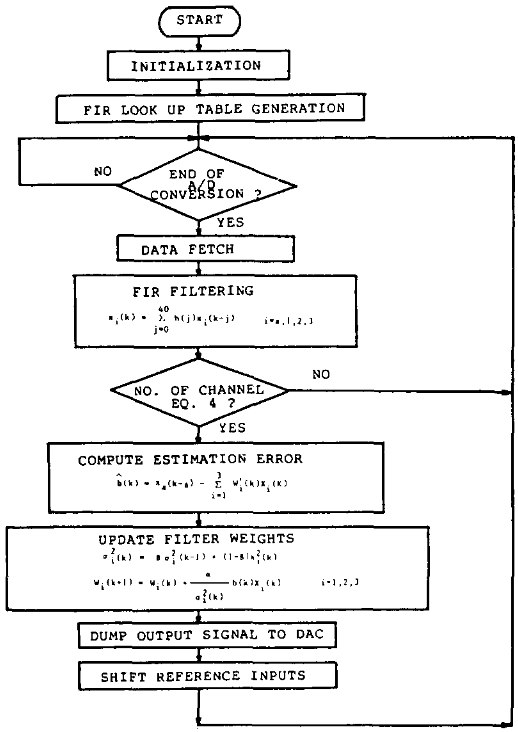

Fig.6. Flowchart of the software realizing the DSP algorithms.

The results in Fig. 7 demonstrate that the abdominal ECG should be properly delayed before applying it as the desired signal and those in Fig. 8 indicate that increasing the number of coefficients may result in reduced amplitude of the fetal QRS complex. Also, comparisons of the enhanced fetal ECG's for different values of β are presented in Fig. 9. As the final off-line experimental results, Fig. 10 displalys the enhanced fetal ECG's when different number of chest ECG's were used as the reference input signals of the adaptive multi-channel noise canceller. Other results indicate that, if the shape of the maternal PQRST complexes in both the abdominal and the 3 chest ECG's are similiar, increasing the number of reference input signals does not make much performance improvement. However, the results in Fig. 10 well justify the use of multiple reference signals, particularly when the polarities of the part of the maternal PQRST complexes are reversed.

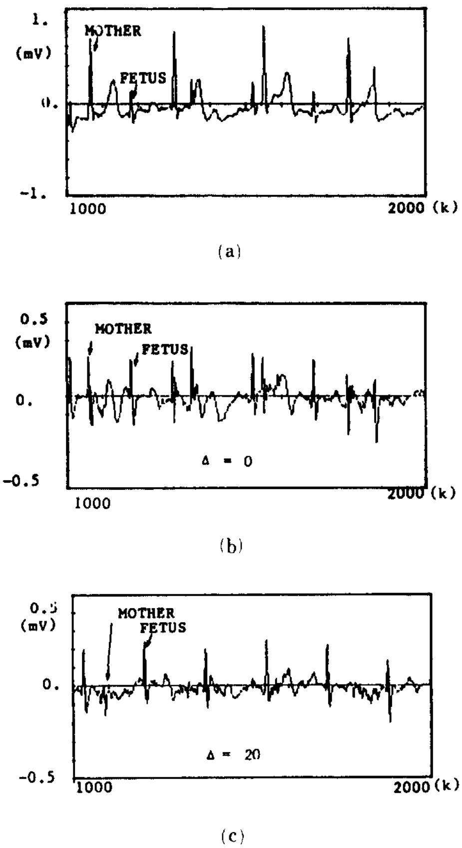

Fig.7. (a) Abdominal ECG and enhanced fetal ECG's for.
(b) △= 0 and (c) △= 20.

For the effectiveness of the off-line experimental results for on-line processing, the digital signal processing algorithms were performed using fixed point arithmetic operations. The results so obtained were almost identical to the results obtained using floating point operations as demonstrated in Fig. 11.

On-Line Experiments

The ECG's recorded on an FM recorder were applied to the prototype system and the relevant signals were recorded using paper ECG recorders. The results in Fig. 12 demonstrate the effectiveness of the real time fetal ECG monitoring system described in this paper.

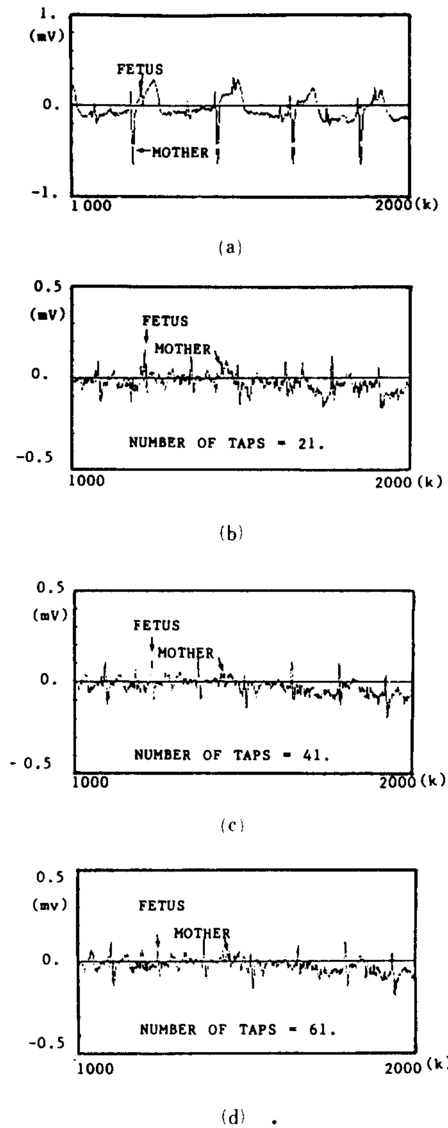

Fig.8. (a) Abdominal ECG and enhanced fetal ECG's for
(b) N = 21,
(c) N=41 and
(d) N =61.

V. Conclsuions

The implementation of a real time fetal ECG monitoring system is presented. The digital signal processing algorithms are performed using the Texas Instruments TMS32020 programmable digital signal processor. Parameters to realize the

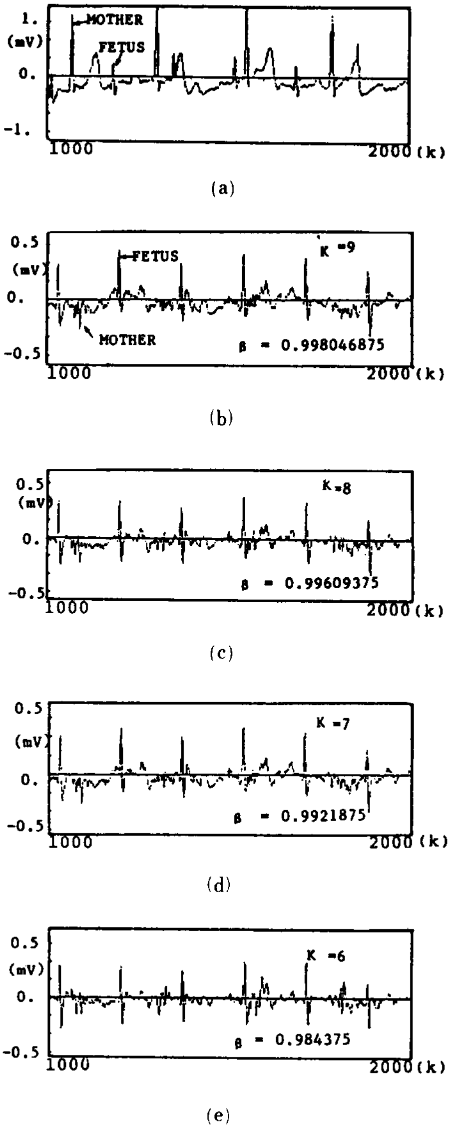

Fig.9. (a) Abdominal ECG and enhanced fetal ECG's for (b) $\beta = 1 - 2^{-9}$, (c) $\beta = 1-2^{-8}$, (d) $\beta=1-2^{-7}$, and (e) $\beta=1-2^{-6}$.

adaptive multi-channel noise canceller were decided by processing a variety of clinic ECG signals in off-line environments. Since only 51.3% of the computing power of the TMS32020 is used, other important features such as fetal heart rate counting and fetal QRS complex averaging to obtain a better shape of the fetal ECG are possible.

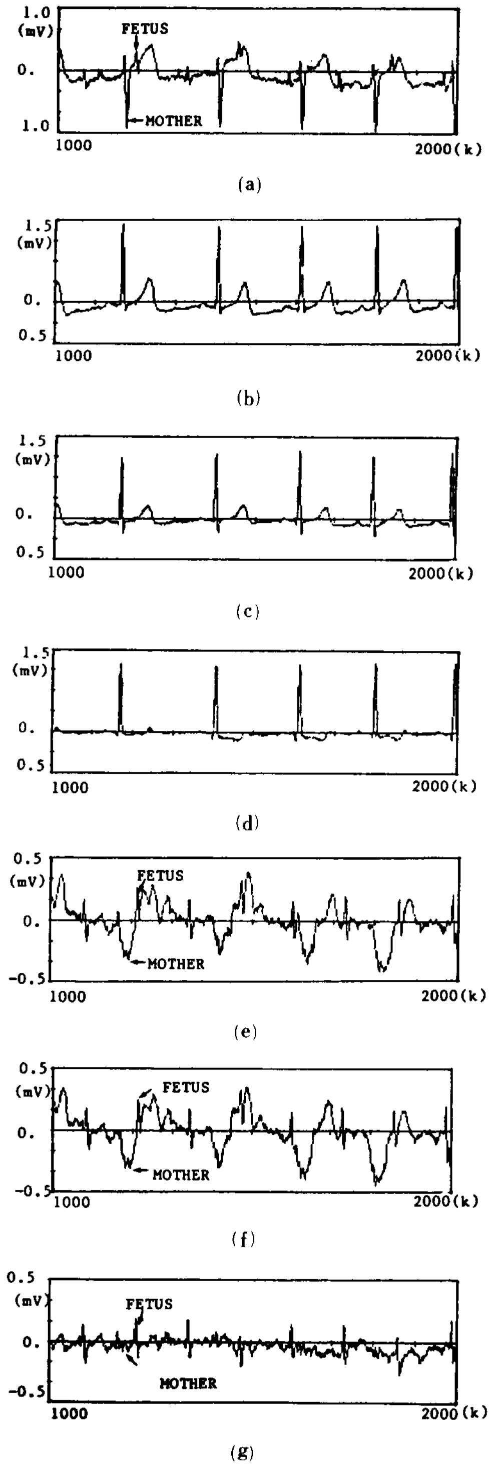

Fig.10. (a) abdominal ECG, chest ECGs from (b) CL-I, (c) CL-II, (d) CL-III and (e), (f), (g) enhanced ECG's using different numbers of reference signals.

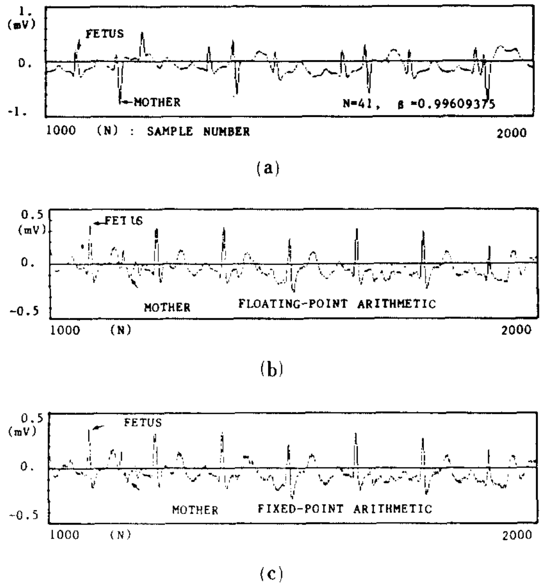

Fig.11. Enhanced fetal ECG using fixed point arithmetic operations.
(a) Abdominal ECG,
(b) result of floating point operations.
(c) Result of fixed point operations.

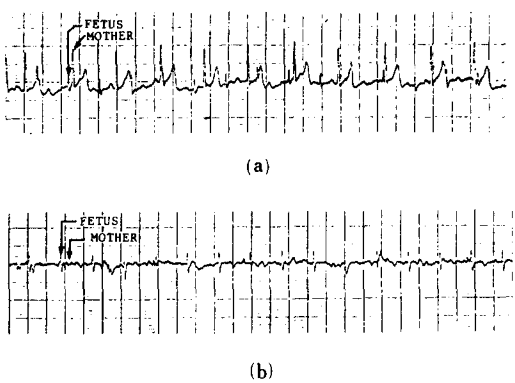

Fig.12. Results of real-time fetal ECG enhancement.
(a) abdominal ECG and
(b) enhanced fetal ECG.

Also, the digital signal processing system described in this paper can be applied to other bio-signal processing problems.

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著 者 紹 介

朴 榮 喆(正會員) 1964年 2月 28日生. 1986年 2月 연세대학교 전자공학과 졸업. 1988年 2月 연세대학교 대학원 전자공학과 공학석사학위 취득. 1988年 2月－현재 연세대학교 대학원 전자공학과 박사과정 재학중. 주관심분야는 어레이 신호처리, 적응 신호처리 등임.

曺 秉 模(正會員) 1958年 3月 14日生. 1982年 2月 인하대학교 전자공학과 졸업. 1984 8月 연세대학교 대학원 전자공학과 공학석사학위 취득. 1985年 8月－현재 연세대학교 대학원 전자공학과 박사과정 재학중. 주 관심분야는 음성 신호처리, 적응 신호처리 등임.

尹 大 熙 (正會員) 第26卷 第3號 參照. 현재 연세대학교 공과대학 전자공학과 조교수

金 南 鉉 (正會員) 第26卷 第6號 參照. 현재 연세대학교 의과대학 의용공학과 전임강사.

金 源 麒 (正會員) 第25卷 第11號 參照. 현재 연세대학교 의과대학 의용공학과 조교수.

朴 相 曦 (正會員) 第25卷 第11號 參照. 현재 연세대학교 공과대학 전기공학과 교수.