ABSTRACT

This paper presents a review of fetal electrocardiograms (FECG) detection and enhancement methodologies developed since 1960. The methods discussed include the subtraction, correlation, orthogonal basis, adaptive filtering and linear combination techniques.

The subtraction method is the oldest and most straightforward approach. It involves the direct subtraction of a near-thoracic maternal ECG (MECG) from an abdominally-measured composite of maternal and fetal heart signals.

The correlation method is used for detection rather than enhancement. Today, other methods exist which make this technique obsolete.

The most current methods for FECG detection and enhancement are the orthogonal basis, adaptive filtering and linear combination methods. These techniques were developed with the idea of producing a scheme which would allow greater flexibility in electrode positioning. An overview will be given of the adaptive filter technique and the different orthogonal basis methods. Finally, a method using a linear combination of electrodes to enhance FECG signals will be discussed.

INTRODUCTION

During the development and delivery of a fetus, it is often desirable and necessary to monitor the unborn child's electrocardiogram (ECG) via a non-invasive technique. The physician can observe and use the information contained in the ECG to verify that the development and delivery processes are satisfactory. A non-invasive technique is desired to eliminate the potential of damaging the fetus. Historical ECG data can also be used to determine if any abnormalities of the fetus are due to natural causes or human error.

By using non-invasive methods such as shown in Figure 1, it is relatively difficult to reliably observe the fetal ECG (FECG) before and possibly after detection or enhancement. The difficulty arises in analyzing the abdominal ECG signal which consists of both the maternal ECG (MECG) and the FECG. This composite signal may also contain a relatively large amount of noise, and may be further distorted by muscle and breathing contractions. This may be especially strong during the delivery process with all the associated contractions and trauma. This is further complicated by the positioning of electrodes, which is nontrivial.

Fig. 1. The electrode placement for a non-invasive FECG enhancement method[1].

Finally, a relatively weak FECG causes difficulties. The signal strength of the MECG can be from 10 to 1000 times that of the FECG. While this in itself may not be a problem if the
noise level is low, it is definitely an issue if the maternal and fetal ECG QRS's are coincident to each other. This causes the MECG to completely overlap the FECG so that only the MECG signal is observable.

To overcome the above problems, physicians and engineers have collaborated to devise methods of detecting and enhancing FECG signals. This paper reviews five methodologies that are used in FECG detection and/or enhancement. These techniques are known as the subtraction, correlation, orthogonal basis, adaptive filtering and linear combination methods.

MATHEMATICAL MODEL

The abdominal and thoracic signals can be represented by

$$A_i(t) = R_i(t)[M_i(t) + F_i(t) + N_i(t)]$$ (1)

and

$$T_i(t) = R_i(t)[M_i(t) + N_i(t)]$$ (2)

respectively, with the $i$th lead at time $t$. $T_i(t)$ is an ECG signal that is made up of just the MECG and noise. A reasonably pure MECG ($T_i(t)$) can be readily obtained by placing an ECG lead near the mother's heart. $M_i(t)$ is the MECG. $F_i(t)$ is the FECG and $N_i(t)$ is the noise. $R_i(t)$ is the effect of muscle and breathing contractions.

Figure 2 shows a signal that is just made up of $M_i(t)$ and $N_i(t)$ (top figure). Figure 2 also shows a signal that is made up of $M_i(t), F_i(t), N_i(t)$, and $R_i(t)$ (bottom figure).

CORRELATION TECHNIQUE

The correlation technique was developed for detecting the presence of a fetal heart signal in an abdominal signal corrupted by heavy noise as seen in Figure 3[2]. However, correlation technique is not generally effective in detection of a FECG since the FECG signal is not necessarily periodic[4]. Additionally, ultrasound is an easier and more reliable technique for providing information about the fetal heart activity and rate. However, correlation and ultrasound do not provide information about the electrophysiological activity of the fetal heart. To obtain electrophysiological information, FECG enhancement methods have been developed such as the orthogonal basis, adaptive filtering and linear combination methods.

Fig. 3. A abdominal signal with heavy noise. The correlation method can detect a FECG in this kind of a signal[2].

Fig. 2. The upper recording shows an ideal abdominal signal which consists of $M_i(t)$ and $F_i(t)$. The lower recording shows an actual abdominal recording made up of $M_i(t), F_i(t), N_i(t)$ and $R_i(t)$[2].
ORTHOGONAL BASIS METHODS

Overview

A recent method for FECG detection and enhancement are the orthogonal basis techniques. Authors have stated that the subtraction and correlation techniques are not reliable[3-5]. Further, they note that these techniques do not lend themselves to difficult clinical settings[3]. The advantages claimed by the orthogonal basis method include the need for few electrodes, ease of use in clinical settings, real-time implementation and, most importantly, good results.

All the techniques classified under the orthogonal basis method have one element in common. This element is the orthogonalization of three electrode abdominal signals by the Gram-Schmidt procedure. After the signals have been orthogonalized, several different methods have been devised to produce a clear FECG signal from the orthogonalized signals. The following discusses some of the methods that have been developed.

Description of Techniques

One orthogonal basis technique for FECG detection consists of taking three separate thoracic signals and constructing a fourth ECG signal that only contains the MECG part of the original signal[5]. This is done via a linear combination of the three orthogonalized signals (3).

\[ M(t) = Y_1V_1(t) + Y_2V_2(t) + Y_3V_3(t) \]  

The newly constructed maternal signal is then subtracted from an abdominal signal, which contains both the fetal and maternal signals. The resulting signal contains only the FECG (4).

\[ F(t) = A(t) - M(t) \]  

Another approach in producing a clear FECG relaxes the strict orthogonal requirement. It avoids the delays and storage requirements of the preceding technique. In fact, this technique can be implemented in real-time. It is referred to as the near-orthogonal basis technique. Some accuracy is lost in performing the near-orthogonal basis technique, but the error introduced is small.

One aspect that this technique does not take into consideration is the signal-to-noise ratio. Adaptive filtering and linear combination methods, which are described in the next two sections, take this into account.

ADAPTIVE FILTER TECHNIQUE

Another method for FECG enhancement is adaptive filtering[6-7]. This method uses adaptive noise cancellation to produce a clear FECG signal from four thoracic signals and one abdominal signal. The results using this technique, as seen in Figure 4, are promising.

Fig. 4. The top recording is an abdominal signal. The bottom recording is a FECG enhancement after the adaptive filter technique has been applied[7].

LINEAR COMBINATION METHOD

The linear combination method has been developed by Bergveld, Meijer, Kolling and Peuscher[1-3]. Their method is done in real-time and improves the signal-to-noise ratio.

This method is based on the fact that any abdominal signal may be represented by equation (1). When a given number of abdominal signals are then combined through optimizing bounded coefficients, a good FECG can be obtained with an increased signal-to-noise ratio.

The following presents the method in more mathematical detail. The abdominal signal can be written as

\[ A(t) = Y_1V_1(t) + Y_2V_2(t) + Y_3V_3(t) \]  

where the \( Y_i \) are optimized to produce a clear FECG and

\[ V_i(t) = M_i(t) + F_i(t) + N_i(t). \]
For now, the modulation function is ignored and the abdominal signal can be written as

\[ A(t) = \sum_i Y_i M_i(t) + \sum_i Y_i F_i(t) + \sum_i Y_i N_i(t). \] (7)

The goal is to optimize the \( Y_i \) coefficients to produce an FECG from the chosen number of original signals. Meaning,

\[ \sum_i Y_i M_i(t) = 0 \] (8)

and

\[ \sum_i Y_i F_i(t) \neq 0. \] (9)

The optimization is performed by developing boundary conditions and applying them to a method developed by Hildreth and d'Esopo[8]. The first condition is the exclusion of the zero solution (all \( Y_i \) are zero). The second condition helps increase the signal-to-noise ratio by excluding

\[ \sum_i Y_i = 0. \] (10)

Experiments have shown that the multiplication factor \( R_i(t) \) does not influence MECG elimination in the linear combination method. This indicates that the factors \( R_i(t) \) are strongly correlated in the abdominal leads. With the factors \( R_i(t) \) completely correlated \( R_i(t) = R(t) \) and

\[ A(t) = R(t) [\sum_i Y_i F_i(t) + \sum_i Y_i N_i(t)]. \] (11)

The number of electrodes must be kept small to eliminate patience discomfort. Usually, four electrodes is adequate to enhance an FECG signal. The abdominal lead consists of a potential difference between a cross section at the height of the umbilicus and a reference electrode above the symphysis pubis. The FECG's in the abdominal leads are positively correlated giving an increase in the signal-to-noise ratio if all the coefficients are positive. Bergveld and Meijer give more details of the electrode position in a simulation article[9]. Figure 5 shows some results using the linear combination method.

CONCLUSION

The subtraction and correlation techniques are generally ineffective in producing usable information about the fetal heart during pregnancy and birth. The orthogonal basis techniques have been somewhat successful in producing a clear FECG, but leave an unfavorable signal-to-noise ratio in the final enhancement. By comparison, adaptive filtering and linear combination methods generally produce a clear fetal signal and also improve the signal-to-noise ratio.

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REFERENCES


