A noncontact instrument based on ultrasound for the evaluation of asynchronous thoracoabdominal movement in respiratory diseases

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Abstract. Several respiratory diseases, as well as surgical procedures, may introduce changes in the thoracoabdominal movement. Non-intrusive techniques have the potential to simplify the exam of these patients. This work describes the design of a noncontact system able to evaluate changes in the thoracic and abdominal movement. Two ultrasonic transducers were used, providing analogue signals to a virtual instrument. In vitro evaluations using a flat surface in motion showed small errors in the evaluation of the asynchrony (∆φ=6.8°), and the relative contributions of the abdominal (CRAb) and thoracic (CRTx) compartments (CRAb=1.3%; CRTx=-1.3%). In vivo tests in normal subjects simulating abnormal conditions resulted in higher values of asynchrony (p<0.005), and differences in the CRAb (p<0.02) and CRTx (p<0.005). We concluded that the system is able to detect both, normal breathing and modifications associated with simulated respiratory disease.

1. Introduction

The respiratory process causes synchronized movements in the chest wall and abdomen. However, various respiratory diseases as well as surgical procedures cause changes in the timing of these movements. This asynchrony is usually classified into: (1) a delay between the movement of the chest (Ch) and the abdomen (Ab) during expansion or contraction and (2); a paradoxical movement, consisting of opposite movements between the chest and the abdomen, also known as full asynchrony [1, 2]. The diseases that cause changes in thoracoabdominal movement include asthma and chronic obstructive pulmonary disease (COPD).

In a previous study on healthy individuals and patients with COPD [3] we observed that in some individuals, the straps used to monitor respiratory movements could cause small changes in the normal ventilation pattern due to tactile stimulation as well as restriction due to the positioning of the straps. These transducers are obtrusive because they need to be adapted to the patient's body and may limit the application of the system in patients with respiratory diseases in an advanced state.

Using optical principles, Uhlig et al. [4] obtained promising results in the development of a monitor suitable for the evaluation of spontaneous breathing in adults and of a mechanical model that

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simulated high-frequency breathing. Other studies have shown promising results using systems based on optical principles [5, 6], including 3D movement analysis [7] and radar-based systems [8-10].

A promising alternative for the development of non-intrusive systems involves the use of ultrasound-based methods [11, 12]. The use of these transducers is suitable because the signals are easily generated and detected, the wavelength is relatively small compared with the movement of the chest and abdomen, and the low energy level does not negatively affect the monitored individuals.

This study describes the development of an entirely non-intrusive system based on ultrasonic transducers.

2. Materials and Methods

2.1. System development

2.1.1. Hardware design. Figure 1 depicts a simplified diagram of the instrument and transducers positioning. Two ultrasonic transducers (model 18-11117, Sick Automation Inc., Minneapolis, USA) were used [13]. The signals coming from the transducers were associated with a DC level generated from the positioning of the participant. Therefore, the first processing block consisted of a high-pass filter (23 mHz, first order). After that, we observed the first amplification stage with a gain of 2. The resulting signal was adapted to a second high-pass filter (23 mHz, first order) and an amplifier (gain of 455). The signal was further processed by a low-pass filter (Butterworth, fourth order, 1 Hz) to remove external noise and prevent aliasing.

The two position signals were adapted to a data acquisition module (NI 6008, National Instruments, Austin, Texas) with a resolution of 12 bits, four channels, and a maximum sampling frequency (Fs) of 10 kHz. The Fs value used in this study was 196 Hz [3].

Figure 1: Simplified block diagram of the instrument. HPF = high-pass filter; A = amplifier and LPF = low-pass filter.

2.1.2. Software design. The asynchrony between the respiratory movements of the chest and abdomen is generally evaluated by analysing the phase difference (Δφ) between the signals obtained in these two compartments [14, 15]. This phase difference reflects the delay between excursions of the chest and abdomen. When the two compartments move in perfect synchrony, Δφ=0°. With increasing asynchrony, Δφ increases to a maximum of 180°, which corresponds to the point at which the compartments are completely out of phase. Analysis of the Lissajous curves is the method traditionally used for obtaining Δφ [14]. However, this approach assumes that the excursions of the chest and abdomen are sine waves. In practice, these excursions are irregular in healthy individuals and tend to be more irregular in patients, which may introduce problems with these measurements [14]. A method that uses cross-correlation [15, 16] has been suggested for the analysis of thoracoabdominal asynchrony. In this particular application, this method presents significant advantages since it is independent of the waveforms and is robust in the presence of noise. In this study, this method was implemented using the subroutines available in LabVIEW 8.2 environment (National Instruments, Austin, TX).

2.2. System evaluation

2.2.1. In vitro tests. Before using the system in humans, its proper functioning was evaluated using a mechanical system that realistically simulated normal thoracoabdominal movement. To this end, we
used a vibrating platform, which consisted of an oscillator connected to a DC-coupled amplifier, which in turn was connected to a loudspeaker (Arlen, 12 inches, Subcompact) that produced the desired movements. The system was tested over a moving range of approximately 2 mm using a sinusoidal signal of 0.3 Hz.

2.2.2. In vivo tests in healthy individuals during normal spontaneous respiration and simulated asynchronous conditions. These studies were conducted in 12 healthy subjects with no history of respiratory disease or smoking (mean age 31.0 ± 9.0 years, mean height 1.70 ± 0.09 m; mean weight 72.3 ± 13.6 kg). The volunteers were asked to perform 20 s analyses under four conditions: (1) normal breathing; (2) breathing primarily via the abdomen; (3) breathing primarily via the chest; and (4) in simulated asynchrony. The results are presented as the mean ± standard deviation. The results were compared using the Wilcoxon test. The protocol followed the guidelines of the Helsinki Declaration and Brazilian National Health Council Resolution No. 196/96 and was approved by the Research Ethics Committee of Pedro Ernesto University Hospital. Before the examinations, all subjects were fully informed about the content of the tests and signed a consent form.

3. Results

3.1. System development

Figure 2 illustrates the system and its use. The program consisted of three main modules, which were presented in a tab control structure. The first tab (Figure 3A) was dedicated to patient data (name, age, height, and weight) and the visual analysis of the signals of the respiratory movements measured during the test.

![Figure 2: Photo illustrating the developed system and its use.](image)

The second tab (Figure 3B) automatically calculated the mean peak and valley values of the abdominal movements (Ab) and thoracic movements (Tx) and the relative contribution of the abdomen (RCAb) and thorax (RCTx) to the total movement (TM = Ab + Tx) of the respiratory system (RCAb = 100% Ab/TM and RCTx = 100%Tx/TM). A graphic representation of the cross-correlation between the signals of the abdominal and thoracic movements and the Δφ value are shown in the second tab.

![Figure 3: Frontal panels of the software modules associated with data acquisition (A) and cross-correlation and asynchrony evaluation (B).](image)
The final test result was obtained by averaging the three partial tests. After each partial test, the instrument allowed the researcher to save the data to an ASCII file for later visualization. The program allows the averaging of the measurements obtained in each partial test and saving the final data in an ASCII file.

3.2. System evaluation

3.2.1. In vitro tests. Figure 4 shows the in vitro test results. The asynchrony observed was small ($\Delta \phi = 6.8^\circ$). Similarly, the error ($\varepsilon$) in the assessment of the contribution of each compartment was small ($\varepsilon_{RCTx} = -1.3\%$ and $\varepsilon_{RCAb} = 1.3\%$).

3.2.2. In vivo tests in healthy individuals during normal spontaneous respiration and simulated asynchronous conditions. Figure 5 shows the typical plots of the movements measured in the chest and abdomen of a healthy individual during spontaneous breathing and during abnormal movement simulation. Figure 6 describes the analysis of the abdominal (A) and thoracic (B) relative contributions during spontaneous thoracic and abdominal ventilation. Note the phase difference observed during the simulation of asynchrony (C).

4. Discussion

The assessment of asynchronous respiratory movements is usually performed using straps with transducers around the chest and abdomen. However, these measurements can affect the pattern of the chest and abdominal movement [17, 18]. The system proposed in this study eliminated the need to adapt transducers to the patient.
During the initial phase of in vitro testing (Figure 4), errors smaller than 7° were observed. The theoretical values of RCTx and RCAb on in vitro testing were 50%. In practice, these tests presented errors smaller than 2.0% (Figure 4). Therefore, the cited values are appropriate for the target application.

The low Δφ values observed in healthy individuals indicate the presence of synchronous movements between the chest and abdomen (Figure 5C). These results, as well as the RCAb and RCTx values found in healthy individuals (Figure 5), are consistent with the results of a previous study from our group using piezoelectric straps [3] and of other studies [2, 19, 20]. The relative contribution of simulated predominantly abdominal breathing (Figure 6A) was higher than under conditions of spontaneous breathing, indicating that the system properly identified this movement. Moreover, the system suitably identified the movement that simulated predominantly chest breathing (Figure 6B). The Δφ values obtained by simulating asynchrony (Δφ = 113.9±47.1°, Figure 6C) were higher than the values obtained during spontaneous breathing (Δφ = 13.9±12.5°; p <0.001), indicating that the system properly identified this movement. Therefore, the description of the changes in the respiratory movements provided by our system are in close agreement with the physiological foundations involved in breathing, [19, 20] and the simulated abnormal respiratory movements were properly identified by the proposed system.

Conclusion & future work

A new instrument that allows a non-intrusive analysis of the respiratory system movement was developed. The applications of the system in a mechanical model and normal individuals simulating respiratory movement abnormalities showed results in close agreement with a literature, as well as with the physiological principles involved. The system has high potential to contribute to the improvement of the analysis of alterations due to respiratory diseases or associated to rehabilitation procedures. The next phases of this project include its use in the evaluation of patients with different respiratory diseases attended at our University Hospital and the development of a three dimensional version of the instrument to produce images associated with respiratory movements.

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