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Validation of Respiratory Signal Derived from Suprasternal Notch Acceleration for Sleep Apnea Detection

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Abstract— **This study evaluates the respiration signal derived from an accelerometer mounted on the suprasternal notch in three body positions and three respiration types simulating normal sleep conditions. The Acceleration Derived Respiratory signal (ADR) is compared with single strain gauge belt and a standard spirometry signal taken as reference. The results demonstrate the potential of ADR as a simple, low cost and unintrusive method of screening breath disorders such as obstructive sleep apnea/hypopnea.**

I. INTRODUCTION

Precise monitoring of respiratory components is of great interest in detection of breath disorders such as Obstructive Sleep Apnea/Hypopnea (OSA/H). Monitoring of the total volume of air entering the lungs and its rate is usually achieved by having a subject breathe through a mouthpiece or face mask attached to a pneumotachygraph or a spirometer. In spite of their accuracy, these methods alter the natural breathing pattern of subjects and often induce significant discomfort to the subject. Therefore, these methods are not preferred for continuous or ambulatory monitoring of respiratory components. In overnight full-channel Polysomnography (PSG), the gold standard for detecting sleep apnea, the nasal and oral airflow are measured using pressure transducers and/or thermocouples, fitted in or near the nostrils [1]. Besides inducing discomfort to the subjects, this method may also produce false positives, as some patients open and close their mouth while obstructive apneas occur, inducing air flow that does not reach the lungs. The pressure transducer and thermocouple will detect this diminished airflow and the respiratory event may be falsely identified as a period of reduced airflow instead of an obstructive apnea.

In standard PSG, respiratory efforts, i.e. the movements of the rib cage and the abdomen, are also measured in concert with nasal/oral airflow by the use of dual strain-gauge respirometers (SGR) [1]. Double belts detect both the diaphragm and intercostal muscle induced breaths. Considerable variance in results may be introduced by inconsistent placement or tension of the strain-gauge belts, and variations in the chest size. Therefore, the use of respirometry belts requires laborious and complex calibration procedure.

Alternative methods for continuous or ambulatory monitoring of breath exist, where the rate and volume are extracted from other signals. The ECG Derived Respiratory (EDR) [2] and the thoracic impedance derived respiratory signal [3], [4] are categorized as such. These methods are not free from false positives as the extracted respiratory signal is very dependent on the thoracic movement. In some cases of OSA the respiratory efforts are present, while there is no air entering the airways or lungs. Another indirect estimation of respiratory volume and rate is based on measurements of tracheal breath sounds. As much as it is an efficient method for detecting deep breathing, low breath sound amplitude (e.g. breathing during sleep) does not exceed the background noise and the relationship between the sound amplitude and air flow is very difficult to detect [5]. In a recent study [6], respiratory rate has been extracted from an accelerometer fixed on suprasternal notch of subjects resting supine. The results show that the respiratory rates calculated from the accelerometer signal are very close to those extracted from a thermistor. However, all measurements were limited to the supine position, which hampers the generality of the findings.

The current respirometry measurement methods induce a tradeoff between accuracy and intrusiveness. It is especially challenging in measuring breathing activity in sleep conditions, where subject must remain comfortable and the breathing patterns must not be affected to maintain representative results. To this end, in this study we validate the respiratory components derived from suprasternal acceleration measurement (ADR) in various situations simulating normal sleep conditions. We demonstrate that the use of a small MEMS accelerometer can lead to precise and unobtrusive evaluation of both breath rate and flow waveform. We selected the suprasternal notch for accelerometer placement, opposed to Xiphoid [7], to measure the airflow in the upper airway instead of thoracic or abdominal movements. This choice has been made based on the fact that in some cases of breathing disorders, such as OSA, there are thoracic and abdominal efforts (movements) while there is no airflow in the upper airway. To assess the validity of suprasternal notch Acceleration Derived Respiratory (ADR), we compared it with standard pressure spirometry and Strain Gauge Respirometry (SGR). Results were obtained from 9 healthy adult subjects in 3 sleep positions (supine, prone, left side) for deep, normal and shallow breathing (9 datasets per subject). Finally, we discuss the possible advantages of using ADR as a method of screening sleep disorders during sleep.

II. MATERIALS AND METHOD

A. Participants

The participants of this study were 7 men and 2 women aged 27 to 35, with no history of cardiopulmonary disorders.

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B. Test Setup

The dataset of this study was acquired at CiBER lab, Simon Fraser University. The data acquisition involved measurement of spirometry, Strain Gauge Respirometry (SGR), acceleration (three axis of measurement) and ECG. The spirometric components of respiration were obtained by SPR-BTA spirometer (Vernier Software & Technology, Beaverton, OR) designed to make human respiratory measurements at rest and during moderate activity. The SGR components were recorded using a strain gauge transducer (BioPac Systems Canada Inc, Montreal, QC) mounted on an elastic belt that measures the changes in thoracic circumference. The belt was attached on the lower part of the subject's rib cage to account for both thoracic and abdominal breathing. The acceleration signal was acquired with a miniature ADXL335z three-axis MEMS accelerometer (Analog Devices Inc, Norwood, MA). The accelerometer was mounted in the suprasternal notch using a double sided polyurethane foam tape (3M, Maplewood, MN) and further secured using an over-the-top single sided paper tape. Despite the fact that the proposed method accounts for both nasal and oral breathing, the spirometry signal used as reference measures oral breathing only. Therefore, a nose clip was used to prevent nasal breathing during recordings. Data acquisition was performed with a data acquisition system NI9205 (National Instruments, Austin, TX). Finally, data storage and processing was performed on a personal computer running a custom built LabVIEW Virtual Instrument (VI).

C. Procedure

The experimental session for each subject lasted for approximately 30 min. The experiment consisted of 9 different conditions, each of which had 1 min duration. Three different positions were used (supine, prone and left side) simulating normal sleep styles and three breath types (deep, normal, shallow). A brief pause was introduced between each change of conditions to allow patient to rest and relax. The subject was instructed which position to take and which breath type to use before each recording session.

III. Data Analysis and Processing

Five signals were acquired using the procedure described above. Each sampled at 8 bit precision and 2000 Hz sampling rate and processed in 1 min segments: SGR, spirometry, and three axis of acceleration (x, y and z). The spirometry and SGR signals were filtered through an 8th order Butterworth bandpass filter with cut-off frequencies 0.1 Hz and 1 Hz.

A. Acceleration Derived Respiratory (ADR)

After removing the DC level, the x, y and z signals were passed through an 8th order Butterworth low-pass filter with a cut-off frequency of 1 Hz, in order to remove noise and information out of the band of interest. The acceleration vector computed using the three acceleration axes constitutes the ADR.

TABLE I

Across subject mean and standard deviation (σ) of the breathing rate for the requested patterns.

	Deep	Normal	Shallow
Mean	13.5	16.5	39.7
σ	4.3	5.2	30.3

B. Validity of ADR against spirometry

Validity of the ADR signal against spirometry was assessed using the Pearson's temporal correlation function (similarity of waveform morphology) and the corresponding breathing rates.

C. Validity of SGR against spirometry

Since the spirometry signal shows the flow rate, we applied an integration function to it to obtain the respiratory volume. The signal was then detrended using a 4th order polynominal curve-fitting method. Validity of the SGR signal against spirometry was assessed by the same methods as described above for validating ADR against spirometry.

D. Respiratory rate

Counting method suggested by Schaffer et al. [8] was used to evaluate the respiratory rate. For every segment 1 minute segment, algorithm was applied to ADR, SGR and spirometry to obtain a mean respiratory rate. The relative error was computed for each method (ADR and SGR) against spirometry for each subject and condition giving 81 distinct results [9].

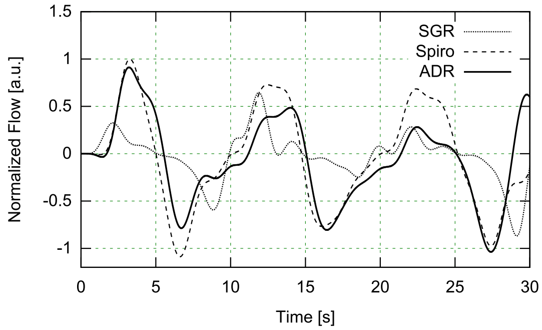
IV. Results

A. Breathing patterns

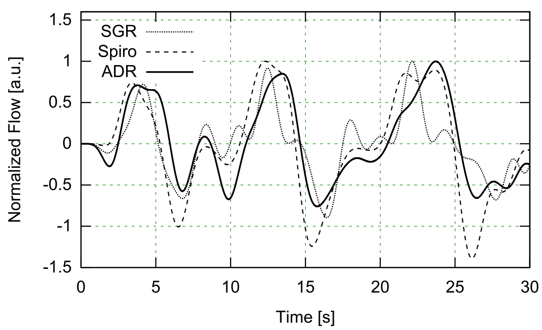
During the test, subjects were asked to breathe in deep, normally, and shallow manner. In the shallow breath, subjects were asked to use mostly their diaphragm for breathing. Obviously, each subject demonstrated a different breathing rate for each breathing pattern. Table I presents the mean and standard deviation of breath rate for each pattern estimated for spirometry for all subjects and all positions. It can be seen that standard deviation in the shallow breath is very high, meaning that subjects interpreted the required speed of shallow breathing differently.

B. Signal Correlation

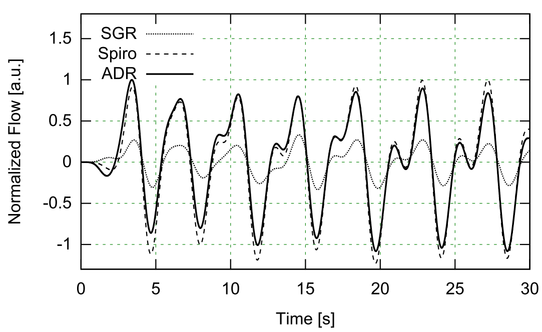
Figure 1 shows 30 second segments of breath signals obtained with the three measurement methods in the side position in three breath patterns. As illustrated in these figures, ADR shows the closest correspondence to the spirometric measurements. The mean value of the correlation coefficient between ADR and spirometry for all subjects and conditions is 0.88 (σ = 0.09) and 0.68 (σ = 0.21) for SGR. Figure 2 presents the cross patient mean correlation coefficient values and standard deviations for different positions and breath patterns for ADR and spirometry.



(a) Deep breathing



(b) Normal breathing



(c) Shallow breathing

Fig. 1. Examples of normalized flow rates for the three breath patterns used it this study acquired with standard spirometry (Spiro), SGR, and ADR.

C. Breath Rate

Using the method described in the previous section, average breath rate was extracted from each 60 second segment for the 9 subjects and the 9 breath conditions (81 independent values per method). Bland Altman diagrams [9] for the respiratory rates obtained from ADR and SGR signals, relative to spirometry, are shown in Figures 3(a) and 3(b) respectively. The bias values are 0.042 (95% confidence levels: upper 0.74, lower -0.65) for ADR and 0.381 (95% confidence levels: upper 3.81, lower -3.046) for SGR.

Table II summarizes the mean values of the absolute value of the relative error of breathing rates obtained from the ADR and SGR signals relative to breath rates obtained from the spirometry signals in the three different postures across all subjects. The overall relative error for all subjects and conditions is about 1.55% for ADR and 4.9% for SGR.

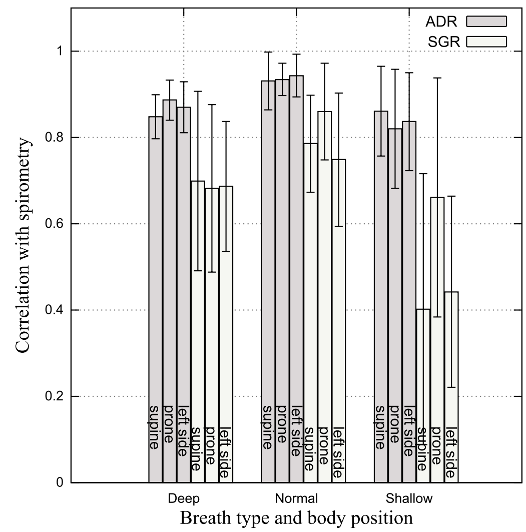


Fig. 2. Correlation between ADR and SGR relative to spirometry

TABLE II

THE ABSOLUTE RELATIVE ERROR OF BREATHING RATES OBTAINED FOR ADR AND SGR RELATIVE TO SPIROMETRY.

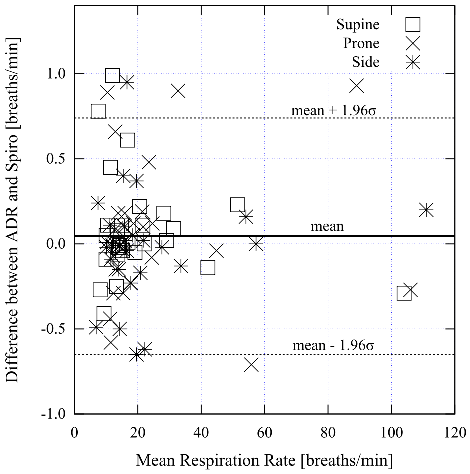
Method	Suping	Prone	Left side	Overall
ADR	1.61%	1.63%	1.40%	1.55%
SGR	3.88%	4.27%	6.61%	4.9%

V. DISCUSSION

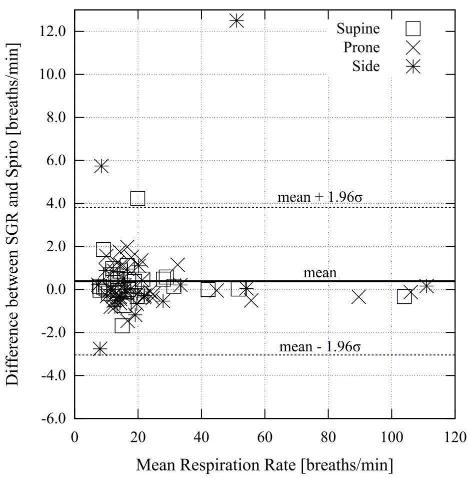
The present results demonstrate that the Accelerometer Derived Respiratory (ADR) can provide a more accurate measure of respiration than the standard strain gauge belt in common sleeping positions. In respect to waveform morphology, ADR is strongly correlated with spirometry while the correlation between SGR and spirometry is below 70%.

The results shown in Fig. 2 show that the ADR method performs well in all body positions and breathing types, with only slightly higher standard deviation for the shallow breath. On the other hand, SGR not only presents lower correlation levels with spirometry overall, but also fails in representing the shallow breath patterns. In the shallow breath style, subjects were mostly using their diaphragm. Therefore, the chest mounted belt was not a good measurement method. Application of two measurement belts with one on the diaphragm would improve SGR results, but it would also greatly complicate the setup. The fact that ADR produces good results for both thorax and diaphragm induced respiration shows its great usefulness as a simple, unobtrusive and low cost surrogate to SGR in monitoring breath in sleep conditions. Considering the relative error of breath rates, ADR shows better results again. For every position, the relative error of breath rates is considerably lower than the one obtained from SGR.

An additional finding of this study is that there is a consistency between the results obtained with ADR in different



(a) ADR derived breath rate



(b) SGR derived breath rate

Fig. 3. Bland Altman diagrams presenting the difference between the values of the breath rate calculated from the ADR (a) and SGR (b) relative to spirometry versus the mean values of the breath rate obtained from the two compared methods.

positions and breath types. On the other hand, the results obtained with SGR are much more scattered, as they are very dependent on the actual place the belt is fastened and its tension. For instance, the relative error of breathing rate obtained with SGR in left side position is about twice of the one measured in prone position. This shows that the accuracy of ADR is less sensitive to body position making it a more reliable method in applications where various postures and breath conditions are expected, such asg during sleep.

Furthermore, given the relation of respiration representation using both SGR and ADR, knowledge of the position of the subject during recording can help in improving the results. As the MEMS accelerometer used in the ADR method can provide both the AC and DC (gravity) acceleration values, the body position can be obtained from the ADR method with no hardware overhead. Compared with results obtained with phonospirometry [5] which are strongly dependent on the type of breathing and the background sounds, the ADR is more robust.

The potential limitation of the current study is that ADR is potentially more prone to movement artifacts than SGR. Finally, besides extracting the respiratory components from the accelerometer signal, there are algorithms allowing extraction the heart activity components from the accelerometer signal [6] [10]. This possibility of acquiring both respiratory and heart activity information from one device gives more credit to accelerometer-based approaches as a simple and cost effective solution for monitoring OSA/H.

VI. Conclusions

We have presented a simple and unobtrusive method for monitoring breath activity in common sleep conditions. We extracted the respiratory components from a 3-axis accelerometer mounted on the suprasternal notch. Experimental study was performed on nine healthy subjects to evaluate the performance of the proposed method in three sleep positions (supine, prone, left side) and three breath types (deep, normal, shallow). In order to validate the proposed ADR method, we compared the derived respirometry signals against the spirometry and compared the results with standard strain gauge belt respirometry (SGR). In contrast to SGR, a very high correlation was found between ADR and spirometry in all conditions. Furthermore, the overall error between the respiratory rates obtained from ADR and spirometry is very low at 1.5% compared with 4.9% for SGR. In the future, the proposed method will be evaluated in overnight recordings on subjects with OSA/H.

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