Evaluation of Laplacian Diaphragm Electromyographic Recording in a Dynamic Inspiratory Maneuver

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***Abstract*— The analysis of the electromyographic signal of the diaphragm muscle (EMGdi) can provide important information for evaluating the respiratory muscular function. The EMGdi can be recorded using surface Ag/AgCl disc electrodes in monopolar or bipolar configuration. However, these non-invasive EMGdi recordings are usually contaminated by the electrocardiographic (ECG) signal. EMGdi signal can also be noninvasively recorded using concentric ring electrodes in bipolar configuration (CRE) that estimate Laplacian surface potential. Laplacian recordings increase spatial resolution and attenuate distant bioelectric interferences, such as the ECG. Thus, the objective of this work is to compare and to evaluate CRE and traditional bipolar EMGdi recordings in a healthy subject during a dynamic inspiratory maneuver with incremental inspiratory loads. In the conducted study, it was calculated the cumulative percentage of power spectrum of EMGdi recordings to determine the signal bandwidth, and the power ratio between the EMGdi signal segments with and without cardiac activity. The results of this study suggest that EMGdi acquired with CRE electrodes is less affected by the ECG interference, achieves a wider bandwidth and a higher power ratio between segments without cardiac activity and with cardiac activity.**

I. INTRODUCTION

The electromyographic signal of the diaphragm muscle (EMGdi) can be used to monitor its contractile activity during respiration. One of the major concerns in analysis of the EMGdi amplitude and frequency is the electrocardiographic (ECG) interference. The ECG interference introduces a distortion in both EMGdi signal power and frequency content. Moreover, the power spectrum of EMGdi and of the ECG is overlapped. The EMGdi signal can be noninvasively recorded using disc electrodes in monopolar or bipolar configuration. However, conventional disc electrodes have a poor spatial resolution mainly due to the smearing effect caused by the torso volume conductor. As an alternative, for improving the spatial resolution and the reduction of bioelectrical interferences signals, the Laplacian of surface potential can be estimated [1]. Laplacian potential has found application for the non-invasive recording of ECG [1], muscle activity in the tibialis anterior [2], digiti minimi [2], biceps brachii [2], [3] and masseter [4] muscles, EMGdi from static inspiratory maneuvers [5], intestinal myoelectrical activity [6]; electrohysterogram during uterine dynamics [7]; or electroencephalogram [8]. A direct and simple method to estimate Laplacian potential is using concentric ring electrodes (CRE) [1]–[7] in which the differential voltage between an external ring and inner disc is worked out. This kind of electrodes has proven to be advantageous to reduce the orientation problems regarded to conventional monopolar and bipolar configurations [2]. The aim of this work is to compare and evaluate the performance of EMGdi signals, during a dynamic respiratory test with incremental inspiratory load, obtained with conventional bipolar recordings using disc electrodes with those obtained from bipolar Laplacian estimation with concentric rings of two different sizes.

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II. MATERIAL AND METHODS

A. Experimental protocol

Signals were acquired from one non-smoking healthy male with no medical history of cardiorespiratory nor neuromuscular disease. The subject was seated in a comfortable chair upright and worn a disposable nose clip to prevent nasal breathing. The protocol consisted of two parts. First, a breath hold maneuver, in which the subject was asked to interrupt his breath for a period of 12 s. Second, a dynamic inspiratory maneuver (DIM), consisting of breathing against an inspiratory load.

During the DIM maneuver the subject inhaled via a mouthpiece attached to an inspiratory muscle training device (Threshold IMT, Philips Respironics, Amsterdam, The Netherlands) held with his right hand. During the inspiratory phase, this device provides an inspiratory pressure threshold load, independent of the flow, which increases the inspiratory muscle activity [9], whilst no additional load is present during expiratory phase. The subject must exert the necessary inspiratory pressure to open the valve of the IMT device in order to breathe. The DIM was performed in four steps of 1 minute length: without the IMT device (tidal volume) and then using the IMT device with pressure resistance set to 17, 29 and 41 cmH_2O.

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B. *Signal Acquisition*

Prior to the study, the skin area was mildly abraded with an abrasive gel (Nuprep, Weaver and Company, USA) and cleaned with alcohol-soaked cotton to ensure low contact skin/electrode impedance. To record the EMGdi activity, a pair of conventional Ag/AgCl electrodes in bipolar configuration (disposable, pre-gelled, disc of 10 mm diameter contact area, foam electrode 50/PK – EL501, Biopac Systems Inc, Santa Barbara, CA, USA) was placed on the lower left chest, between the seventh and eight intercostal space at the midclavicular line (as shown in Fig. 1b). Two additional EMGdi signals were acquired using a flexible tripolar concentric ring (CRE) electrode. The differential signal between the external ring (36 mm diameter) and the central disc (10 mm, diameter) of the CRE; and between the middle ring (24mm diameter) and the central disc were obtained.

To assure a simultaneous record over the same muscle area, the CRE was placed between the conventional bipolar electrode configuration and attached to the subject's skin using medical tape in a similar fashion to the methodology reported in [5]. CRE are commonly used as dry electrodes [10]; nonetheless, in the present study, to improve the signal to noise ratio of the EMGdi signal, the contact area of the CRE was carefully impregnated with gel (Signa Gel, Parker Laboratories, Inc., Fairfield, NJ, USA). All EMGdi signals were amplified with a gain of 2000 and filtered between 1 and 500 Hz (EMG 100C, Biopac Systems Inc, Santa Barbara, CA, USA). To monitor the cardiac activity, the electrocardiographic signal was obtained from the standard lead-I configuration using disposable Ag/AgCl electrodes attached to both arms. A disposable electrode was placed as a reference on the right ankle. Lead-I configuration was plugged into a modular amplifier (ECG 100C, Biopac Systems Inc, Santa Barbara, CA, USA) with a gain of 2000 and an analog high-pass filter with a cut-off frequency of 0.5 Hz. Moreover, airflow (AF) was measured using a pneumotacograph transducer (TSD107B, Biopac Systems Inc, Santa Barbara, CA, USA), connected to a modular amplifier (DAC100C, Biopac Systems Inc, Santa Barbara, CA, USA) with an analog low-pass of 300 Hz and with gain of 1000. The picked up signals were digitized at 2000 Hz by means of an acquisition system (MP150, Biopac Systems, Santa Barbara, CA, USA), monitored and stored in a computer via the associated software (AcqKnowledge software v.3.2, Santa Barbara, CA, USA). An example of 20 s of the signal recordings during apnea, tidal volume, and respiration with an inspiratory load of 17 cmH_2O, 29 cmH_2O

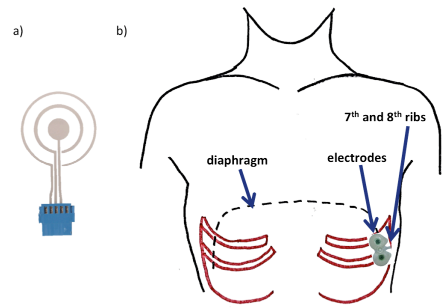

Figure 1. (a) Concentric ring electrode for Laplacian EMGdi recording. (b) Placement of conventional AgAgCl electrodes in bipolar configuration and concentric ring electrode between 7th and 8th intercostal spaces, lateral to the right midclavicular line.

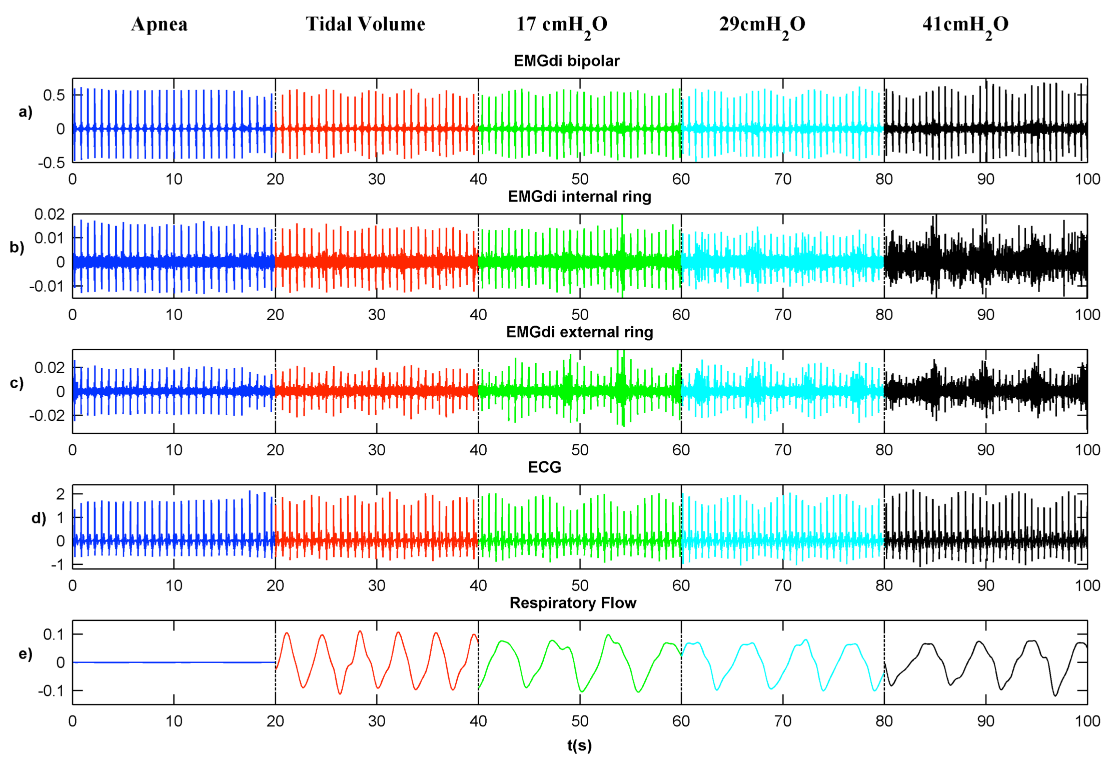

Figure 2. Example of signal recordings during apnea (blue), tidal volume (red), and respiration with an inspiratory load of 17 cmH_2O (green), 29 cmH_2O (cyan) and 41 cmH_2O (black): (a) EMGdi signal acquired with conventional AgAgCl electrodes in bipolar configuration, (b) EMGdi signal acquired with the inner ring and the central disc of the concentric electrode, (c) EMGdi signal acquired with the outer ring and the central disc of the concentric electrode, (d) ECG signal, (e) respiratory flow signal.

and 41 cmH_2O is shown in Fig. 2. Strong ECG interference can be observed in all EMGdi signals in every step of the DIM.

C. Data Analysis

Identification of respiratory cycles and detection of onset and offset of inspiration was done on the AF signal; detection of the R peak of the QRS complexes was done on the ECG signal. All EMGdi signals were bandpass filtered using a zero-phase fourth-order Butterworth filter with cut-off frequencies of 10 and 300 Hz. Estimation of the power spectral density (PSD) of every signal was performed by applying the Welch modified periodogram method (Hamming window, 0.5 seconds length, 4096 - point FFT, and 50 % overlap). EMGdi power spectrum was analyzed between f1 = 10 to f2 = 100 Hz.

Cumulative percentage of the power distribution (CmPS), calculated as the ratio of the integral of the power spectrum up to a given frequency 'f' and the total power spectrum, was used to compare the spectral distribution of the EMGdi signals and estimate the signal bandwidth. To evaluate the influence of the cardiac activity on the signals, the EMGdi was analyzed into two signal segments: with and without cardiac noise (WCN and NCN, respectively). It was considered that the most relevant ECG interference is due to QRS complexes. Thus, the signal segments of the EMGdi between 0.125 s before and 0.125 s after an R peak were considered as WCN segments. Conversely, the signal segments between 0.125 s after an R point peak 0.125 s before the next R point were considered as NCN segments. The power ratio between NCN and WCN sections was analyzed in all EMGdi signals for every frequency of the spectrum between f1 and f2, and for the whole spectrum.

TABLE I. FREQUENCIES CORRESPONDING TO 5 %, 50 % AND 95 % OF THE CUMULATIVE PERCENTAGE OF POWER BETWEEN 10 AND 100 HZ

		Apnea	Tidal Volume	17 cmH_2O	29 cmH_2O	41 cmH_2O
EMGdi Bipolar	$f_{5\%}$(Hz)	11.2	11.2	11.2	11.2	11.2
	$f_{50\%}$(Hz)	17.4	17.3	17.4	17.5	17.5
	$f_{95\%}$(Hz)	30.3	30.0	30.4	30.8	33.5
EMGdi internal ring	$f_{5\%}$(Hz)	11.2	11.3	11.4	11.3	11.3
	$f_{50\%}$(Hz)	18.0	18.1	18.4	18.6	19.4
	$f_{95\%}$(Hz)	34.3	35.8	40.0	48.5	67.6
EMGdi external ring	$f_{5\%}$(Hz)	11.2	11.2	11.2	11.2	11.2
	$f_{50\%}$(Hz)	16.8	16.9	17.0	17.6	18.7
	$f_{95\%}$(Hz)	30.8	36.9	39.6	46.0	64.2

III. RESULTS

The PSD and CmPS of all EMGdi signals are represented in Fig. 3. In the conventional EMGdi recording it is observed that the increase of load produces an increase of EMGdi energy that mostly occurs in the frequency band between 10 and 30 Hz (matching with the cardiac activity spectrum). However, in the CRE recordings this energy increase extends to higher frequencies (between 30 and 100 Hz), which is more noticeable in the signals from the inner ring.

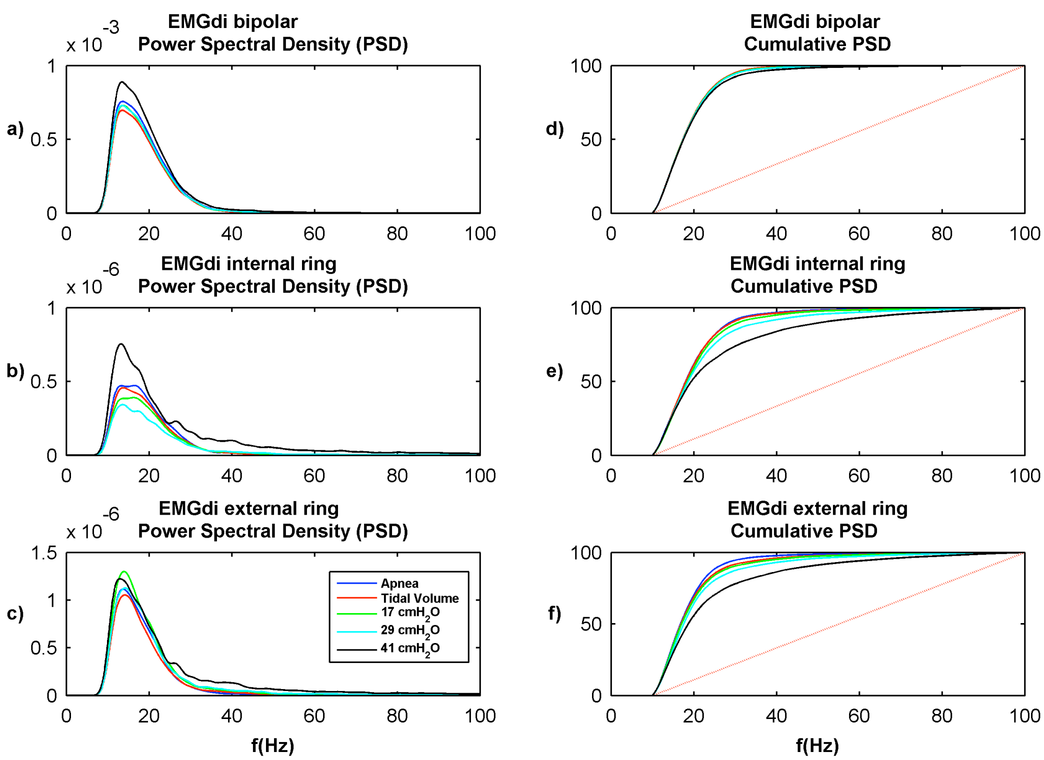

Figure 3. Power spectral density (a, b and c) and cumulative percentage of power between 10 and 100 Hz (d, e and f) of the conventional bipolar EMGdi signal (a and d), EMGdi signal acquired with the inner ring and the central disc of the concentric electrode (b and e), and EMGdi signal acquired with the outer ring and the central disc of the concentric electrode (c and f), for the recordings during apnea (blue), tidal volume (red), and respiration with an inspiratory load of 17 cmH_2O (green), 29 cmH_2O (cyan) and 41 cmH_2O (black).

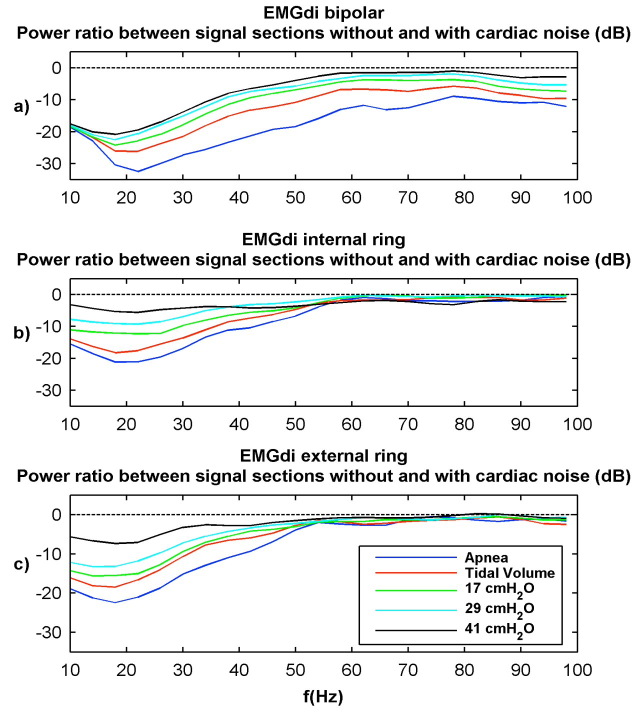

Figure 4. Spectral distribution of power ratio between signal sections without and with cardiac noise for the conventional bipolar EMGdi signal (a), EMGdi signal acquired with the inner ring and the central disc of the concentric electrode (b), and EMGdi signal acquired with the outer ring and the central disc of the concentric electrode (c), for the recordings during apnea (blue), tidal volume (red), and respiration with an inspiratory load of 17 cmH_2O (green), 29 cmH_2O (cyan) and 41 cmH_2O (black).

All EMGdi signals show CmPS with exponential trend with a steep accumulation of power in the ECG frequency band. However, this accumulation is less steep in the CRE recordings. Table I shows the frequencies that include the 5%, 50 % and 95 % of the total power of the signal ($f_{5\%}$, $f_{50\%}$ and $f_{95\%}$, respectively). These results confirm that the CRE recordings present a wider bandwidth than the conventional recording. Table II shows the results of the power ratio between the NCN and WCN signal segments. In this case, a power ratio of 0 dB would mean that both segments have the same energy and therefore that the cardiac interference is not present. In contrast, a negative power ratio indicates the presence of cardiac activity in the signal. As expected, the higher the respiratory load the higher the power ratio. It can also be seen that the lowest values are obtained for bipolar conventional recording proving again that cardiac interference is stronger in this signal. The CRE recordings show a better behavior, reaching values close to zero for high inspiratory loads. Fig. 4 shows the frequency distribution of this power ratio. In the case of CRE, the power ratio is higher, especially for frequencies over 50Hz where it reaches values of about 0dB, while conventional bipolar recording still presents values lower than -10 dB.

TABLE II. POWER RATIO (DB) BETWEEN SIGNAL SECTIONS WITHOUT AND WITH CARDIAC NOISE

	Apnea	**Tidal Volume**	**17 cmH_2O**	**29 cmH_2O**	**41 cmH_2O**
MGdi Bipolar	-23.6	-21.8	-20.2	-18.7	-16.2
EMGdi int.ring	-14.4	-12.2	-10.4	-7.6	-2.8
EMGdi ext. ring	-15.3	-12.1	-11.5	-9.8	-3.8

IV. DISCUSSION AND CONCLUSION

EMGdi recordings are severely interfered by cardiac activity, especially in the left diaphragm. ECG greatly affects conventional EMGdi recordings. The outcomes of this work suggest that EMGdi acquired with CRE electrodes is less interfered by the ECG; and presents a wider signal bandwidth. As reported by other authors [8], recording with CRE permits to enhance spatial resolution, thus reducing the spatial filtering effect and enlarging the bandwidth of the signals recorded on the body surface. This is also in agreement with our previous findings in surface EMG from biceps brachii [3]. The reduction of cardiac interference is an important issue for the correct interpretation of EMGdi signals. Nonetheless, the influence of inter electrode distance of the bipolar configuration, the study of different sizes of the Laplacian electrode in a more comprehensive database need to be performed to confirm these results.

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