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

Cardiac Interference Reduction in Diaphragmatic MMG Signals during a Maintained Inspiratory Pressure Test

L. Sarlabous, A. Torres, *Member, IEEE*, J.A. Fiz, *Member, IEEE*, R. Jané, *Member, IEEE*

Abstract— **A recursive least square (RLS) adaptive filtering algorithm for reduction of cardiac interference in diaphragmatic mecanomyographic (MMGdi) signals is addressed in this paper. MMGdi signals were acquired with a capacitive accelerometer placed between 7th and 8th intercostal spaces, on the right anterior axillary line, during a maintained inspiratory pressure test. Subjects were asked to maintain a constant inspiratory pressure with a mouthpiece connected to a closed tube (without breathing). This maneuver was repeated at five different contraction efforts: apnea (no effort), 20 cmH_2O, 40 cmH_2O, 60 cmH_2O and maximum voluntary contraction. An adaptive noise canceller (ANC) using the RLS algorithm was applied on the MMGdi signals. To evaluate the behavior of the ANC, the MMGdi signals were analyzed in two segments: with and without cardiac interference (WCI and NCI, respectively). In both segments it was analyzed the power spectral density (PSD), and the ARV and RMS amplitude parameters for each contraction effort. With the proposed ANC algorithm the amplitude parameters of the WCI segments were reduced to a level similar to the one of the NCI segments. The obtained results showed that ANC using the RLS algorithm allows to significantly reduce the cardiac interference in MMGdi signals.**

I. Introduction

Surface mechanomyography is the non-invasive recording of mechanical activity generated by muscle fibers and captured from the skin surface of the body by accelerometers. Since the diaphragm is the main muscle responsible for the mechanical respiratory activity, the analysis of the mechanomyographic signal of this muscle (MMGdi) could provide useful information about the strength and/or respiratory muscle fatigue.

In previous studies we have analyzed the MMGdi signal recorded in an animal model (dogs) [2] and in patients with COPD [3], [4], obtaining in both cases a positive correlation between the amplitude of the MMGdi signal and the muscle strength, assessed by the inspiratory mouth pressure. In these studies the MMGdi signal was acquired using a capacitive accelerometer placed on the lateral chest wall surface. The frequency content of the MMGdi signal is between 5 and 35 Hz [3], [4].

Due to the its mechanical origin, the MMGdi signal is greatly affected by other biological sources of mechanical origin such as the cardiac vibration, also known as seismocardiographic signal or mechanocardiographic (MCG) signal, whose frequency content is below 15 Hz [5]. Therefore, there is an overlap between the frequency content of the MMGdi signal and the heart vibration.

The amplitude of the MMGdi signal is usually estimated by means of the average rectified value (ARV) and the root mean square (RMS). Both parameters are greatly affected by the MCG interference. With the increase of the respiratory effort the amplitude of the MMGdi signal increase, while the amplitude of the MCG interference remains constant.

The adaptive filtering technique has been widely used to reduce the electrocardiographic interference recorded in diaphragm electromyographic signals [6] and in the reduction of cardiac sound in pulmonary sounds [7].

In a previous work [8] we analyzed in a simulated MMGdi signal the behavior of an adaptive noise canceler (ANC) using the least mean squares algorithm. The simulated MMGdi signal was generated by adding a recorded MCG signal (acquired by an accelerometer placed on the chest wall while performing an apnea) to a simulated clean MMGdi signal. In this work was found that the MCG interference greatly affects the MMGdi amplitude parameters, and also that the ANC method is appropriate to reduce the effect of the MCG interference on the amplitude parameters.

In the present work we present an ANC using the recursive least squares (RLS) algorithm applied to recorded MMGdi signals to: (1) evaluate the effect of the MCG interference over recorded MMGdi signals, and (2) evaluate the performance of the proposed ANC, by a comparative study of the power spectral density (PSD) and the RMS and ARV amplitude parameters computed before and after filtering.

II. Material and Methods

A. Signal acquisition

The study was conducted in a healthy subject with its consent. Three biomedical signals were acquired: the inspiratory mouth pressure (IP) signal, the electrocardiographic (ECG) signal and the MMGdi signal. The IP signal was recorded using a pressure transducer placed in the tube through which the subject breathes. To record the ECG signal were used three Ag-AgCl electrodes, two placed on each wrist and one on the right ankle. The MMGdi signal was recorded using a Kistler 8312B2 capacitive accelerometer placed on the surface of costal wall, between the seventh and eighth intercostal spaces in the left anterior axillary line. All

This work was supported in part by the Ministerio de Economía y Competitividad of Spain Government under grant TEC2010-21703-C03-01. The first author was supported by the grant FI-DGR 2010 from the Comissionat per a Universitats i Recerca del Departament d'Innovació, Universitats i Empresa of the Government of Catalonia and the European Social Fund.

L. Sarlabous, A. Torres, and R. Jané are with Dept. ESAII, Universitat Politècnica de Catalunya, Institut de Bioenginyeria de Catalunya (IBEC) and CIBER de Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN), Barcelona, Spain (e-mail:leonardo.sarlabous@upc.edu, abel.torres@upc.edu, raimon.jane@upc.edu).

J. A. Fiz is with Pneumology Service of Hospital Germans Trias i Pujol, Badalona, Spain, and IBEC and CIBER-BBN, Barcelona, Spain (e-mail: jafiz@msn.com).

signals were amplified, analog filtered, digitized with A/D system of 12 bits at a sampling frequency of 2 kHz.

B. Respiratory test

The subject was asked to maintain a constant inspiratory pressure with a mouthpiece connected to a closed tube (without breathing). This maneuver was repeated at five different levels of contraction effort: apnea (no effort), 20 cmH_2O, 40 cmH_2O, 60 cmH_2O and maximum voluntary contraction (MVC: 80 cmH_2O). The inspiratory pressure was maintained constant for a time period of 10 to 30 seconds, approximately. During the test, the subject is seated and relaxed, and breathes through the mouth with a mouthpiece connected to a pressure transducer. At the beginning of each maneuver the tube was stoppered and the subject was asked to generate inspiratory pressure. Using a screen, the subject could know and maintain constant the developed inspiratory pressure.

Figure 1 shows an example of the ECG and MMGdi signals recorded during apnea, 40 cmH_2O and MVC. In this figure it can be seen that the amplitude of the MMGdi signal increases as the inspiratory pressure increases. In Table I is shown the duration, the number of heartbeats and the heart rate of each of the respiratory tests.

TABLE I. DURATION, NUMBER OF HEARTBEATS AND HEART RATE

Inspiratory pressure	Duration (s)	Number of heartbeats	Heart rate (beats per minute)
Apnea	21	21	64.6
20 cmH_2O	25.5	32	78.8
40 cmH_2O	28	41	86
60 cmH_2O	26.3	39	88
MVC (80 cmH_2O)	10.7	17	102.2

C. Adaptive noise canceller using RLS algorithm

The ANC is based on a transversal filter of finite impulse response whose parameters are estimated with the RLS algorithm. The RLS algorithm is described in detail in [9]. The primary input of the filter is the MMGdi signal (with the MCG interference). The reference input should be uncorrelated with the mechanomyographic components of the MMGdi signal and correlated with the MCG interference. The methodology for generating the reference signal is described in detail in [8]. Briefly, this reference signal was generated by the convolution between a MCG template (that was obtained by averaging in the MMGdi signal all the cardiac vibrations corresponding to each beat) and an impulse train synchronized with the R points of the ECG signal. The output of the filter (MCGf), is an estimation of the MCG interference present in the MMGdi signal. Finally, the cleaned estimation of the MMGdi signal (MMGdif) is obtained by subtracting the estimated MCGf interference to the original MMGdi signal.

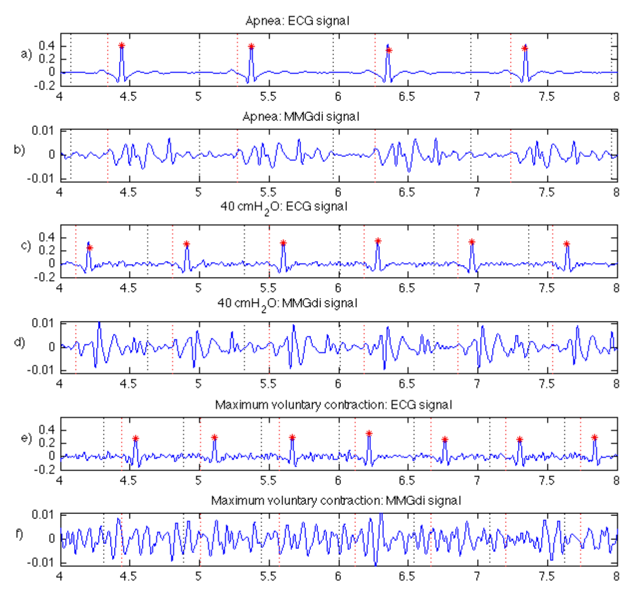

Figure 1. ECG (a, c and e) and MMGdi (b, d and f) signals acquired in the respiratory test with: apnea (a and b), 40 cmH_2O (c and d) and MVC (e and f), respectively

D. Signal processing

For automatic detection of the R points in the ECG signal it was used the Pan-Tompkins algorithm [10]. These positions of the R points are used as reference points for determining the time at which the MCG interference occurs on the MMGdi signals. The MMGdi signal was band-pass filtered between 5 and 35 Hz, using a bidirectional Butterworth filter of the fourth order. To evaluate the behavior of the ANC-RLS, the MMGdi signals were analyzed in two segments: with and without cardiac interference (WCI and NCI, respectively). The segments of the MMGdi signal between 0.1 s before the R point and a 60% of the R-R interval were considered as WCI segments. The segments between the 60% of the R-R and 0.1 s prior the next R point were considered as NCI segments.

In both WCI and NCI segments it was analyzed the behavior of the power spectral density (PSD), and it was computed the ARV and RMS amplitude parameters for each levels of contraction effort. These parameters were also calculated for the complete cardiac cycle (CCC=WCI+NCI).

III. RESULTS

The parameters of the ANC-RLS, filter order, forgetting factor (λ) and regularization parameter (δ), were chosen based on a study with the simulated signals used in [8]. Figure 2 shows the result of this study: the Pearson's correlation coefficient (r) between the RMS and ARV parameters, estimated in the simulated MMGdi signal filtered, and the theoretical amplitude value. The optimum values for the ANC-RLS (the parameters that yielded a maximum r) were an order between 40 and 60, λ equal to 1, and δ^{-1} between 100 and 1000. Figure 3 shows an example of the adaptive filtering of a MMGdi signal corresponding to an IP of 40 cmH_2O, using an order equal to 50, a λ equal to 1, and a δ^{-1} equal to 500.

Fig. 4 a, b and c show the PSD obtained for the analysis of the CCC, WCI and NCI, respectively. In each case, it is shown the spectra corresponding to all the inspiratory pressures. In Figure 4 d, e and f it is shown the corresponding PSD of the same signals after applying the ANC (CCCf, WCIf and NCIf).

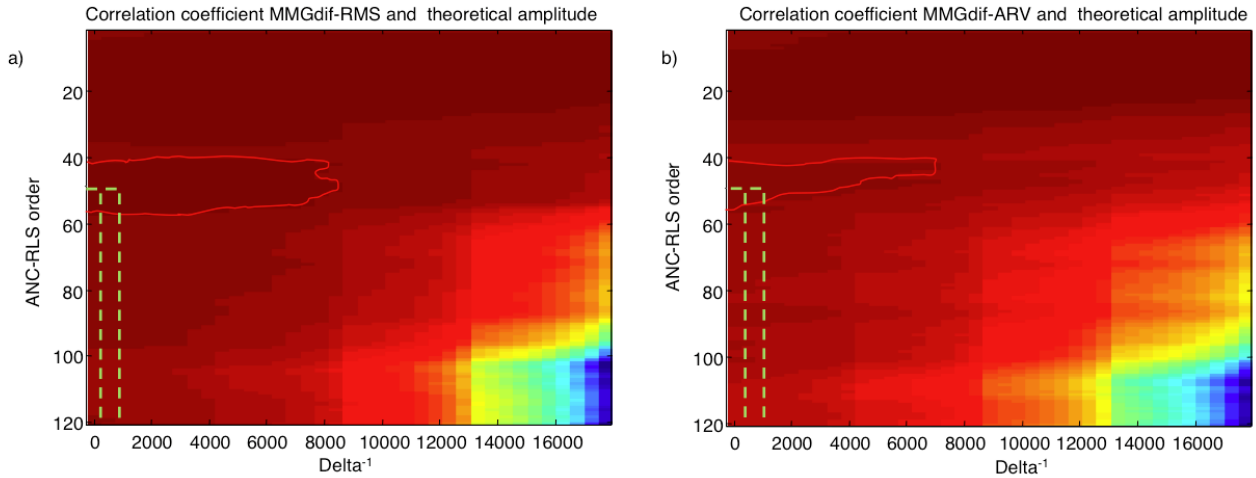

Figure 2. Correlation maps between the theoretical amplitude of the simulated MMGdi signal, and the amplitude parameters of the filtered simulated MMGdi signal. a) RMS, b) ARV

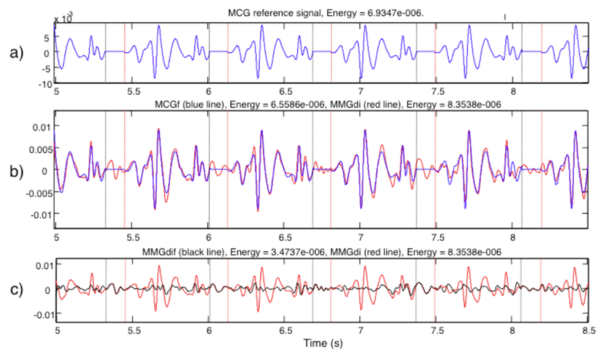

Figure 3. Example of input and output signals of the ANC-RLS corresponding to an inspiratory pressure of 40 cmH_2O: a) reference signal (MCG), b) canceling signal (MCGf: blue) and input signal contaminated heart sound (MMGdi: red), and c) comparison between the input signal (MMGdi) and the filtered signal (MMGdif): black).

As seen in Figure 4 a, b and c, the energy of the spectra increases with increasing inspiratory pressure. In the case of the apnea signal (blue line) it is observed that the energy of the mechanocardiographic activity is between 5 and 35 Hz, that is, it is completely overlapped with the energy of the mechanomyographic activity.

The energies corresponding to the CCC segments (Figure 3) are slightly higher than those obtained in the WCI sections. Clearly, the energy in the NCI sections is smaller. The energy of these sections has been used as reference levels to eliminate or attenuate the MCG interference signal. As seen in Figure 4 d, e and f, after applying the ANC, the NCI sections were practically not affected, while for CCC and WCI sections the energy has decreased greatly.

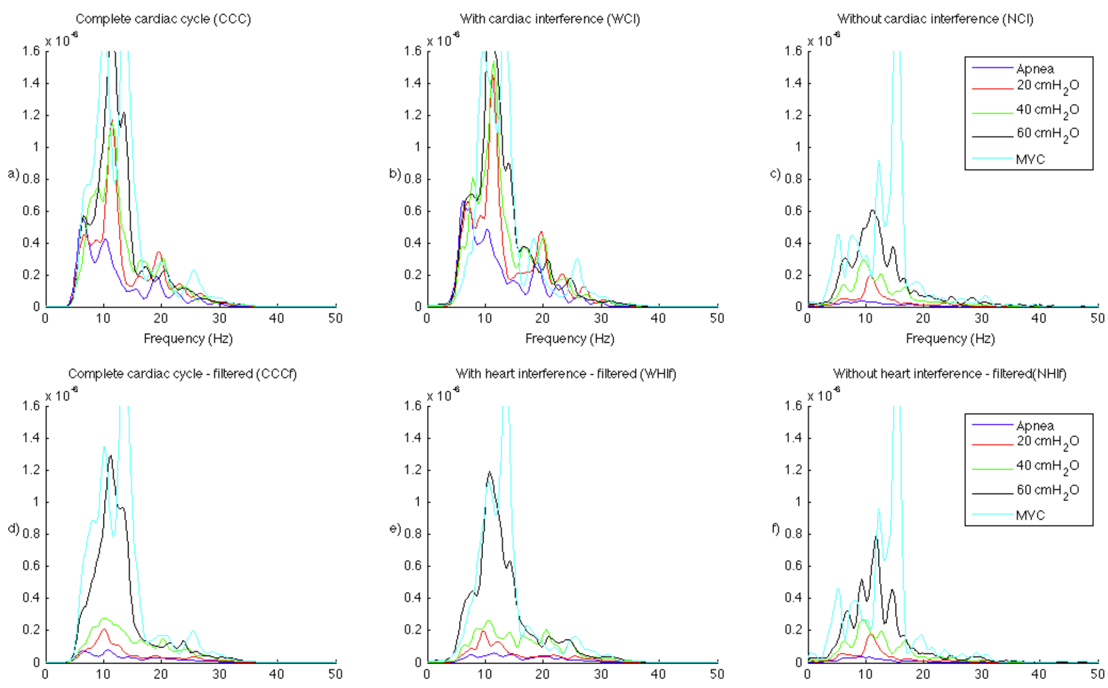

Figure 4. Power spectral density (PSD) obtained before (a, b and c) and after applying the ANC-RLS (d, e and f) for apnea (blue), 20 cmH_2O (red), 40 cmH_2O (green), 60 cmH_2O (black) and maximum voluntary contraction (cyan), considering the complete cardiac cycle (CCC), segments with cardiac interference (WCI) and segments without cardiac interference (NCI)

The evolution of the RMS and ARV amplitude parameters in function of increasing inspiratory pressure is shown in Figure 5 a and b, respectively, for the three segments studied: CCC (Δ), WCI (o) and NCI (x). Solid lines correspond to the parameters obtained before applying the ANC-RLS, while dashed lines correspond to the parameters after applying the ANC. In both parameters is observed a similar trend. Before applying the ANC-RLS a perfect differentiation is observed between the amplitude values for each kind of segments. In this sense, the greatest amplitude is reported in the WCI segments, while the lower amplitude is observed in the NCI segments. It is also noted that with the increase of the inspiratory pressure, the separation between the three types of segments is smaller (for the MVC the three segments tend towards the same value). After applying the ANC-RLS is observed that the amplitude values of the NCIf segments report values similar to those obtained before applying the filter. This indicates that no MMGdi signal components were removed in these segments. In the case of CCCf and WCIf segments, there is a significant reduction of the amplitude, indicating that the MCG interference has been reduced considerably.

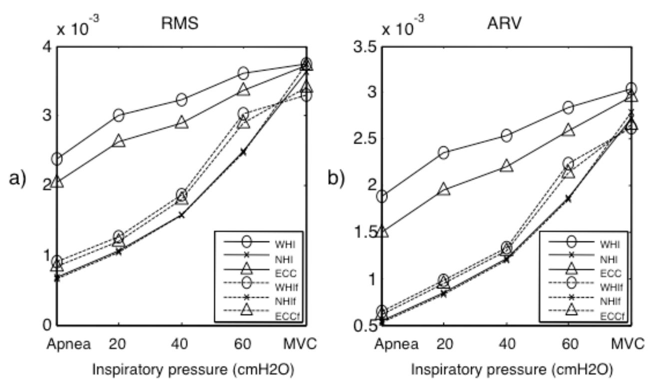

Figure 5. RMS and ARV amplitude parameters in function of inspiratory pressure. The amplitude parameters were computed in the complete cardiac cycle (CCC: Δ), segments with cardiac interference (WCI: o) and segments without cardiac interference (NCI: x). Solid lines correspond to values before applying the filter and dashed lines correspond to values after applying the adaptive filter

IV. Conclusions

In this work, an ANC using the RLS algorithm was applied to reduce the cardiac interference present in MMGdi signals recorded during respiratory tests in which different inspiratory pressure levels were kept constant.

The results obtained in this study are consistent with those obtained in a previous study in which and ANC-LMS algorithm was applied to simulated MMGdi signals [8]. In contrast to this study, in the present paper it was not available a clean MMGdi signal to evaluate the performance of the ANC. Therefore we have analyzed the original and filtered MMGdi signals in two different signal segments: segments of the signal without the presence of cardiac component (NCI) and the segments with presence of cardiac component (WCI). The behavior of the ANC-RLS was analyzed in terms of variation in the PSD and the RMS and ARV parameters between these segments. The values of these parameters in the NCI segments were used as a reference MMGdi signal clean of cardiac interference. With the ANC-RLS it was possible to reduce considerably the MCG signal interference in the WCI segments, while in NCI segments no significant changes were observed.

We concluded the ANC method presented in this paper is a useful technique to reduce the cardiac interference in recorded MMGdi signals. Further investigation should be carried out to evaluate the performance of the ANC algorithm in other respiratory conditions.

References

[1] C. Orizio, “Muscle Sound: bases for the introduction of a mechanomyogaphic signal in muscle studies,” Crit. Rev. Biomed. Eng., 21, pp. 201–243, 1993.

[2] A. Torres, J.A. Fiz, J. Morera, A.E. Grassino,and R. Jané, “Time-Frequency representations of the diaphragmatic movement measured by a surface piezoelectric contact sensor in dogs,” 25th Ann. Conf. IEEE-EMBS, 2003.

[3] L. Sarlabous, A. Torres, J.A. Fiz, J. Gea, J.M. Martínez-Llorens, R. Jané, “Evaluation of the respiratory Muscular Function by means of Diaphragmatic Signals in COPD Patients,” 31th Ann. Conf. IEEE-EMBS, pp: 3925-3928, 2009.

[4] A. Torres, L. Sarlabous, J.A. Fiz, J. Gea, J.M. Martínez-Llorens, J. Morera, R. Jané, “Noninvasive Measurement of Inspiratory Muscle Performance by means of Diaphragm Muscle Mechanomyographic Signals in COPD patients during an Incremental Load Respiratory Test”, 32th Ann. Conf. IEEE-EMBS, pp: 2493 - 2496, 2010.

[5] P. Castiglioni, P. Meriggi, F. Rizzo, E. Vaini, A. Faini, G. Parati and M. Di Rienzoand, 'Seismocardiography While Sleeping at High Altitude', 34h Ann. Conf. IEEE-EMBS, pp: 3793-3796, 2012.

[6] Y. Deng, W. Wolf, R. Schnell and U. Apple, “New Aspects to Event-Synchronous Cancellation of ECG Interference: an Application of the Method in Diaphragmatic EMG Signals”, IEEE Trans. Biomed. Eng., vol. 47, no. 9, pp. 1177-1184, 2000

[7] J. Gnitecki, Z. Moussavi, and H. Pasterkamp, “Recursive Least Squares Adaptive Noise Cancellation Filtering for Heart Sound Reduction in Lung Sounds Recordings”, 25th Ann. Conf. IEEE-EMBS, pp: 2416 - 2419, 2003.

[8] L. Sarlabous, A. Torres, J.A. Fiz, J Morera, R. Jané, “Evaluation and Adaptive Attenuation of the Cardiac Vibration Interference in Mechanomyographic Signals,” 34th Ann. Conf. IEEE-EMBS, pp: 3400-3403 , 2012.

[9] S. Haykin, Adaptive Filter Theory. Upper Saddle River, NJ: Prentice-Hall, 2002, ch I. 8, and 9.

[10] J.P. Pan and W.J. Tompkins, “A Real-Time QRS Detection Algorithm”. IEEE Trans. Biomed. Eng., vol. 32, no. 3, pp. 230-236, 1985.