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Evaluation of the Respiratory Muscles Efficiency during an Incremental Flow Respiratory Test

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***Abstract*— The aim of this study was to evaluate the respiratory muscles efficiency during a progressive incremental flow (IF) respiratory test in healthy and Chronic Obstructive Pulmonary Disease (COPD) subjects. To achieve this, the relationship between mouth Inspiratory Pressure (IP) increment, which is a measure of the force produced by respiratory muscles, and respiratory muscular activity increment, evaluated by means of Mechanomyografic (MMG) signals of the diaphragm muscle, was analyzed. Moreover, the correlation between the respiratory efficiency measure and the obstruction severity of the subjects was also examined. Data from two groups of subjects were analyzed. One group consisted of four female subjects (two healthy subjects and two moderate COPD patients) and the other consisted of ten male subjects (six severe and four very severe COPD patients). All subjects performed an easy IF respiratory test, in which small IP values were reached. We have found that there is an increase of amplitude and a displacement towards low frequencies in the MMG signals when the IP increases. Furthermore, it has also been found that respiratory muscles efficiency is lower when greater the obstructive severity of the patients is, and it is lower in women than in men. These results suggest that the information provided by MMG signals could be used to evaluate the muscular efficiency in healthy and COPD subjects.**

I. INTRODUCTION

THE study of breathing pattern requires the development of non-invasive techniques. Measuring apparatus (such as: spirometers, flowmeters, face mask or mouth piece) add resistance and alters respiratory pattern [1]. Inductive plethysmography, one of the most utilized non-invasive techniques for qualitative monitoring of the respiratory activity, is not capable to give a quantitative measure of the respiratory effort without performing previously an individual and complex calibration of the apparatus.

The surface mechanomyogram (MMG) is a noninvasive technique that quantifies the low-frequency lateral oscillations of the muscle fibers during contraction. These oscillations have been suggested to be a function of the gross lateral movement of the muscle and smaller lateral oscillations due to the summation of the muscle fibers movement from the recruited muscle motor units [2]. In general, a positive correlation coefficient has been found between amplitude parameters of the MMG signal and the force produced by the muscle [2]-[8].

The diaphragm is the main respiratory muscle responsible for the mechano-respiratory activity. The respiratory muscular fatigue can be monitored by means of techniques that study the muscular electric activity in amplitude and frequency through the electromyographic (EMG) signal of respiratory muscles. The main inconvenience of using the diaphragmatic EMG signal is that a complex and invasive instrumentation is needed for its implementation (esophageal electrode catheter). On the other hand, the use of surface electrodes has great inconveniences due to the contamination of bioelectric noise coming from other origins, making its application questionable.

In patients with Chronic Obstructive Pulmonary Disease (COPD) of type A (lung emphysema), the respiratory muscular function and the mechanic of the thoracic cage are very affected. The muscular efficiency (relationship between electric and mechanic activities of the muscle) is very reduced, due to the changes in the thoraco-diaphragmatic space configuration produced by the disease, and that makes ineffective the muscular contraction, wasting great amounts of energy.

In a previous work [9] we studied the relationship between amplitude variations of mouth Inspiratory Pressure (IP) and amplitude variations of diaphragmatic MMG signals registered in the left and right hemidiaphragms (MMG_L and MMG_R, respectively). In that work six COPD patients who performed a progressive incremental flow (IF) respiratory test were analyzed. The results obtained in that study suggest that the small IP increments are correlated with amplitude

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variations and displacements towards low frequencies in the respiratory muscles MMG signals. Furthermore, it was observed that in very severe patients a greater MMG muscular activity was needed to achieve the same IP value. It was found that there is an inverse relationship between the efficiency of the respiratory muscles and the obstructive severity of subjects.

The aims of the current study are to (1) define a new parameter to measure the efficiency of the mechanical activity developed by the respiratory muscles and evaluate its behavior as a function of the obstructive severity, and (2) corroborate the results obtained in [9] increasing the number of subjects.

II. METHODOLOGY

A. *Study population*

The study population consisted of four female subjects (two healthy and two moderate COPD patients) and ten male subjects (six severe and four very severe COPD patients). The classification of patients in function of the obstructive severity was performed considering the standards reported by [10]. Table I reports the anthropometric data and the parameters of the pulmonary function tests (PFTs) of the different subgroups of subjects.

TABLE I
PATIENTS CHARACTERISTICS AND PARAMETERS OF THE PULMONARY FUNCTION TESTS

	Females		Males	
	Healthy	Moderate	Severe	Very severe
Age (yrs)	**71.5 ± 0.7**	**64.5 ± 17.7**	**72.8 ± 4.1**	**65.8 ± 9.4**
FEV_1%	**108 ± 22.6**	**60.5 ± 4.9**	**40.0 ± 6.5**	**25.2 ± 10.8**
FEV_1/FVC	**78.5 ± 2.1**	**56.5 ± 10.6**	**49.1 ± 2.9**	**36.4 ± 9.03**
DLCO%	**81.0 ± 8.5**	**77.5 ± 29**	**60.7 ± 19.6**	**39.6 ± 16.0**
KCO%	**76.5 ± 4.9**	**84 ± 32.5**	**63.7 ± 11.8**	**58.8 ± 13.7**

FEV_1 = forced expiratory volume over one second, FVC = forced vital capacity, FEV_1/FVC = proportion of the forced vital capacity exhaled in the first second, DLCO = carbon monoxide diffusing capacity, KCO = carbon monoxide transfer coefficient, PIMmax = Maximum Pressure value obtained in Maximal Inspiratory Pressure maneuvers (PIM), % = percentage regarding the predicted value.

B. *Signals and instrumentation*

The subjects were instrumented to acquire IP signal and MMG_L and MMG_R signals. IP signal was measured with a pressure transducer placed in the tube through which the patients breathe. MMG_L and MMG_R signals were acquired with two Kistler 8312B2 capacitive accelerometers placed on the surface of the thoracic cage. The sensors were placed between the seventh and eighth intercostal spaces in the left and right anterior axillary lines, respectively.

All analog signals were amplified, analog filtered, digitized with a 12 bit A/D system at a sampling rate of 2 kHz, and decimated at a sampling rate of 200 Hz for MMG signals and 50 Hz for IP signal.

C. *Respiratory protocol*

All subjects performed a progressive incremental flow respiratory test. This test is very suitable for patients with very severe obstructive respiratory problems because there is no need to achieve high levels of IP. With the guide of a medical staff instructor the subjects progressively increase the rhythm and intensity of breathing from basal tidal volume until they reach almost their vital capacity. Later the rhythm and intensity of the breathing progressively are decreased until reach again quiet respiratory breathing at basal tidal volume. This process is realized two or three times for each subject. In [9] the IF respiratory test was described more detailed and an example of both IP and MMG signals was shown. Table II shows the duration, the number of respiratory cycles, and the maximum IP reached during the IF respiratory test.

TABLE II
DURATION, NUMBER OF CYCLES AND MAXIMUM INSPIRATORY PRESSURE DEVELOPED IN THE RESPIRATORY TESTS

	Females		Females	
	Healthy	Moderate	Severe	Very severe
Number of cycles	**122 ± 4.2**	**111.5 ± 9.2**	**121.7 ± 28.1**	**140.6 ± 35.4**
Duration (s)	**198.9 ± 86.1**	**323.5 ± 40.3**	**286.8 ± 43.9**	**354.4 ± 62.6**
Max. IP (cmH2O)	**7.22 ± 3.6**	**2.61 ± 0.5**	**4.0 ± 0.7**	**3.45 ± 0.4**

D. *Signal Processing*

An automatic algorithm for detecting the respiratory cycles and the initial and final time of diaphragm muscle contraction from IP signal was performed. In each respiratory cycle the maximum IP (IP_{max}) was estimated. Four MMG parameters were estimated in each respiratory cycle in both hemidiaphragms. Three of these parameters measure the signal amplitude: the root mean square (RMS), the Rényi entropy with α=0.5 (H_α) [11], and the Multistate Lempel-Ziv coefficient with 500 states (MLZ) [12]. The fourth parameter measures the frequency content: the maximum frequency (fmax) that corresponds with the 95 % of the energy of the spectrum.

The relationship between the variations of IP_{max} and the variations of MMG parameters was analyzed by means of *Pearson* correlation coefficient. The respiratory muscles efficiency is estimated as the slope of the linear regression line of this relationship (ΔIP_{max} / ΔMMG amplitude parameter). The correlation between this efficiency measure and the PFTs parameters was computed to evaluate the relationship between the respiratory muscular efficiency and the obstructive severity of the subjects.

TABLE III
CORRELATION COEFFICIENTS BETWEEN INSPIRATORY PRESSURE AMPLITUDE AND THE MMG PARAMETERS

	Left MMG				Right MMG			
	RMS	H	LZM	fmax	RMS	H	LZM	fmax
Females	0.845 ± 0.066	0.866 ± 0.062	0.844 ± 0.064	-0.700 ± 0.24	0.777 ± 0.090	0.813 ± 0.119	0.750 ± 0.172	-0.686 ±0.228
Males	0.817 ± 0.189	0.833 ± 0.178	0.763 ± 0.307	-0.489 ±0.298	0.856 ± 0.064	0.878 ± 0.044	0.845 ± 0.064	-0.532 ±0.312

Mean values and standard deviation of correlation coefficients between maximum inspiratory pressure amplitude and MMG parameters. RMS = Root Mean Square, H = Rényi entropy, MLZ = Multistate Lempel-Ziv, fmax = Maximum frequency.

III. RESULTS

Mean values and standard deviation of the correlation coefficients between the IP_{max} values and the MMG parameters are shown in Table III. The results are showed separated in only two groups (females and males, due to the small number of subjects in each subgroup. In both groups similar trends are described. The parameter that reported the highest correlation coefficients was the $H\alpha$ parameter, according with the results obtained in [9].

Table IV shows the correlation coefficients between the PFTs parameters and the respiratory muscles efficiency. As it can be seen, in both groups the correlation coefficients for MMG amplitude parameters are positive. That means that the greater is the obstructive severity of the subject (a smaller value in the PFTs) the lower is the respiratory muscles efficiency: there is a higher augment in the MMG signals amplitude for the same increment of IP. In contrast, fmax parameter reported negative correlation coefficient values. This suggests a displacement towards low frequencies with increasing the obstructive severity of subjects.

A graphic example of the correlation between the forced expiratory volume in the first second (FEV_1) spirometry parameter and the respiratory muscles efficiency is shown in Fig. 1. In each group the linear regression line and their corresponding correlation coefficient is shown (r_F match with females group and r_M match with males group). In females group, healthy subjects are represented by an “*”, and moderate COPD subjects are represented by a “**.**”. In males group, severe COPD subjects are represented by a “x” and very severe COPD subjects are represented by a “+”. It can be seen that in both male and female groups the respiratory muscles efficiency is greater the lower is the severity of the subject, and the respiratory muscles efficiency is greater in men than in women.

IV. CONCLUSIONS

In this work diaphragmatic MMG_L and MMG_R signals have been analyzed acquired during a respiratory protocol. This protocol is of short duration and easy to carry out for subjects with obstructive respiratory problems such as the COPD patients. The study was conducted in two groups: females and males, with the intention of analyzing the differences of the mechanical activity developed in function of the obstruction severity in both groups.

It has been observed that the small increments of IP_{max} that take place during the tests are correlated with the amplitude variations and displacements toward low frequencies in the respiratory muscles MMG signals**.** Furthermore, the increasing of MMG amplitude is related with patient obstructive severity. These results are consistent with the

TABLE IV
CORRELATION COEFFICIENTS BETWEEN THE SLOPE VARIATION OF THE MMG PARAMETERS AND THE PULMONARY FUNCTION TESTS PARAMETERS

Group	**Parameters**	**Left MMG**				**Right MMG**			
		RMS	**H**	**LZM**	**fmax**	**RMS**	**H**	**LZM**	**fmax**
Females	FEV1%	0.993	0.962	0.947	-0.888	0.956	0.938	0.904	-0.858
	FEV1/FVC%	0.931	0.745	0.714	-0.624	0.796	0.706	0.652	-0.570
	DLCO%	0.388	0.292	0.288	-0.316	0.447	0.314	0.323	-0.280
	KCO%	0.034	-0.049	-0.048	-0.006	0.115	-0.016	0.007	0.019
	Me ± STD	0.587±0.46	0.488±0.45	0.475±0.44	-0.458±0.38	0.578±0.38	0.486±0.42	0.472±0.39	-0.422±0.38
Males	FEV1%	0.688	0.711	0.703	-0.125	0.658	0.612	0.790	-0.048
	FEV1/FVC%	0.427	0.480	0.567	0.122	0.410	0.479	0.680	-0.109
	DLCO%	0.730	0.677	0.516	-0.091	0.692	0.544	0.732	-0.014
	KCO%	0.260	0.129	0.132	-0.133	0.536	0.376	0.267	0.040
	Me ± SD	0.527±0.22	0.499±0.27	0.480±0.25	-0.057±0.12	0.574±0.13	0.503±0.1	0.617±0.24	-0.033±0.06

RMS = Root Mean Square, H = Rényi entropy, MLZ = Multistate Lempel-Ziv, fmax = Maximum frequency, FEV_1 = forced expiratory volume over one second, FVC = forced vital capacity, FEV_1/FVC = proportion of the forced vital capacity exhaled in the first second, DLco = carbon monoxide diffusing capacity, Kco = carbon monoxide transfer coefficient % ref= percentage regarding the predicted value, Me = mean, SD = standard deviation.

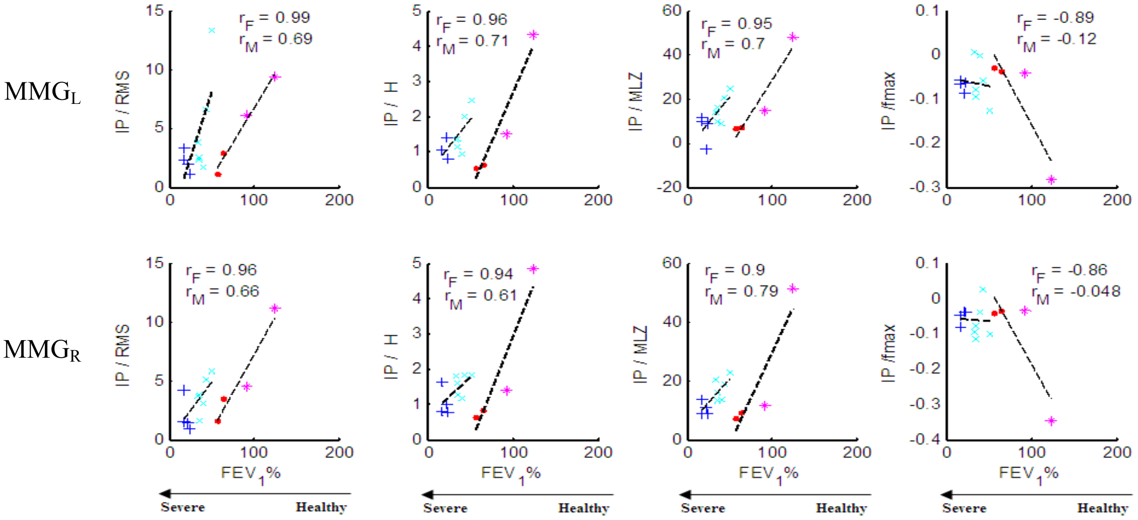

Fig. 1 Example of correlation between forced expiratory volume over one second (FEV$_1$%) and the slope of the lineal regression line obtained between maximal inspiratory pressure and MMG parameters calculated in MMG$_I$ (up) and MMG$_D$ (down) signals. RMS = Root Mean Square, H = Rényi entropy, MLZ = Multistate Lempel-Ziv, fmax = Maximum frequency. r_F (Females) and r_M (Males) = correlation coefficients. Females group: healthy (*) and COPD moderate EPOC (.), and Males group: severe (x) and very severe (+).

results obtained in [9], where only six severe and very severe COPD male patients were analyzed. With increasing of the number of subjects in the males group, the correlation between amplitude of IP$_{max}$ and variations of MMG parameter reported higher means values and lower standard deviation values than reported in the preliminary study [9].

The spirometry parameters correlate better with the respiratory muscles efficiency than the gas exchange parameters. This is more pronounced in males than females. In this case, the slope of the linear regression line between the amplitude variations of IP$_{max}$ and the amplitude variations of RMS parameter reported in females group the highest correlation values in both hemidiafragms. On the other hand, the gas exchange parameters correlate better in males group than females group. This behavior more pronounced in the DLCO% parameter of the MMG$_L$.

The results obtained in this work suggest that the information provided by MMG signals could be useful to evaluate both the effort and the efficiency of respiratory muscles in healthy and COPD subjects.

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