Sleep Apnea Screening with a Contact-Free Under-the-Mattress Sensor

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Abstract

Sleep apnea is a highly prevalent yet under-diagnosed condition. This study tested a novel algorithm for sleep apnea screening with a contact-free system based on a piezo-electric sensor (PE system – EarlySense Ltd). The study population included 96 subjects who were referred to a sleep study, and underwent a full overnight polysomnography (PSG) in a sleep lab. 16 participants were diagnosed with severe sleep apnea, 18 with moderate, 30 with mild and 32 with no sleep apnea. All subjects were simultaneously measured with the PE system. Respiration waveform was analyzed to extract time and frequency domain features and calculated an internal index for the number of apnea/hypopnea events. It also used an algorithm for sleep wake detection which is described elsewhere. Based on the internal apnea index and the duration of sleep, the system classified the subjects into two groups: one above and one below an Apnea-Hypopnea-Index (AHI) of 15. The classification was compared to a PSG classification of a blinded sleep expert.

The novel algorithm detected moderate-to-severe sleep apnea patients with sensitivity of 88% (100% of the severe sleep apnea patients, and 78% of moderate sleep apnea), specificity of 89%, and positive predictive value (PPV) of 81%. These results together with the convenience of being contact-free make the PE system, with the novel algorithm, suitable for apnea screening at home or hospital setups. It may also be usable for long-term monitoring.

1. Introduction

Obstructive Sleep Apnea (OSA) is a highly prevalent yet under-diagnosed condition [1]. Untreated, sleep apnea has a short-term effect on vigilance and everyday performance, as well as long-term effect in a growing number of known health problems, including high blood pressure, stroke, heart failure, atrial fibrillation and other irregular heartbeats, myocardial infarction and diabetes [1]. It is also recognized as a risk factor for patients undergoing anesthesia during surgery [2].

Diagnosis of sleep apnea requires detection of sleep as well as detection of air flow interruptions. Polysomnography (PSG), the gold-standard for diagnosis of sleep apnea, is a cumbersome and expensive process. Hence there is a continuous search for screening devices that are easy-to-use and less expensive. Most screening solutions use 1-3 types of measurements to detect apnea during the night. Some use SpO2 to detect desaturations, thermistors to detect air flow, or respiratory inductive plethysmography to detect rib cage movement or volume. These screening devices do not detect sleep and wake, or use only movement to do so.

In this study we used a system with an established accuracy for sleep wake detection [3], and tested a novel algorithm that detects sleep apnea. The combination of a contact free under-the-mattress measurement with good sleep wake and apnea detection makes the system appealing for screening purposes.

2. Methods

2.1. Study population

The study population included 96 subjects who were referred to a sleep lab and signed an informed consent form. 16 participants were diagnosed with severe sleep apnea, 18 with moderate, 30 with mild and 32 with no sleep apnea. Three of the subjects were measured with their CPAP machine. Subjects were 23-88 years old (average ± std was 51.1 ± 14.3), BMI ranged from 19-62 (34.3 ± 9.7), 77 (80%) were males and 19 females.

2.2. Data acquisition

Subjects underwent full polysomnography (PSG, Alice 5, Respironics) overnight in a sleep lab (Millennium Labs, IL), and simultaneous measurement with the PE system. The contact-free system measures respiration effort, heart rate and movement using a piezo-electric sensor placed under the mattress. Polysomnography results were manually scored by a blinded sleep expert (Millennium Labs, IL), according to AASM guidelines. This gold-standard reference of Apnea-Hypopnea-Index (AHI) for each subject, quantifies the number of apnea and hypopnea

events per hour of sleep.

2.3. Sleep/Wake detection algorithm

The PE system is based on a piezo-electric transducer that records a combination of gross body motion, rib cage movements, and the cardioballistic effect. Analysis of the superimposed waveform allows separation into its 3 components and extraction of motion, respiratory rate, and inter-beat-intervals. The accuracy and validity of measuring these basic vitals is described elsewhere [3,4]. Using movement, Heart-Rate-Variability analysis, and respiration rate variability the system detects sleep and wake as described in a paper submitted to the Journal of Clinical Sleep Medicine [3].

2.4. Apnea/Hypopnea detection algorithm

The Apnea/Hypopnea detection algorithm is comprised of frequency domain and time domain algorithms to detect apnea and hypopnea events, as described below. The results from the two algorithms are combined, and the number of apnea/hypopnea events is calculated. The number of apnea/hypopnea events is divided by the total sleep time to calculate the Apnea Hypopnea Index (AHI).

2.4.1. Frequency domain path

The respiration waveform extracted from the PE system is down sampled to 10Hz. The signal is analyzed in segments of 5 minutes to detect dominant peaks in the frequency domain in the range between 0.009-0.062Hz. This is equivalent to a search of recurring apnea events with a period of 18-102sec. Peaks in the spectrum with a distinguishable power compared to neighborhood are selected as candidates. If the frequency of the candidate peak remains stable within several segments – then it is marked as an event. This part of the algorithm is aimed at detecting reoccurring apnea events, hence periods that do not contain enough peaks are filtered out to reduce false positives. The remaining peaks are marked as apnea/hypopnea events. The number of apnea/hypopnea events is calculated by multiplying the marked events by a normalization coefficient, based on the frequency of the events, and summing them all up.

2.4.2. Time domain path

A running window of 3 seconds is applied to the respiration waveform, and then a 15 seconds running average is used for envelope detection. Peaks in the envelope that are followed by a significant reduction in amplitude for at least 10 seconds are selected. Criteria for the time difference between peaks, as well as respiration amplitude, stability of the time difference between peaks, and the smoothness of the amplitude envelope, are used to narrow down peak selection. Peaks meeting those criteria are marked as apnea/hypopnea events if they appear in close proximity to other peaks.

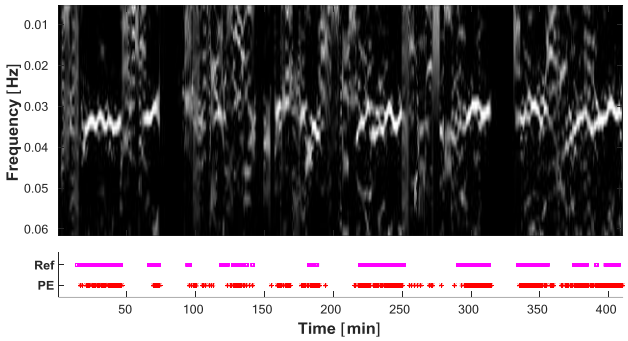

Figure 1: Frequency domain analysis: a spectrogram, showing power of the respiration waveform as a function of time, together with reference (pink) and PE (red) detection of periods with apnea events.

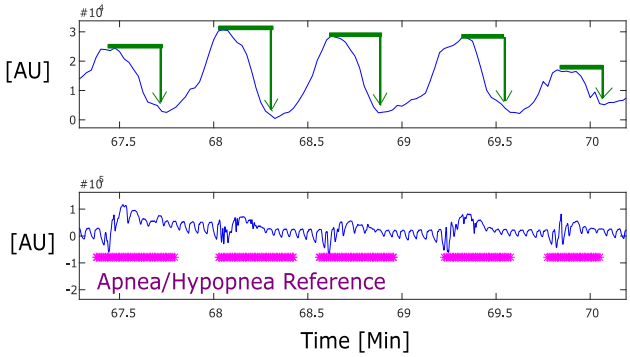

Figure 2: Time domain analysis: upper panel depicts the amplitude of a smoothed envelope of the respiration signal on the lower panel. The time scale is 3 minutes, and the figure captures 5 cycles of apnea.

3. Results

Figure 3 depicts 4 minutes of waveforms recorded in the sleep lab. The upper 3 panels are recorded with standard sensors – abdomen Respiratory Inductive Plethysmograph (RIP) belt, thorax RIP belt, and pulse oximeter respectively. The lower panel is the waveform recorded with the PE system. One apnea event is marked for all panels – note that the saturation occurs a few tens of seconds after the actual apnea.

Figure 4 presents a comparison of AHI estimates of the PE system (y-axis), for all 96 patients, with the AHI of the reference (x-axis). Overall correlation was high (R^2=0.86). Bland-Altman analysis of the same data is presented in Figure 5. This analysis shows an average difference of 0.8 AHI between the systems (median 1.8), and a bias which is not dependent on AHI value. Two standard deviations are within AHI of ±16 (relative to average bias).

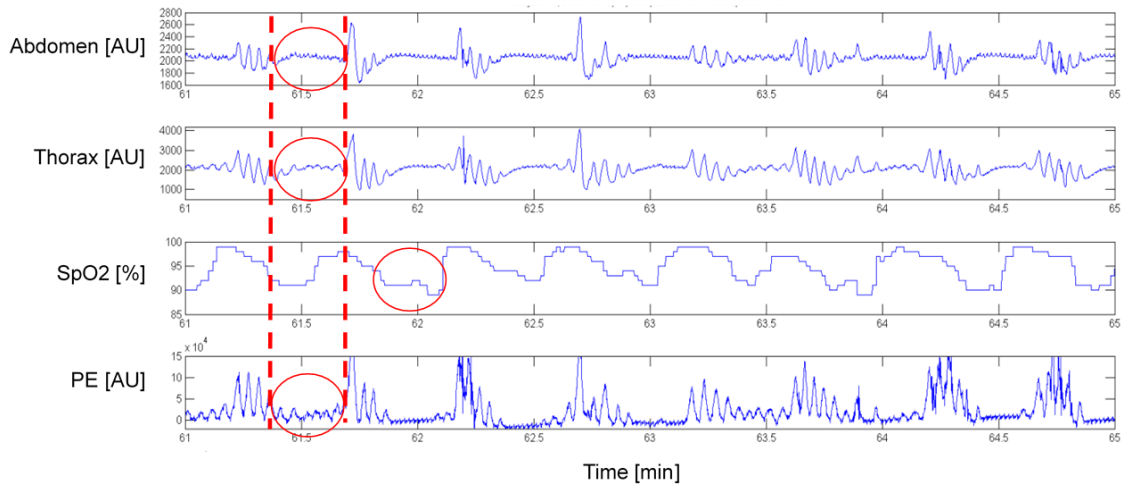

Figure 3: The figure shows 4 minutes of PE respiration signal (lower panel) compared to sleep lab abdomen RIP signal (upper panel), Thorax RIP signal (2nd panel), and pulse oximeter (3rd panel). The red circles indicate 1 apnea event with reduced abdomen and thorax volume, delayed decrease in saturation, and reduced movement of the rib cage as captured by the respiration signal from the PE system.

A confusion matrix for classification of each patient into one of two categories is given in Table 1. The cutoff AHI 15 was used as it is the most common threshold in clinical practice for CPAP therapy administration [5]. The system had a sensitivity of 88% in detecting AHI of 15 and above. It detected 100% of severe sleep apnea (AHI above 30), and 78% of moderate sleep apnea. Additionally, specificity was 89%, and positive predictive value (PPV) was 81%. Six out of 7 false positive detections were found to have AHI in the range of 10-14 (close to threshold), and only 1 had an AHI of 5 (this patient had Periodic Leg Movement that was erroneously captured as respiratory signal). Two out of 4 of the false negative detections, were borderline patients with AHI 15-18, and the other 2 had AHI 23-24 according to reference.

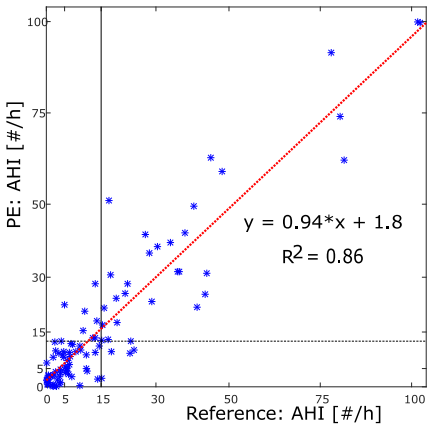

Figure 4: Gold standard reference (x-axis) vs. PE system estimated AHI (y-axis). Linear regression line is red, vertical black line indicates reference threshold (AHI 15), and dashed horizontal line indicates PE system threshold.

Table 1: The confusion matrix for PE validation

		Gold standard		
		AHI > 15	AHI < 15	
PE system	moderate/severe apnea detected	30	7	PPV 81%
	moderate/severe apnea NOT detect	4	55	NPV 93%
		Sensitivity 88%	Specificity 89%	

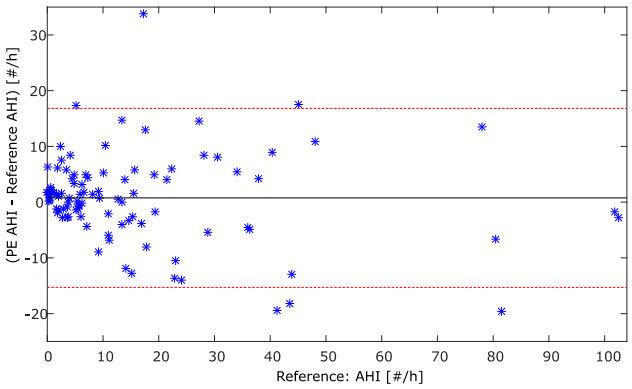

Figure 5: Bland-Altman analysis. X-axis is the AHI according to gold standard PSG reference, and the y-axis is the difference between the PE estimate of AHI and the reference. Black horizontal line indicates the average bias (AHI 0.8), and the red dashed lines are the 2 standard deviation limits.

4. Conclusions and discussion

The PE system with the novel apnea detection algorithm was found to have a high correlation with gold standard device. All (100%) of severe patients (AHI>30) were correctly classified with the suggested threshold for moderate-to-severe sleep apnea. Also it was shown that all false positive patients had mild apnea according to reference.

Part of the systems accuracy may be attributed to its sleep wake detection [3], which many of the screening devices lack. This accuracy is comparable to FDA approved systems for OSA diagnosis [6]

Being contact free makes this system suited for home use and long-term monitoring to assess sleep apnea in the natural patient's environment. It may also be used to reflect the effect of interventions (e.g. CPAP administration, or tonsillectomy) on apnea prevalence, or to encourage adherence to treatment when using chronic therapy (e.g. CPAP).

Hospitalized patients, which are already monitored by this PE system, may benefit from adding apnea detection algorithm. A physician may consider referring a patient with detected OSA for full diagnosis in the community upon discharge. And an anesthesiologist may reconsider opioids dosage during operation or use further monitoring after procedures.

Further work is required to determine the usability of the system with children. Sporadic events might need different algorithms for accurate apnea detection. Future work will also target the ability to detect position-related apnea events.

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