35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

The effect of applying orthogonal projection technique in short window segments to obtain fetal magnetocardiogram

Bhargavi Sriram, James D. Wilson, Rathinaswamy B. Govindan, Curtis L. Lowery, Hubert Preissl *Member, IEEE* and Hari Eswaran* *Member, IEEE*

***Abstract*— Non-invasive recordings of fetal heart and brain have been possible for almost a decade with the advancement in biomagnetic sensors using the SQUID (Superconducting Quantum Interference Device) technology. Techniques such as orthogonal projection and ICA have been applied to attenuate interference from other biological sources such as maternal heart. Successful application of such techniques among other factors depend on the non-stationary characteristics of the signals. To minimize the effect of non-stationarity due to maternal and/or fetal movement in long duration datasets, we proposed to investigate the minimal time window that is needed to obtain averaging with good SNR to apply the orthogonal projection technique to attenuate maternal magnetocardiogram (MCG) and obtain fetal MCG. The quantifying measure is based on spectral power of signals from 151-channel SQUID array system.**

I. Introduction

Fetal magnetocardiogram (fMCG) is a diagnostic tool capable of providing clinicians with non-invasive detection and analysis of fetal heart measurements comparable to that of electrocardiography. Parameters such as cardiac time intervals, heart rate variability can supply essential information about fetal well-being especially in high risk cases. To collect fMCG data, we used an instrument called SARA, an acronym for SQUID Array for Reproductive Assessment that has been devised and installed at the Department of Obstetrics and Gynecology, University of Arkansas for Medical Sciences. SARA is a 151 channel array system that captures maternal cardiac signal, fetal cardiac signal, fetal brain signal and other biological signals pertinent to fetal development. The sensors are distributed evenly on a concave surface. They cover an area greater than 850cm^2 spanning the maternal abdomen longitudinally from the symphysis pubis to the uterine fundus and a similar distance laterally (Figure 1). SARA is completely non-invasive and provides a higher signal to noise ratio than fetal electrocardiogram (fECG). Compared to SARA, single channel SQUID systems, ultrasound and other fetal monitoring systems require repositioning of the sensors to capture fetal signals during fetal movements.

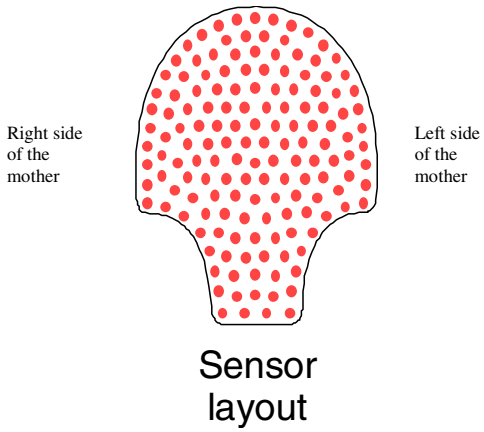

Fig.1 Shows 151 channel arrangement in SARA space. The dots represent channels. The shape matches a pregnant abdomen. The maternal MCG is usually present in the top channel and the fetal MCG are present in the mid to lower channels.

The fMCG is measured in the presence of environmental noise and other biological signal interference like maternal magnetocardiogram (mMCG). After removing the environmental noise [4], the largest interference is mMCG. A variety of techniques can be applied for separating fMCG from mMCG and each has their own advantages and disadvantages. Orthogonal projection (OP) is one of the methods that have been used for close to a decade to separate fetal MCG signals from maternal MCG [3]. The projections are carried out in the temporal domain. The unwanted interference is projected out of the measurement by constructing the orthogonal projection operator from signal space vectors corresponding to the interfering components, in this case mMCG. These vectors are determined by template matching, averaging, and orthogonal construction. Even though OP has been used extensively, the resulting fMCG can contain maternal residue as a consequence of non-stationarity in long duration data sets. Non-stationarities can be caused by maternal and fetal movements. Hence if the data can be limited to shorter time segments, some stationarity can be achieved to get better fetal signals. Hence the aim of this paper is to determine the minimum time window required by OP for averaging and removal of the interfering mMCG without distorting the fetal signals. This will also improve the fMCG quality when there is non-stationarity.

This work was supported by grants from National Institutes of Health (NIH) R01EB007826-01A1 and 1R01NS368277-08A1. *Asterisk indicates corresponding author*

B. Sriram and J. D. Wilson are with the Graduate Institute of Technology, University of Arkansas, Little Rock, AR 72204 USA (e-mail: bxsriram@ualr.edu and jdwilson@ualr.edu).

*H. Eswaran, H. Preissl and C. L. Lowery are with the Department of Obstetrics and Gynecology, University of Arkansas for Medical Sciences, Little Rock, AR 72205 USA.

R. B. Govindan is with Division of Fetal and Transitional Medicine, Children's National Medical Center, 111 Michigan Avenue, N.W., Washington, DC 20010, USA

H. Preissl is also with the MEG-Center, University of Tuebingen, D-72076 Tuebingen, Germany.

II. Methodology

A. Data Collection

Twenty datasets of fetuses ranging in gestational age from 30 to 37 weeks were collected using a 151 SQUID array system. Data was sampled at 312.5Hz. Each recording lasted for 15 minutes. OP was applied on the entire data for the removal of mMCG. These data sets were selected because in all of them the fMCG signals were clean and without mMCG residual. This was confirmed visually by experts for our lab. Hence considering the spectral estimate of these data as standard for comparison, we devised a method to determine the minimum time window length to apply OP.

The following steps provide the method used in the OP process to project out mMCG. The data were band-pass filtered using 4th order Butterworth filter with zero phase distortion having a pass band of 1-60 Hz. The maternal R waves were automatically identified using the adaptive Hilbert transform approach [1-2]. To build the averaged mMCG needed for the OP algorithm, the mean RR interval was calculated and 40% of data before R and 60% after R was selected to so as to include maternal P and T waves. This procedure was carried out on all the channels. The resulting averaged cardiac cycle is used to determine the signal space vectors corresponding to mMCG. The largest amplitude time point in the averaged mMCG defines a signal space vector that is projected out using Gramm–Schmidt orthogonalization. The procedure is then repeated on the residual, and the next signal space vector is selected and projected out, and so on. The vector selection procedure is stopped when the residual drops below a specified threshold, a multiple of the rms noise estimate. Details of the algorithm are found in [3]. Typically yields about 10 mMCG vectors are used. If these vectors are denoted by v_1, v_2, v_3,….,v_n, where n is the number of vectors and using these a matrix, V, is constructed. The dimensions of this matrix are [m by n], where m is the number of channels.

$$V = (v_1, v_2, v_3,\ldots,v_n)$$

The projector operator is given as

$$P = I - (V\,(V^T V)^{-1} V^T)$$

where I is an identity matrix.

Then the vectors are projected out of data by multiplying the operator P with the data.

To get a minimal time window to apply orthogonal projection without distorting the resulting fMCG signal, we followed the steps below. For this purpose we chose time window length from 1 to 5 minutes.

1. Using OP, in the entire data, the mMCG was projected out to get fMCG. Let that variable be $dfMCG_e$
2. Again using OP, in the time segmented raw data, the mMCG was projected out and hence retaining fMCG. Let these variables be $dfMCG_1$ to $dfMCG_5$.
3. The spectral estimation was constructed on the fMCG signal from step 1. *fft* function of MATLAB was used to get it.
4. Then spectral powers of each channel, up to 55Hz were added. Let that variable be SP_e. Alternately, the power can be computed in the time domain over the same spectral range.
5. Step 3 & 4 were repeated on time segmented fMCG data. Let the summed spectral power variables of each time segment be SP_1, SP_2, SP_3, SP_4 and SP_5.
6. Finally spectral difference (SD) was calculated as added power spectral from step 5 of each time windowed data subtracted from added power spectral from step 4.

$$SD_n = SP_e - SP_n$$

where *n* represents the length of the time window.

7. If the SD for all the channels was close to zero, then we considered that data from that time length has a clean fMCG result from OP.

III. Results and Discussion

To assess the performance of orthogonal projection in the shorter windowed data sets, spectral difference was calculated. Figure 2 shows a single data set that represents the SD result. Figure 3 shows 10-second segments of the same data set. Figure 4 shows the contour plot of spectral estimates of each channel in SARA space. Figure 2(a) is the spectral difference obtained subtracting SD_1 from SD_e. From around channel 88 onwards the SD is high indicating that SP_1 (Figure 4(a)) is lower than SP_e (Figure 4(f)). These are mid-lower to lower channels in the SARA space from which the fetal signals are usually acquired. So this would indicate that fMCG was also attenuated to a larger extent along with

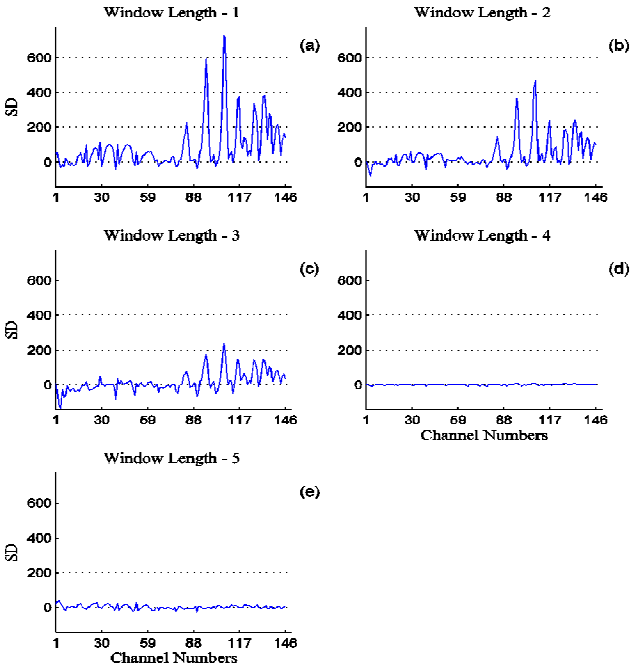

Fig.2. It shows Spectral difference (SD) in $pT/\sqrt{Hz}$ in each channel for one data set. Each subplot (a)-(e) represents SD of data obtained from OP applied to window length of 1 to 5 in minutes

mMCG hence implying that there was not enough data selected for averaging based on R waves. This fMCG output, where no clear fetal R wave is seen, will not be useful for any further analysis. The corresponding fMCG data is shown in Figure 3(a) where the blue signal is $dfMCG_1$ and red is

dfMCG$_e$. Even though data of time window length of 2 and 3 minutes show fetal R waves (Figure 3(b) and 3(c)), their signal strength is much lower than that of dfMCG$_e$. This could lead to missed beats when calculating measurements related to the fetal heart. In the case of a 4 minute time window, the SD$_4$ is close to zero for all the channels (Figure 2(d)), the dfMCG$_4$ overlaps dfMCG$_e$ (Figure 3(d)) and the contour plot of the spectral estimate of dfMCG$_4$ is similar to that of dfMCG$_e$. The same applies to the data dfMCG$_5$ from a 5 minute time window. The above method was applied to all 20 data sets and the results are described in Table 1.

Table 1: Represents the number of data sets for which SD = 0 in each of the 5 time window lengths.

Time window length (in minutes)	# of data sets (out of 20) where SD≈0
1	2
2	5
3	9
4	18
5	18

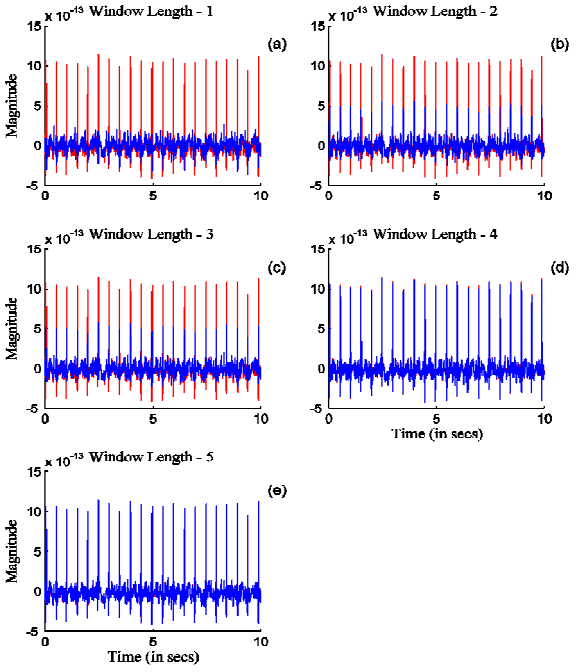

Fig.3. It shows fMCG data obtained from OP applied in time window length of 1-5 minutes ((a)-(e)) to the raw data. The Red indicates fMCG by applying OP to the entire data and Blue are fMCG from time windowed data. Each subplot corresponds to subplots in Fig 2.

Hence by this method we found that the four-minute time window is the minimum time duration for which the fetal data is not distorted after applying orthogonal projection. As given in Table 1, in this time window, spectral difference close to zero was observed in 18 out of 20 data sets. In the other two data sets, even though SD was not close to zero, it was significantly lower than 1-, 2- and 3-minute windows. Even in this shorter time segment stationarity cannot be assured.

In summary, interference elimination by projection is robust and relatively easy to automate. The unwanted interference is projected out of the measurement by constructing the orthogonal projection operator from signal space vectors corresponding to the interfering components. For MCGs, these vectors are determined by averaging, and orthogonal construction. We determined that the current analysis strategy needed to be improved to compensate for non-stationarity aspects of the data that were encountered in long duration data sets. The assumption is that we can minimize the effect of non-stationary by using shorter window size and apply the orthogonal projection to attenuate maternal MCG. This study was an attempt to provide an insight in to minimal window size while maintaining the quality of the maternal MCG averaging that is used for extraction of fetal MCG. In future, we plan to apply OP on four-minute window segments in large duration datasets where there are extensive movement artifacts in several sections of the recording.

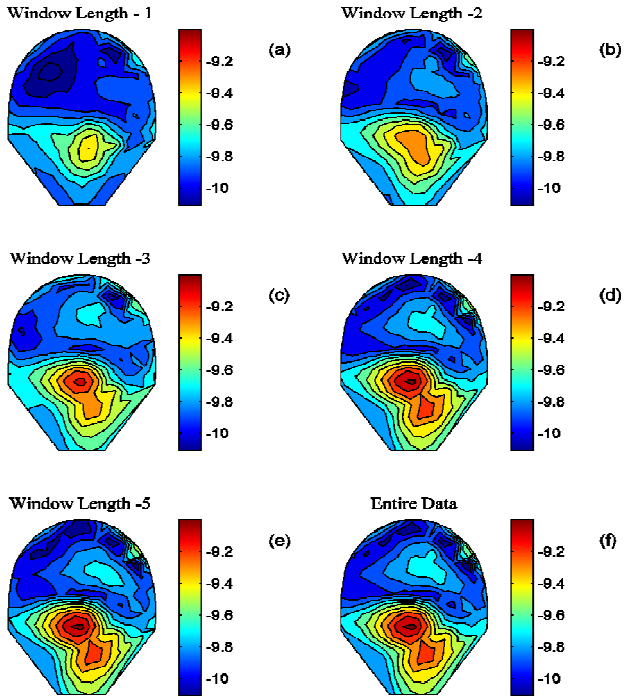

Fig.4. Spectral power of different time window of a single fetus as a contour plot. (a)-(e) shows spectral power of data obtained by applying OP to time window lengths corresponding to 1-5 minutes and (f) shows the spectral power of OP applied to entire data. The color scale units are the log of spectral power.

ACKNOWLEDGMENT

We thank Ms. Pamela Murphy for editing this manuscript.

REFERENCES

[1] J. D. Wilson, R. B. Govindan, J. O. Hatton, C. L. Lowery, and H. Preissl, “Integrated approach for fetal QRS detection,” IEEE Trans Biomed Eng, vol. 55, pp. 2190-7, Sep 2008.

[2] U. D. Ulusar, R. B. Govindan, J. D. Wilson, C. L. Lowery, H. Preissl, and H. Eswaran, “Adaptive rule based fetal QRS complex detection using hilbert transform,” Conf Proc IEEE Eng Med Biol Soc, vol. 1, pp. 4666-9, 2009.

[3] J. Vrba, S. E. Robinson, J. McCubbin, C. L. Lowery, H. Eswaran, J. D. Wilson, P. Murphy, and H. Preissl, “Fetal MEG redistribution by projection operators,” IEEE Trans Biomed Eng, vol. 51, pp. 1207-18, Jul 2004.

[4] Vrba, J, "Multichannel SQUID biomagnetic systems. In: Weinstock, H. (Ed.), Applications of Superconductivity". Kluwer Academic Publishers, Dordrecht, pp. 61–138, 2000.