MULTICHANNEL FETAL ECG EXTRACTION AND ENHANCEMENT USING TRIGGERED ADAPTIVE FILTERING AUGMENTED WITH WEIGHTED TRANSITIONS

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ABSTRACT

In this paper, we extend the adaptive noise cancellation (ANC) and adaptive system identification (ASI) methods for noninvasive fetal electrocardiogram (FECG) extraction and enhancement, respectively, by including an adaptation trigger augmented with weighted transitions. These techniques are applied to remove unwanted interferences from a multichannel noninvasive abdominal measurement, with the dominating interference being the maternal ECG (MECG). Evaluation of this method was performed on data which used an externally applied electrical stimulus pulse (SP) to simulate the FECG. A current pulse was applied to a subject's lower back and acquired from multiple channels on the abdomen. Our results indicate that the use of triggering with linearly weighted transitions outperforms triggering with on/off transitions and no triggering, with an improvement in the estimated SNR of 12.5 % and 36.2 %, respectively.

I. INTRODUCTION

Analysis of the ECG is a simple and noninvasive method of effectively assessing a patient's general health and diagnosing cardiovascular diseases. The ECG can also be used to clinically evaluate the health of prenatal infants [1,2]. Variations in the FECG waveform morphology can provide important diagnostic information that is not available in current fetal monitoring techniques, such as ultrasound and phonocardiography [3]. Such evaluations offer the opportunity to combat prenatal health conditions sooner, and offer prenatal awareness of potential physical abnormalities and complications.

Invasive methods to acquire the antepartum FECG have associated health risks, such as infection and stress to the fetus, as well as the difficulty of accessing the fetus during this period. Given the sensitivity and inaccessibility of the *in utero* environment, invasive methods are restrictively performed only during cephalic presentation during labor when there is access to the fetal scalp, which is an accurate measurement location. Prior to childbirth, FECG monitoring is only feasible using noninvasive methods; however, a noninvasive abdominal recording using surface electrodes reveals a composite signal containing an additive mixture of the FECG with unwanted interference. The dominating interference is the MECG, which is much stronger than the FECG. Other interfering signals include power-line coupling, muscular and respiratory interference, thermal noise, and noise due to the electrode-skin interface.

Adaptive filtering is capable of extracting the FECG by attempting to model and subtract the MECG component of the abdominal signal; however, during training of the adaptive filter, adaptation that is meant to attenuate the MECG also partially attenuates the FECG component that occurs simultaneously. This is the basis for the inclusion of triggering in the adaptive scheme [4]. The proposed approach uses an estimate of the temporal location of the FECG, such as through its correlation to fetal heart sounds or ultrasound data, as an adapt-disable trigger for triggered ANC (TANC), halting adaptation during a fetal heartbeat; and conversely, as an adapt-enable trigger for triggered ASI (TASI). In this paper, we extend the triggered adaptive scheme, introducing a novel form of triggering where the adaptation learning rate is weighted during trigger transitions so as to mitigate the transient response of the system to switching between adapt-disable and adapt-enable states.

II. TRIGGERED ADAPTIVE FILTERING WITH WEIGHTED TRANSITIONS

In [4], it has been shown that the use of FECG adapt-disable triggering in a TANC scheme improves the accuracy of the extracted FECG. The concept of triggering in this method is analogous to an on/off switch. For example, using FECG adapt-disable triggering, the adaptive filter adapts only during periods in between FECG pulses. Adaptation is completely disabled during the FECG pulse by setting the learning rate to zero. With adapt-disable triggering, the adaptive filter may 'experience' a transient discontinuity during adaptation. The proposed solution is a novel form of triggering termed *weighted triggering*. Weighted triggering smoothes the transition between adapt-enable and adapt-disable states. Adapt-disable is associated with a weight of zero and adapt-enable is associated with a weight of one. The transition contains intermediary values to control the learning rate associated with that period. To prevent the transient effect associated with completely disabling adaptation, a small number can be used (instead of zero) during adapt-disable periods.

The use of weighted triggering in the adaptive algorithm requires the inclusion of an extra term to the weight-update calculation. Thus, we extend the RLS algorithm. According to [5], the change in filter-weights is normally given by

$$\Delta\hat{\vec{w}}(n) = \vec{k}(n) \times \xi^*(n)\,, \quad (1)$$

where $\Delta\hat{\vec{w}}$ represents the change in weight, $\vec{k}$ is the gain vector and ξ^* is the complex conjugate of the cost function. An additional term, $w_t \in [0,1]$, which represents the trigger weight, is then included in this formulae; that is,

$$\Delta\hat{\vec{w}}(n) = \vec{k}(n) \times \xi^*(n) \times w_t(n)\,, \quad (2)$$

so that the change in weight is dependent on the period of adaptation.

For this paper, we use *linear transition weighted triggering*. This is implemented with a linearly spaced vector from the minimum to the maximum trigger weight, as illustrated in Fig. 1 for TANC. A maximum slope, which was found to be empirically optimal, is applied starting at the on trigger to the midpoint of the adapt-enable window and decreasing with the same slope ending at the off trigger.

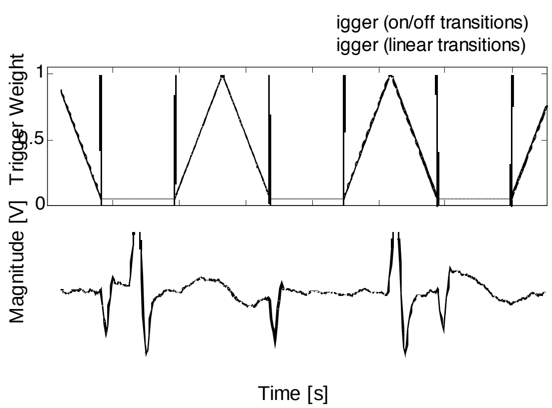

Figure 1: Triggering modes used for TANC

A. Stage 1: Fetal ECG Extraction using TANC

TANC extends the classic ANC scheme through an adaptation trigger input. This is useful for pulsating signals. Figure 2 shows the TANC scheme for single channel inputs. The primary input, $p(n)$, is the thoracic MECG and the reference input, $r(n)$, is the abdominal composite signal. The output of the TANC scheme is $e(n)$, which is the extracted signal.

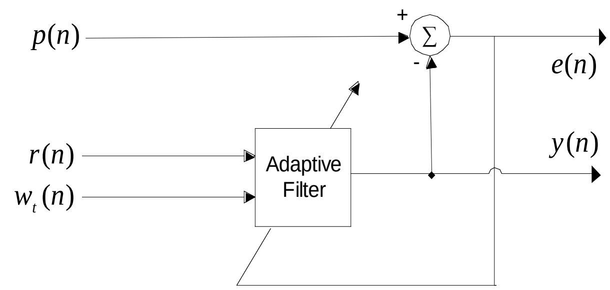

Figure 2: Single-channel triggered adaptive filtering (used for both TANC and TASI)

Stage 1, shown in Fig. 3, uses multiple independent TANC blocks. These blocks receive a common thoracic MECG; however, each block receives a different abdominal signal. The outputs are N estimates of the desired pulse, where N is the number of abdominal channels acquired. These outputs form the inputs to stage 2.

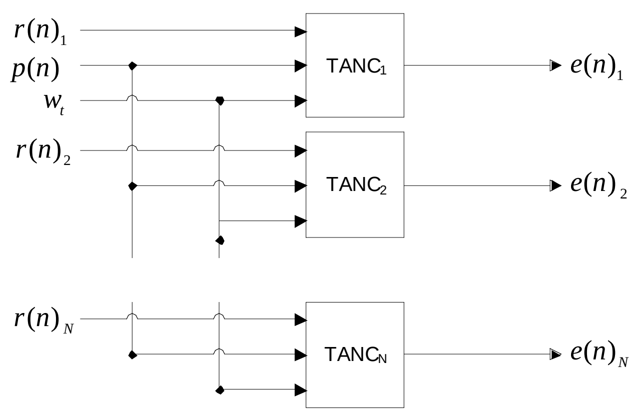

Figure 3: Multichannel TANC

B. Stage 2: Fetal ECG Enhancement using TASI

A primary concern in selecting a method for FECG extraction is to be able to process input signals that have low SNR. To account for this, multiple abdominal channels can be acquired. Assuming that noise between channels is independent, the pulse estimate can be enhanced using TASI. Figure 2 shows the scheme used for single-channel TASI. The primary input is the best estimate of the pulse given by stage 1. This selection is made by choosing the estimate with the highest estimated SNR. The reference input is one of the other N-1 estimates. The output of the TASI scheme is $y(n)$, which is an enhanced model of the reference input.

Stage 2 employs N-1 independent TASI blocks. The best pulse estimate is presented to each TASI block as a common primary input. The other estimates from stage 1 are presented as separate reference inputs. The outputs of this stage are N-1 enhanced pulse estimates with reduced noise. Since it is now the desired pulse which is to be modeled by the adaptive filter (as opposed to the modeling of the subject's ECG in stage 1), triggering is performed by disabling adaptation in between the pulses and enabling adaptation during the pulse. After stage 2, the N-1 enhanced estimates and the best estimate from stage 1 are ensemble averaged to give a single output.

III. DATA COLLECTION

The data used to test the two-stage multichannel FECG extraction and enhancement system were collected from a non-pregnant subject, using an external electrical SP to simulate the FECG. This study has been reviewed and received ethics clearance through the Carleton University Research Ethics Committee in accordance to the Tri-Council Policy Statement for Ethical Conduct for Research Involving Humans.

A current pulse was applied to the back of the subject and acquired from multiple channels on the front, as illustrated in Fig. 4. The pulse is allowed to propagate through the abdomen, experiencing tissue filter effects and additively mixing with the subject's ECG and other interference sources; similar to processes experienced by an FECG before it is noninvasively acquired. The stimulus was a rectangular pulse delivered using a stimulator (Grass S48, Astro-Med) with a constant-voltage isolation unit (Grass SIU5, Astro-Med), an amplitude of 20 V (0.1 – 1.5 mA) at a rate of 2 pulses per second (*i.e.*, 120 bpm, which is in the range of a typical fetal heart rate), and duration of 20 ms per pulse. The duration of the pulse was chosen specifically so that the duration of acquired pulse was similar to that of an FECG. The pulse was delivered using an Ag-AgCl electrode pair (Red-Dot 2237, 3M), off-axis from the spine.

Five minutes of data from five recording sites were collected from the subject's front using Ag-AgCl surface electrodes (Red-Dot 2237, 3M) placed in a circular configuration. This consisted of four channels of abdominal composite data and one channel of thoracic MECG data. The external stimulus signal was also collected to provide temporal locations of the applied SP. Data were differentially amplified using a high gain AC amplifier (Model 15A54, Grass Telefactor), with a gain of 1000 and bandwidth of 1-100 Hz. Signals were sampled at 250 Hz using a 12-bit A-D converter board (PCI-6071E, National Instruments). Power-line interference was removed adaptively offline. Figure 5 displays a segment of the acquired data from each channel. It is interesting to note that channel 1 most prominently shows the SP, while the SP is not visible in channel 3. We suspect the reason for this can be deduced from the electrode configuration as seen in Fig. 4. Channel 1 is aligned with the SP delivery electrodes, and thus provides a maximum voltage between the positive and negative electrode sites. Channel 3, being perpendicular to the SP delivery electrodes, acquires a smaller voltage. Due to the virtually nonexistent SP within channel 3, these data will not be useful and is excluded from the data set.

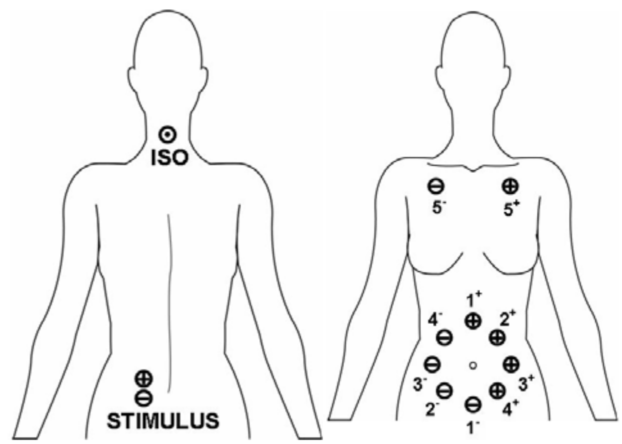

Figure 4: Stimulus delivery and data acquisition electrode placements

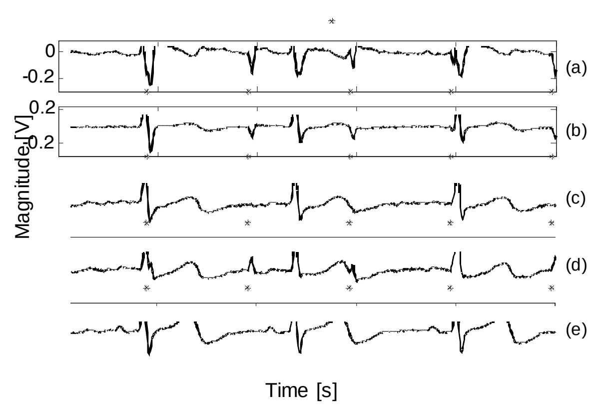

Figure 5: Acquired data: (a)-(d) Abdominal channels 1-4, respectively. (e) Thoracic channel 5

IV. PERFORMANCE MEASURE

For this study, there is no ideal pulse with which to compare the system's estimated output. Thus, reference-based performance measures cannot be applied. Instead, we define a secondary performance measure. The SNR estimate, SNR_{est}, is defined as the ratio of the estimated SP power to the estimated noise power in the data. The noise power is considered only during periods where the SP does not occur. This is not a completely accurate measure of the SNR since remnants of the subject's ECG and random noise overlap with the SP; however, it provides a reasonable measure of the attenuation of the interferences and enables a comparison of the relative performance of different algorithms.

V. RESULTS AND DISCUSSION

Initially, stage 1 simulations were run using TANC, with no triggering, on/off transition triggering, and linear transition triggering (with a minimum trigger weight of 0.05). The adaptive filter employed the RLS adaptive algorithm with adaptive memory in an FIR filter. The results after stage 1 are displayed in Table 1. The use of triggering has performed equally or better than no triggering, and in the latter case only by a small percentage. This indicates similar performance with and without triggering in terms of the attenuation of the subject's ECG.

The SP estimate from channel 2 was used as the best estimate for the primary input to stage 2. The results after stage 2, displayed in Table 1, indicate a clear improvement with the use of triggering, and even more so when the TASI scheme is augmented with linearly weighted transitions. Linear transition weighted triggering provided a final SNR_{est} of 9.83. This is a 12.5 % improvement compared to results using on/off triggering, and a 36.2 % improvement compared to the results given with no triggering.

Table 1: SNR_{est} of SP estimates

Stage	**SNR_{est}**		
	No Triggering	**Triggering (on/off transitions)**	**Triggering (linear transitions)**
1	3.24	3.29	3.24
2	7.22	8.74	9.83

Figure 6 displays a segment of the extracted SP after stages 1 and 2. Multichannel TASI significantly attenuates the noise power in the extracted signal. The remnants of the subject's ECG, which are apparent at 0.3 s and 1.1 s after stage 1, have been reduced as a consequence. Although the subject's ECG *is* correlated between channels, it contains a somewhat 'random' interchannel relationship due to the different tissue-filter effects that transform the ECG as it propagates through the subject to be measured at different locations. Comparing the signal in between the pulses, it can be seen that after TASI, these regions are nearly flat. This is a desired result since the applied SP does not contain any activity here.

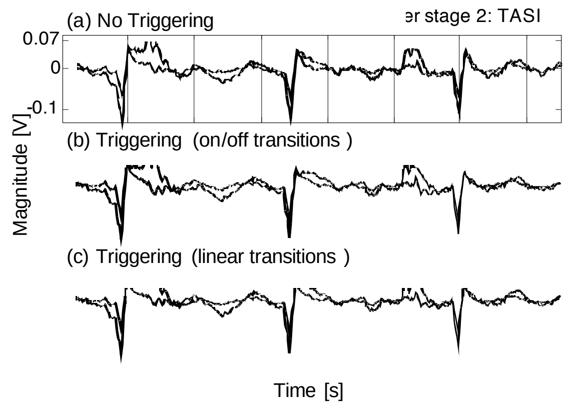

Figure 6: Estimated SP

VI. CONCLUSIONS

In this paper, we have proposed a triggered adaptive two-stage multichannel signal extraction and enhancement scheme augmented with weighted transitions. We have implemented this system in a linear FIR filter using the RLS adaptation algorithm. In stage 1, TANC was performed to extract the desired SP. Results of these simulations show similar SNR_{est} values across the various triggering modes (no triggering, triggering with on/off transitions and with linear transitions). In stage 2, we enhance the estimate by exploiting the multiple channels using a TASI scheme. The results indicate better performance using triggering with linear transitions, which has improved the SNR_{est} by 12.5 % compared to results using triggering with on/off transitions, and by 36.2 % compared to results using no triggering. It is important to note that these encouraging results are not based on an optimal trigger weighting function and there may indeed exist a better technique than linear weighting.

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