NON-INVASIVE MEASUREMENT OF DIAPHRAGMATIC CONTRACTION TIMING IN DOGS

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Abstract – **The movement of thoracic cage (TM) measured with a piezoelectric contact sensor placed on the costal wall is presented in this work as a new non-invasive technique for diaphragmatic contraction period (CP) monitoring. Relationship between CP estimated with this technique is compared with estimations done with other respiratory signals commonly employed for physiological research studies: diaphragm length measured with sonomicrometry (DL), transdiafragmatic pressure (DP) and respiratory airflow (FL). Specific algorithms were developed to determinate the CP in the four signals. Experiments were performed in three pentotarbital-anesthetized mongrel dogs. Two respiratory tests were studied: spontaneous ventilations (SV) and respiration with an inspiratory load (IL). CP estimated with DL signal was used as reference because this signal is the directly related with the diaphragmatic contraction. Different parameters were estimated for the study of the relationship between CP measured with DL signal and CP measured with TM, FL and DP signals. High relationships were obtained in the IL respiratory test. Lower values were obtained in SV protocol, but the parameters obtained from TM signal correlated better with the ones obtained from DL signal than those from FL and DP signals. Results confirm that it is possible to monitor the diaphragmatic contraction timing with a non-invasive piezoelectric contact sensor.**
Keywords –**Piezoelectric contact sensor, thoracic movement, diaphragm, respiratory monitoring, sonomicrometry, transdiaphragmatic pressure, respiratory airflow**

I. INTRODUCTION

The study of breathing pattern under experimental or clinical conditions requires the development of non-invasive techniques for ventilatory monitoring. Measuring apparatus by itself alters respiratory pattern in conscious and unconscious subjects [1]. Spirometers, flowmeters, face mask, or mouth piece add resistance to breathing. Furthermore, it has been shown that the simple act of breathing through a mouthpiece or a face mask affects tidal volume and respiratory frequency [1,2,3]. At present, the most utilized non-invasive method for continuous quantitative monitoring of breathing pattern is respiratory inductive plethysmography. This technique allows study various breathing pattern parameters such as respiratory frequency, but it is not good enough to measure diaphragmatic contraction period with accuracy.

The purpose of this study is to evaluate a new non-invasive method to study the timing of the diaphragmatic function, using an animal model (dogs). Thus the present study was designed to test whether the use of contact non-invasive piezoelectric sensors, placed on the costal wall of the dogs, could be useful in monitoring the diaphragm contraction period in different respiratory conditions.

In previous works it has been shown that the beginning and the end of diaphragmatic contraction were indicated with inflexion points in the thoracic cage movement signal (TM) acquired with the contact sensor [4,5,6]. In [5] an algorithm was proposed to detect the initial and final instants of contraction in the TM signal. In order to evaluate this technique, the results obtained were compared with those obtained with a second algorithm starting from a direct measure of the diaphragmatic muscle change of length, made by sonomicrometry [7]. In [6] both algorithms were validated, comparing with measures done manually by an expert, obtaining high values of correlation.

In the present work, it has been studied two additional respiratory signals commonly employed for physiological research studies and clinical monitoring in the study of breathing pattern: the respiratory airflow and the transdiaphragmatic pressure.

The goals of the present study are: (1) to develop automatic algorithms to detect the initial and final time of contraction, and therefore contraction period, in the four respiratory signals (diaphragm length, thoracic cage movement, respiratory airflow and transdiaphragmatic pressure); and (2) to study the relationship between the diaphragmatic contraction periods estimated with the different signals and evaluate whether the thoracic movement signal is convenient for diaphragmatic contraction period monitoring.

II. MATERIAL AND METHODS

A. Population and Signal Acquisition

Three mongrel dogs (15-20 kg) were surgically instrumented under general anesthesia via femoral venous catheter with pentobarbital sodium (25 mg/kg). Respiratory flow was recorded with a Fleisch pneumotachograph. Diaphragm length was measured via two piezoelectric crystals (Sonomicrometer, Triton Tech. Inc., m. 120) inserted into the costal diaphragm, as described in [7]. Movement of thoracic cage was recorded by a piezoelectric contact sensor (HP 21050A) placed on the costal wall and fixed to the skin via an elastic band. Transdiaphragmatic pressure was measured in the usual way as the difference between gastric and esophageal pressures, each recorded with the conventional ballon-catheter technique [8,9]. All analog signals were amplified (HP 8802A), filtered and digitized with a 12 bit A/D system at a sampling

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Abstract

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rate of 4 kHz. Inspiratory airflow (FL), diaphragm length (DL), thoracic cage movement (TM) and transdiafragmatic pressure (DP) signals were decimated at a new sampling rate (FL,DL,DP: 100 Hz; TM: 200 Hz) and digital filtered (FL,DL,DP: 4-40 Hz; TM: 8-80 Hz).

Measurements were made at a similar level of anesthesia (corneal reflex just suppressed). All animals were in supine position during the study. Spinal anesthesia was applied as a means to isolate the diaphragmatic function by eliminating the activity of the intercostal muscles. All dogs performed spontaneous ventilations (SV) and respiration with an inspiratory resistive load (IL). In Table I is shown the number of cycles and the duration of the respiratory tests performed by the three dogs.

TABLE I
NUMBER OF CYCLES AND DURATION OF THE RESPIRATORY TESTS

	Spontaneous ventilations		Inspiratory load	
	No. cycles	Duration (s)	No. cycles	Duration (s)
DOG1	40	160	159	400
DOG2	29	140	194	600
DOG3	8	30	46	220

B. Signal Processing Algorithms

One representative experimental record of TM, DL, FL and DP signals is shown in Fig. 1. Furthermore it is presented the integral of the TM signal, and the first derivative of the DL, FL and DP signals.

The integral of TM signal was used for respiratory cycle detection. Specific algorithms were developed to detect the initial contraction time (t_i), the final contraction time (t_f) and, at hence, the contraction period (T_C) in the four studied signals. These algorithms use the TM signal, the first derivative of the FL and DP signals, and the first derivative of the DL signal with the sign reversed. Initial contraction time is detected when these signals reach 10 % of the maximum. In a similar way, final contraction time is detected when the signals reach the 10 % of its minimum. Also we computed contraction period ($T_C = t_f - t_i$).

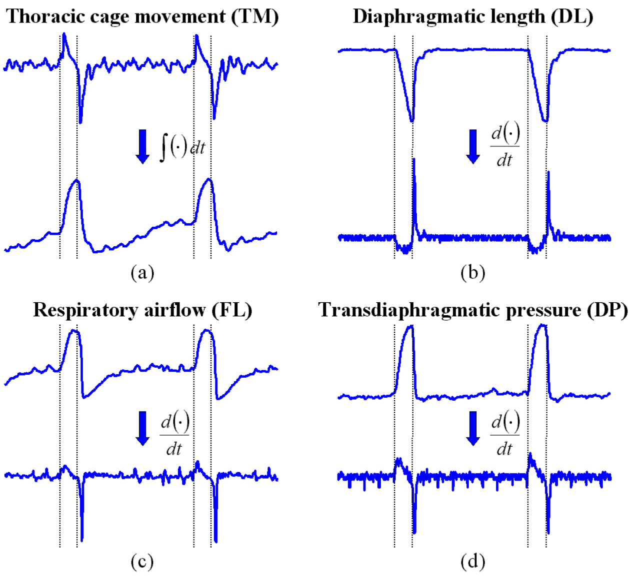

Fig. 1. Morphologies of thoracic cage movement signal and its integral (a), diaphragmatic length (b), respiratory airflow (c) and transdiaphragmatic pressure (d) and their first derivatives. Vertical lines mark initial and final instants of diaphragmatic contraction.

C. Statistical Analysis

DL signal is a direct measure of diaphragm fibers shortening during contraction and furthermore is the most stable of the four studied signals. For this reason it was employed as reference signal, i.e., the results obtained with TM, FL and DP signals were compared with the ones detected in the DL signal.

Differences between contraction periods obtained with DL signal and the other three signals were summarized by the mean (*MEAN*), standard deviation (*STD*), and mean square error (*MSE*).

Relationship between contraction periods of DL and TM signals, DL and FL, and DL and DP were studied by means the Pearson correlation coefficient (*r*), the intraclass correlation coefficient of reliability (or reliability coefficient: *R*) [6,10] and the slope of the linear regression line (*p*).

Unlike the traditional correlation coefficient (*r*), the reliability coefficient (*R*) is directly interpretable as a proportion of variance [10]. The reliability coefficient expresses the relative magnitude among variance of the contraction period (s_{Tc}^2) and variance between methods of detection the contraction period ($s_{methods}^2$):

$$R = \frac{s_{Tc}^{2}}{s_{Tc}^{2} + s_{methods}^{2}} \qquad (1)$$

The estimation of the variance of the contraction period is done using for every respiratory cycle the average of the contraction periods estimated with the different methods of detection. In general, values of *R* below 0.4 or so may be taken to represent poor reliability, values above 0.75 or so correspond to excellent reliability, and values between 0.4 and 0.75 represent fair to good reliability [10].

III. RESULTS

A. Time differences between contraction periods

Differences between contraction period of TM, FL and DP signals ($T_{C\text{-}TM}$, $T_{C\text{-}FL}$ and $T_{C\text{-}DP}$), and contraction period of DL signal ($T_{C\text{-}DL}$) are summarized in Table II. The last row of the table expresses the mean values of the parameters in the six respiratory tests studied.

The mean MEAN error obtained with the TM signal is 34 ms, the mean STD of this error is 23 ms, and the mean MSE is 44 ms. This values are acceptable for the measuring of the contraction period (with a supposed contraction period of one second, an error of 50 ms signifies a five per cent of relative error). Furthermore, the values obtained with the TM signal are very similar with the ones obtained with the FL and DP signals.

TABLE II
MEAN (*MEAN*) STANDARD DEVIATION (*STD*) AND MEAN SQUARE ERROR (*MSE*) OF THE DIFFERENCE BETWEEN CONTRACTION PERIOD MEASURED WITH DIAPHRAGMATIC LENGTH ($T_{C\text{-}DL}$) AND PERIODS MEASURED WITH THORACIC MOVEMENT ($T_{C\text{-}TM}$), RESPIRATORY AIRFLOW ($T_{C\text{-}FL}$) AND TRANSDIAPHRAGMATIC PRESSURE ($T_{C\text{-}DP}$) FOR THE THREE DOGS IN SPONTANEOUS VENTILATIONS (SV) AND INSPIRATORY LOAD (IL) RESPIRATORY TESTS

	$T_{C\text{-}TM}$ - $T_{C\text{-}DL}$		$T_{C\text{-}FL}$ - $T_{C\text{-}DL}$		$T_{C\text{-}DP}$ - $T_{C\text{-}DL}$	
	MEAN ± STD (s)	*MSE (s)*	*MEAN ± STD (s)*	*MSE (s)*	*MEAN ± STD (s)*	*MSE (s)*
Dog 1 (SV)	-0.005 ± 0.030	0.030	-0.020 ± 0.030	0.036	-0.022 ± 0.037	0.043
Dog 2 (SV)	-0.026 ± 0.026	0.037	0.041 ± 0.039	0.057	0.020 ± 0.018	0.027
Dog 3 (SV)	0.030 ± 0.024	0.040	0.003 ± 0.028	0.028	0.015 ± 0.049	0.052
Dog 1 (IL)	-0.086 ± 0.024	0.089	-0.017 ± 0.020	0.026	-0.034 ± 0.017	0.038
Dog 2 (IL)	-0.044 ± 0.019	0.048	0.015 ± 0.045	0.048	-0.008 ± 0.016	0.018
Dog 3 (IL)	0.011 ± 0.015	0.018	0.005 ± 0.018	0.019	-0.039 ± 0.018	0.043
Mean values	0.034 0.023	0.044	0.017 0.030	0.036	0.023 0.026	0.037

TABLE III
CORRELATION COEFFICIENT (*r*), RELIABILITY COEFFICIENT (*R*) AND SLOPE OF THE LINEAR REGRESSION LINE (p) OF THE RELATIONSHIP BETWEEN CONTRACTION PERIOD MEASURED WITH DIAPHRAGMATIC LENGTH ($T_{C\text{-}DL}$) AND PERIODS MEASURED WITH THORACIC MOVEMENT ($T_{C\text{-}TM}$), RESPIRATORY AIRFLOW ($T_{C\text{-}FL}$) AND TRANSDIAPHRAGMATIC PRESSURE ($T_{C\text{-}DP}$) FOR THE THREE DOGS IN SPONTANEOUS VENTILATIONS (SV) AND INSPIRATORY LOAD (IL) RESPIRATORY TESTS

	DL vs. TM			DL vs. FL			DL vs. DP		
	r	*R*	*p*	*r*	*R*	*p*	*r*	*R*	*p*
Dog 1 (SV)	0.6193	0.6189	0.6015	0.5409	0.3912	0.4199	0.3651	0.2302	0.3237
Dog 2 (SV)	0.6905	0.4661	0.8031	0.5111	0.1465	0.7394	0.8498	0.6915	0.9382
Dog 3 (SV)	0.5947	0.2338	0.5514	0.5882	0.6179	0.7103	0.2620	0.2408	0.4579
Dog 1 (IL)	0.9935	0.9145	0.9903	0.9957	0.9924	0.9984	0.9969	0.9843	0.9882
Dog 2 (IL)	0.9653	0.7939	1.0401	0.9136	0.8445	1.3092	0.9754	0.9681	0.9988
Dog 3 (IL)	0.9828	0.9730	0.9383	0.9759	0.9738	1.0118	0.9736	0.8636	0.9869

B. Relationship between contraction periods

Table III shows values of the correlation coefficient (*r*), the reliability coefficient (*R*) and the slope of the linear regression line (*p*) between DL and TM contraction periods, between DL and FL contraction periods, and between DL and DP contraction periods for the three dogs in the SV and IL respiratory tests. Fig.2 shows the corresponding plots of these relationships.

The relationships in the IL respiratory test were linear ($r>0.91$). Furthermore the reliability coefficients indicated a very good reliability in the measures ($R>0.84$) and slopes of the linear regression line were very close to unity (except in the flow of second dog).

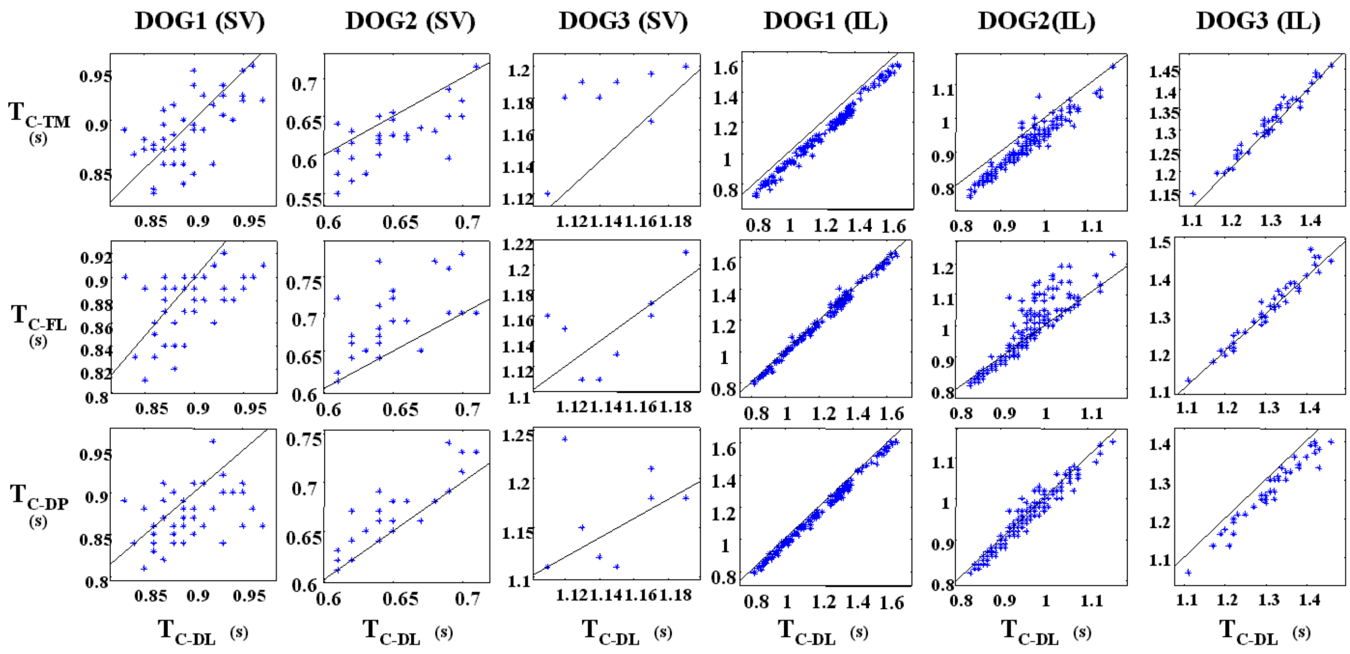

Fig. 2. Contraction period estimated with thoracic movement ($T_{C\text{-}TM}$), respiratory airflow ($T_{C\text{-}FL}$) and transdiaphragmatic pressure ($T_{C\text{-}DP}$) signals versus contraction period estimated with diaphragmatic length signal ($T_{C\text{-}DL}$) for the three dogs in the spontaneous ventilations (SV) and inspiratory load (IL) respiratory tests. Straight black continuous line is the identity function (desired relationship). Each dot represents a respiratory cycle.

In the SV respiratory test results showed a moderate relationship. Correlation coefficients were in general lower than 0.7. Reliability coefficients indicated poor to acceptable reliability in the measure (R among 0.23 and 0.69), and slopes of the linear regression line were not as close to unity as we had desired. However, in general parameters estimated in TM signal were better than estimations in FL and DP signals.

IV. DISCUSSION

In this work algorithms to estimate diaphragmatic contraction period with the TM, DL, FL and DP signals has been developed, and a study of the relationships between diaphragmatic contraction periods estimated with these algorithms has been done.

As it is seen in Fig. 1, the morphologies of the studied signals are similar. Consequently, a good relationship between them is expected; at least, in the diaphragmatic contraction instants detection. This feature is used in this work to elaborate a comparison study of the different signals, to estimate the diaphragmatic contraction period.

The DL signal has been used as reference signal due to its stability, clarity and because is the most directly related with the diaphragmatic contraction.

It has been studied two different respiratory protocols: spontaneous ventilations and respiration with a resistive inspiratory load. High relationship between the different methods for measuring diaphragmatic contraction period have been found in the IL respiratory test. Lower values were found in the SV protocol. These values could have been obtained because the shape of respiratory pattern during the SV respiratory test has usually a lower SNR than the pattern during respiration with the IL test. That produces more errors in the timing detection. Furthermore, there is less variability in the values of contraction period existing in SV respiratory test, and also few respiratory cycles has been studied, as can be seen in Table I.

Usefulness of TM signal for contraction period monitoring can be observed in the example of Fig. 3. It shows the evolution of contraction period detected with DL and TM signals while the third dog performed its IL respiratory test. At the end of the IL tests the dogs reached respiratory fatigue and this condition is highly related with the decreasing of the contraction period. As it is seen in Fig.3, this decreasing of contraction period is easily perceived with both TM and DL signals. Therefore, it seems that TM signal allows non-invasive diaphragmatic contraction period monitoring.

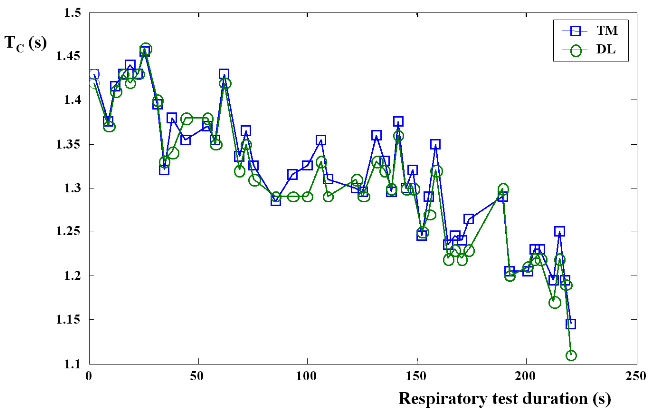

Fig. 3. Evolution of diaphragmatic contraction period estimated with thoracic movement (TM) and diaphragm length (DL) signals during the inspiratory load respiratory test performed by the third dog.

V. CONCLUSIONS

The technique presented in this work provides an indirect method to measure the timing of the diaphragmatic contraction in dogs, using a piezoelectric contact sensor placed on the costal wall. In the future this technique could provide a new method to study the mechanical properties of the diaphragm in humans and will be potentially useful for non-invasive monitoring of respiratory system.

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