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A synchronization system for the analysis of biomedical signals recorded with different devices from mechanically ventilated patients

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Abstract— **Conducting research associated with mechanically ventilated patients often requires the recording of several biomedical signals to dispose of multiple sources of information to perform a robust analysis. This is especially important in the analysis of the relationship between pressure, volume and flow, signals available from mechanical ventilators, and other biopotentials such as the electromyogram of respiratory muscles, intrinsically related with the ventilatory process, but not commonly recorded in the clinical practice. Despite the usefulness of recording signals from multiple sources, few medical devices include the possibility of synchronizing its data with other provided by different biomedical equipment and some may use inaccurate sampling frequencies. Even thought a variant or inaccurate sampling rate does not affect the monitoring of critical patients, it restricts the study of simultaneous related events useful in research of respiratory system activity. In this article a device for temporal synchronization of signals recorded from multiple biomedical devices is described as well as its application in the study of patients undergoing mechanical ventilation with research purposes.**

I. INTRODUCTION

Mechanical ventilation (MV) is a life support technique used in clinical circumstances of deterioration of respiratory function. Nowadays, MV is controlled by means of a wide number of variables such as pressure, volume, flow, the airway resistance and compliance, among others. Even though the respiratory muscles are directly responsible of providing the motive power in the act of breathing [1] [2], a limited number of modern ventilatory modes take into account their activation to provide the ventilatory support, being the Neurally Adjusted Ventilatory Assist (NAVA) the only one available commercially [3]. Other efforts for analyzing the role of respiratory muscles during mechanical ventilation have been carried out, specially in cases of weaning failure [4], [5]. However, all of these initiatives measure the muscular activity by means of invasive techniques. In addition, ventilatory variables must be recorded simultaneously to analyze the interaction between the respiratory muscles activity and other signals of the respiratory system. Our research interest is to analyze the condition of mechanically ventilated patients using a low cost, non-invasive technique such as surface electromyography (sEMG) [6] [7]. Such analysis in conjunction with common ventilatory signals and mechanical ventilation variables will allow the development of novel techniques to support the weaning process and selecting the optimal ventilatory mode. This applications are highly valued in clinical environments such as the Intensive Care Unit (ICU), being the main handicap the lack of medical devices ready to record muscular and ventilatory signals simultaneously. The aim of this paper is to present a system for the synchronization of physiological signals recorded from multiple medical devices with non-completely uniform sampling frequencies.

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II. METHODOLOGY

Currently, a standard procedure to guarantee the synchronization between signals recorded with different devices is not available. Most of the communications protocols implemented by medical devices nowadays are closed, implying that the multiple sensing, processing or analog-to-digital conversion stages involved as well as other configurations are practically unknown to researchers, implying that most signals are not directly available for research purposes. In studies in which functional signals such as EEG, ECG, EMG are compared with pressure or flow signals, a device and a technique that facilitates the synchronization of multiple sources is required.

An electro-pneumatic system for the synchronous recording of respiratory signals by means of multiple devices in patients under mechanical ventilation is presented. The developed approach allows gathering and synchronizing a wider variety of information from the patient, using as many devices as required. In the case presented, the respiratory signals of interest consist of pressure, flow and volume signals, traditional in mechanical ventilation and sEMG of the main respiratory muscles implied in ventilation process, specifically the left and right portions of the costal diaphragm (lEMGdia and rEMGdia, respectively), intercostals (EMGint) and sternocleidomastoid (EMGstrn). The ethic aspects involved in this research have been approved by the ethic committee of La María Hospital (Medellín, Colombia).

A. Recording instrumentation

The ventilatory signals of the patients (pressure, volume and flow) and other ventilatory variables such as resistance of the airways and compliance during inspiration and expiration were acquired from a mechanical ventilator (G5, Hamilton Medical®, Switzerland) using the provided datalogger. The sEMG signals of ventilatory muscles were recorded using a biopotential amplifier device (BAD) with approximately

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known sampling frequency (Mobi6, TMSi®, Netherlands). Besides the inaccurate or variable sampling frequency, the main handicap of the synchronization is the unknowing of the analog to digital converters latency of both devices.

The synchronization proposed technique between different devices is based on the generation and recording of a pattern signal, therefore it is mandatory to the devices involved to have a recording channel available. The G5 ventilator has a channel to record an auxiliary pressure signal unused for ventilatory control and not commonly used for monitoring, while the BAD was properly configured to record an additional monopolar voltage signal. Exporting the ventilatory signals to a PC was possible by means of an application provided by the manufacturer (Hamilton Datalogger, Hamilton Medical®, Switzerland). The BAD was connected to third party software for the storing and visualization of signals (Polybench, Applied Biosignals®, Germany), sent to a PC wirelessly using the Bluetooth protocol. Fig. 1 presents a diagram of the recording devices. The ventilatory signals were sampled at a variable frequency with mean of 9.9 Hz, while the sEMG signals were recorded with an approximately known sampling frequency of 1024 Hz. Neither the accurate sampling frequency nor the time information of the mentioned devices is known.

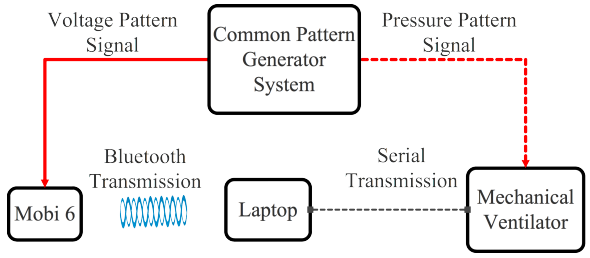

Fig. 1. Schematic diagram of recording configuration.

B. Common pattern generator

Given that both recording systems (i.e., ventilator and BAD) have different sampling frequencies and unknown signal conditioning stages, a continuous time pattern is required instead of a trigger event for synchronization purposes. The basic aspects considered for the electro-pneumatic system named Common Pattern Generator (CPG) design were:

- The CPG system should not interfere with the operation of medical devices for patient monitoring or life support, and the electrical safety of the patient during its use must be guaranteed.
- The CPG should generate a pattern signal consisting of a series of pulses with known temporal characteristics to be recorded by all systems to be synchronized.
- The nature of the signal generated by CPG system should be consistent with the operating features of each medical device (i.e. full scale input range in volts or cmH2O), which should record it seamlessly. This implies that more than one version of the pattern signal must be generated based on the registration systems involved.
- Given that the sampling frequencies of the devices involved in the recording could be inaccurate, the CPG system should record a version of the pattern signal whose sampling frequency is known.

The proposed CPG is a microcontroller-based system and its basic components are depicted in Fig. 2. This device generates three versions of the pattern signal, one for each device recording the signals of interest (i.e., the ventilator and the BAD) and one recorded by the CPG system itself. The version of the pattern signal recorded by the ventilator is a pressure signal generated by a small controlled pump (P54A02R). This pneumatic signal is then converted to an electric version through a pressure sensor (MPX5050GP, Motorola), to be recorded by the BAD. Given that most biopotential amplifiers limit the permissible voltage (in the system used at value of 200 mV), the output of the pressure sensor is attenuated with an operational amplifier (LM358, Analog Devices) in inverse configuration. A non-attenuated version of the voltage pattern signal (i.e., the voltage signal at the output of the pressure sensor) is stored in an SD card included in the system sampled at an accurate frequency of 1024 Hz to be used as the synchronization guide. In order to guarantee electrical safety the CPG includes isolation amplifiers (AD210, Analog Devices) and operates on 9 V with two parallel batteries.

The CPG connected to the ventilator and to the BAD allows acquiring three signals. A plot of these pattern signals is showed in Fig. 3, corresponding to a 35 seconds long recording based on the known characteristics of the pattern signal recorded by the CPG system. The CPG operates during the entire recording process assuring that the pattern signal is permanently generated and available to both connected devices.

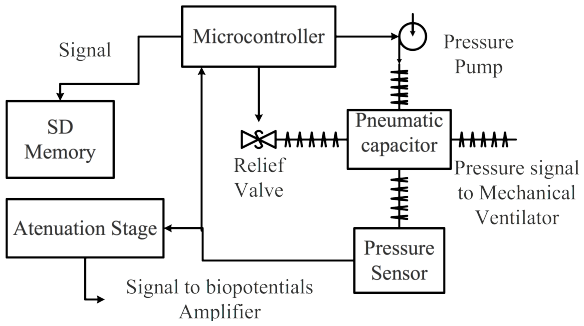

Fig. 2. Schematic diagram of the components of the Common Pattern Generator Signal.

C. Synchronization algorithm

The synchronization of the set of respiratory signals corresponding to each recording device is performed once the registration process is over. Ideally, when all the sampling frequencies are known and accurate, the synchronization process reduces to finding the sample corresponding to the first rising edge of each pattern signal associated to a recording device. For a given pattern signal, once this sample is located, the previous samples are discarded on all the signals

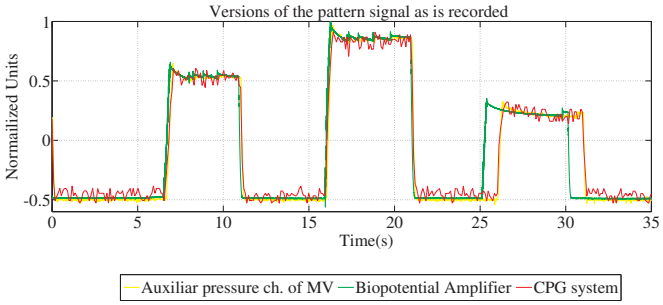

Fig. 3. Different versions of the pattern signal recorded by the involved devices.

recorded by the given device. This process is replicated for each device using the corresponding pattern signal. After deleting the segments not matching temporally, all signals are resampled to a given sampling frequency. Although this process is the simplest possible, is generally useless because the sampling frequencies of some commercial devices are not always accurate.

For the cases where the sampling frequency of one device is unknown or inaccurate, the pattern signal generated by the CPG is used to resample the signals of all devices to a fixed frequency, commonly to the frecuency of the pattern signal recorded by the CPG system. First, the procedure described for the case where all the sampling frequencies of the recording devices are known is implemented to discard the initial nonmatching segments. If there are devices whose sampling frequency is variable but accurate, an interpolation with the time vector of the pattern signal of the CPG system is implemented. In the case of interest, just the signals of the G5 ventilator met this criterion. Then all the rising edges of both versions of the pattern signal are located, and epochs are defined as the segments located between two consecutive rising edges. In order to determine the number of missing (or exceeding) samples in a give epoch of the signals recorded with the device with unknown frequency the correlation function between the pattern signal of the given device and the pattern signal of the CPG system (i.e. the signal with known and accurate sampling frequency) is computed:

$$\hat{R}_{xy}(k) = \frac{1}{N} \sum_{n=0}^{N-1-k} y(n+k)x(n) \qquad k = 0, 1, \ldots, N-1 \tag{1}$$

Where y_n represents the epoch of the signal to be synchronized and x_n the corresponding epoch of pattern signal recorded by the CPG system, n is the sample index, k is the lag index and N is the total number of samples.

An example of how the correlation is computed is shown in Fig 4. Once the number of samples to be inserted or deleted in the signals of the device of unknown or inaccurate sampling frequency is known, the correction is applied, i.e., samples are inserted or removed depending on the resulting lags after the computation of the correlation function. Samples are inserted or removed sequentially in the previous epoch of the one being analyzed, at pseudo random positions. When samples must be inserted to perform the correction, an interpolation process by means of an spline algorithm is implemented. Once the correlation for the current epoch is calculated and the correction has been made on precedent epoch, the window is displaced and initiated on the sample corresponding to the next rising edge of the pattern signal and the process is repeated until the last rising edge is reached.

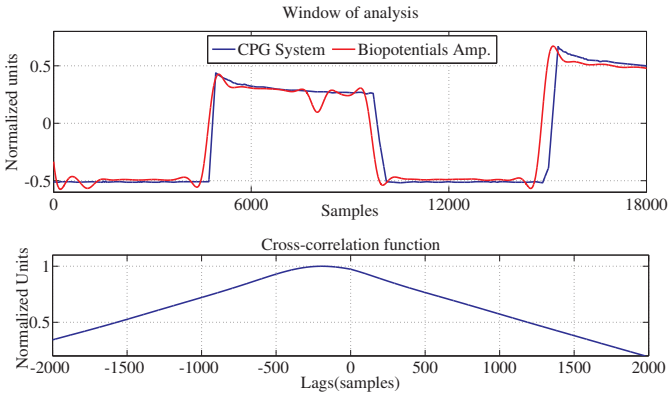

Fig. 4. Calculation of the cross correlation function on a particular window as part of the synchronization process. The number of lags and its sign indicates the number of samples to be removed (if negative) or inserted (when positive).

A criterion that precludes the application of the synchronization process proposed is that the number of lags presented by any signal to be resampled is above the 5% of the number of samples present in the window of analysis, even though this criterion can be omitted if the time characteristics of the signals are known.

D. Validation of synchronization process

The resampling processing described, must not alter the statistical characteristics of the signals, otherwise any posterior analysis would be invalid. In order to validate the method, the statistical characteristics of a set of ventilatory and muscular signals are analyzed before and after its application to a set of signals through the Kolmogorov Smirnov test for two independent samples [8], proper in cases of probability density functions different to normal like is the case.

III. RESULTS

The described technique was applied for the synchronization of ventilatory signals recorded from mechanical ventilated patients in the ICU of La Maria Hospital (Medellń, Colombia). None of the sampling frequencies of the devices used was known accurate, being the version recorded by the CPG system the only one version of the pattern signal whose sampling frequency was known and accurate.

Fig. 5a shows the pattern signal as recorded by the CPG and the BAD and the samples to be inserted or removed from the signals recorded by the biopotential amplifier. From the figure can be inferred that the sampling frequency of the device is actually close to the assumed sampling frequency

of 1024 Hz (according to the information given by the manufacturer), but is evident that slight variations occur. Fig. 5b presents the same patterns signals after synchronization. The resampling frequency selected was the sampling frequency of the pattern signal stored by CPG system, i.e., 1024 Hz.

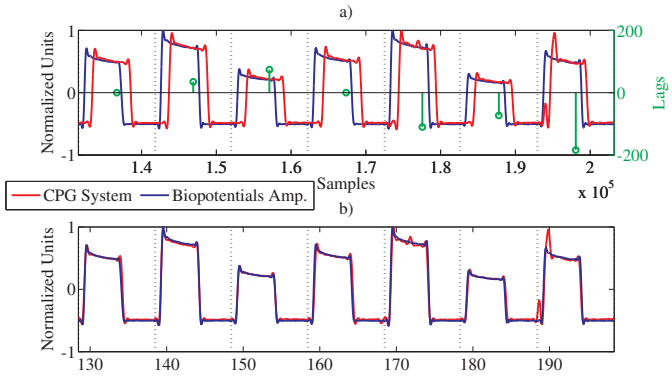

Fig. 5. Graphical representation of the synchronization process. a) Represents the state of the signals before the synchronization process. The green stems represent the samples to be inserted or removed on a given window (window limits are represented with black dotted lines). b) Pattern signals after the synchronization process.

Table 1 presents Kolmogorov Smirnov test results [8] evaluated over all epochs of muscular and ventilator signals after and before the synchronization. No significant differences were found between corrected and original epochs, which means that the correction does not modify the statistical characteristics of the signal. In the case of ventilatory signals the p-value is the highest possible because the sampling frequency of the mechanical ventilator is accurate and none correction was required in contrast to the signals recorded by the biopotential amplifier device.

TABLE I

EVALUATION OF DIFFERENCES BETWEEN BIOMEDICAL SIGNAL BEFORE AND AFTER CORRECTION

Biomedical signal	**p-value** ($\mu \pm \sigma$)
Flow	1 ± 0
Airway pressure	1 ± 0
Volume	1 ± 0
Left Diaphragm sEMG	0.919 ± 0.194
Right Diaphragm sEMG	0.943 ± 0.109
Intercostal sEMG	0.935 ± 0.131
Sternocleidomastoid sEMG	0.890 ± 0.273

Once the set of signals are synchronized they are ready to be processed and analyzed by any technique. A set of synchronized signals is shown in Fig. 6. The plot on the top is the flow signal recorded by the mechanical ventilator, the middle plot is the sEMG of intercostal muscle and the bottom plot is the sEMG of the diaphragm muscle during controlled mandatory ventilation. Although the mechanical ventilator is controlling the ventilatory cycle, the patient was performing ventilatory efforts not only during inspiratory phases but also during expiratory ones as can be inferred from the sEMG of the intercostal and diaphragm muscles and verified inspecting the slight deflections present on the flow signal before the mandatory ventilations triggered by the patient.

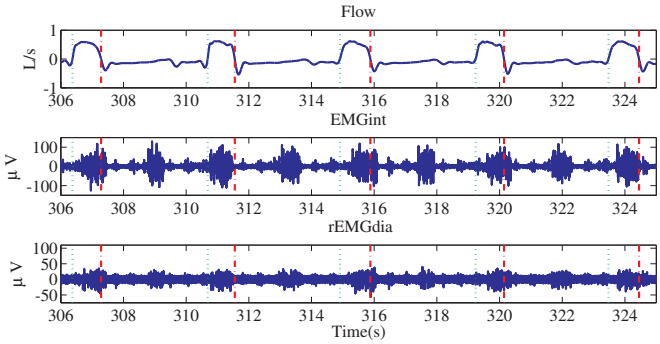

Fig. 6. Set of signals after the synchronization process.

IV. CONCLUSION

A technique for the synchronization of signals recorded with devices with different, unknown or inaccurate sampling frequencies has been presented and validated statistically. This technique permits the analysis of patients connected to vital support devices in an ICU, where only commercial, certified biomedical devices can be used and whose sampling frequencies are commonly unknown or inaccurate. Although variation or inaccuracy of the sampling frequency does not affect the monitoring of critical patients, this can restrict the study of simultaneously related events by means of multiple medical equipment.

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