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A Passive and Portable System for Monitoring Heart Rate and Detecting Sleep Apnea and Arousals: Preliminary Validation

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***Abstract*—The National Institutes of Health (NIH) Sleep Disorders Research Plan expresses a need for methods that can non-invasively monitor sleep characteristics. Forty subjects were tested using a novel, passive ballistocardiography-based system during an overnight study. We examined our system's ability to measure heart rate as compared to EKG while we also investigated our system's apnea and arousal detection capabilities as compared to conventional polysomnography. We found a strong correlation ($r = 0.972$, $p < 0.0001$) in average heart rate computed over 480 thirty-second epochs when our method was compared to EKG. Additionally, we achieved a sensitivity of 89.2% and specificity of 94.6% in the automated detection of apneas. Similarly we attained a sensitivity of 77.3% and a specificity of 96.2% in the detection of arousals. These preliminary results demonstrate the effectiveness of our portable ballistocardiography-based system as compared to polysomnography and show promise that high quality sleep assessment can be performed in a home environment.**

***Index Terms*— Ballistocardiography, Sleep Analysis and Monitoring, In-Home Health Monitoring, Telemedicine, Sleep Apnea.**

I. Introduction

Sleep deprivation is a common problem in the industrialized world. The National Sleep Foundation (NSF) reports that for adults to function properly they should obtain 7-9 hours or more of sleep per night [1]. According to the 2005 "Sleep in America" poll conducted by the NSF, about 26% of adults are getting at least 8 hours of sleep a night during the week, while 49% do so on weekends. This continues the downward trend seen over the last five years. Additionally, 75% indicated they had at least one symptom of a sleep disorder, such as snoring or reduced sleep efficiency, a few nights per week in the last year. However, 76% do not believe they have a sleep problem and only 45% would talk to their doctor if they thought they did [2]. Sleep disorders cost the U. S. economy about $46 billion a year in lost productivity [3]. Nonetheless, sleep disorders like apnea, which affects more than 12 million Americans [4], can lead to severe consequences if left untreated. Yearly, 38,000 deaths are associated with complications from sleep apnea and those that suffer from apnea are 3-6 times more likely to suffer a stroke [3].

According to the National Institutes of Health (NIH) Sleep Disorders Research Plan, current methods for measuring breathing abnormalities are cumbersome, expensive, lack predictive power, and are useless for screening large populations. To further challenge sleep studies, there is no comprehensive database that defines normal sleep-wake patterns based on age or gender. As a result, the NIH identifies a need for new methods that can non-invasively monitor sleep and respiration to quantify breathing problems and their consequences [5]. Longitudinal, non-invasive sleep monitoring using validated assessment and screening tools has the potential to become useful in sleep analysis and possibly provide predictive data for the development of sleep related disorders.

The Non-Invasive Analysis of Physiological Signals (NAPS) system that was tested in this study was designed and developed at the Medical Automation Research Center at the University of Virginia. It uses ballistocardiography (BCG) to detect minute forces generated during cardiac contraction and relaxation, and can also detect body movement from respiratory effort and postural changes. Preliminary data [6], [7] have shown strong correlations between the heart rate passively measured using the NAPS system and conventional clinical techniques such as pulse oximetry. The NAPS system relies on a highly sensitive pressure transducer pneumatically connected to a compliant force-coupling pad installed on top of the mattress of any standard bed, on which the subject lies in order to acquire the data. Multiple pads can be used to acquire data from different parts of the body. The system is sensitive enough to gather data even when sheets and blankets are applied over the sensor, which rests on the mattress. The analog signal is filtered and amplified before being digitized by A-to-D converters. An algorithm has been developed to provide automatic scoring of the instantaneous heart rate and respiration data recorded by the NAPS system. Additionally, the passive nature of the NAPS system allows data to be recorded longitudinally and to establish personalized norms for individuals that can be used to detect changes in physiological parameters, and/or to assess the efficacy of

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interventions. The NAPS system has already proven useful as a home-health tool for qualitative sleep assessment in an assisted living environment [8]. It provided professional caregivers a better picture of their resident's sleep patterns and key information to help assess changes in their health conditions. To supply even more information for this environment and to prove useful as a clinical sleep analysis tool, the NAPS system is undergoing validation against polysomnography, the clinically accepted standard of sleep analysis. This paper presents the preliminary validation results.

II. Methods

A. Study Design

This study was reviewed and approved by University of Virginia's Institutional Review Board (IRB), known as the Human Investigation Committee (HIC), and the General Clinical Research Center (GCRC) Committee. All subjects were educated to the study specifics and informed consents were obtained prior to their participation in the study. Forty generally healthy adult subjects had an overnight sleep study with conventional polysomnography at the University of Virginia Health System's GCRC Sleep Laboratory. The subject population (32 men, 8 women) was quite diverse in age, height, weight and resulting apnea-hypopnea index (AHI) as noted in Table I below. Additionally we achieved a racial demographic similar to that of the surrounding geographical area according to recent census data [9].

TABLE I
SUBJECT DEMOGRAPHICS

Parameter	Mean	Standard Deviation	Minimum	Maximum
Height (in)	68.8	4.0	58.9	77.2
Weight (lbs)	203.8	50.4	127.8	318.8
Age (yrs)	45.0	17.0	18.0	79.0
AHI[a]	24.6	29.3	0.4	95.6

[a]AHI = Apnea-Hypopnea Index

The study subjects were simultaneously monitored using the NAPS system, outfitted with two compliant force-coupling pads and four temperature sensors, and conventional polysomnography. Synchronization of the data was achieved by asking the subjects to sit up and lie down in bed three times following the bio-calibration of the polysomnography equipment. This created movement artifacts in both the polysomnography and NAPS data that could be easily reconciled. Data were recorded for the entire night, which was set by the "lights off" and "lights on" times of the polysomnography study.

After the polysomnography data was scored by a trained sleep technician, it was verified by a sleep physician. Twenty of the subjects had an AHI greater than 10.0 while twenty were under this threshold. This AHI value separates normal and mild cases of sleep apnea syndrome (SAS), called the control group, from the moderate to severe cases, the group considered to have sleep apnea.

The scope of this paper is to report on our initial findings based on two three-minute segments from each subject's study. They were randomly selected based on the requirement that one three-minute segment be from a portion of Stage 4 sleep free from apnea and arousal events while the other contain at least one apnea as recorded in the polysomnography reports. Two subjects never reached Stage 4 sleep, so both segments had apneas and arousals present. In total, over the 40 subjects studied, this amounts to four hours of data broken up into 480 thirty-second epochs. Once these data were isolated from the entire night studies, we compared manually scored EKG data, averaged over thirty second epochs, to automatically scored NAPS heart rate data, which was calculated over the same thirty second epochs. Additionally, we compared apneas, hypopneas and arousals detected with polysomnography to those detected by the NAPS system. Though this portion of the NAPS data analysis was only partially automated, a set of rules was developed and followed to enable automated event detection, which is one of our future directions. For both the heart rate and event comparisons of the first 27 subjects (~67%) were used to help develop the algorithms and scoring rules, while the last 13 subjects (~33%) were used as the test set.

B. Data Acquisition of EKG System

A trained sleep technician fitted the appropriate polysomnography sensors to each subject and monitored the hardware throughout the night. Sleep was monitored with electroencephalograms, electrooculograms, submental electromyograms and leg electromyograms. Breathing was monitored with nasal airflow detected by nasal pressure, oral airflow with a thermistor, and thoracic & abdominal movement with respiratory inductive plethysmography, as well as pulse oximetry. Electrocardiogram was monitored on one channel sampled at 128 Hz. All data was recorded on a Sandman® Computerized Sleep System. The same technician performed the sensor hookups for all 40 subjects and also manually scored each of the datasets. Raw data from each of the channels were provided to us for analysis. Additionally, files reporting detailed information of the various events that occurred during the night (i.e. apneas, arousals, bad data, etc) were also provided to us for analysis. Fig. 1 shows an example of the EKG data obtained.

C. Data Acquisition of NAPS system

The NAPS system deployed in this study used two compliant force-coupling pads that provided cardio-pulmonary data from the upper chest at the approximate level of the heart and the abdomen area above the waist. These pads were attached to a 3 foot square bed pad that was then secured under the normal linens to the mattress; each of the pads was pneumatically connected to a pressure sensor. This configuration ensured consistency of spacing between the two pneumatic pads throughout the study. No adjustments were made to the hardware during the course of

the study. Positional pad placement adjustments, if necessary, were made at the beginning of the study to provide proper positioning of the pad with respect to the height of study participants. There were no restrictions on the subject's sleeping position or orientation following the initial adjustment. The signal from each pressure sensor was pre-amplified and then split into respiration and heart rate signals using analog filters, and the output signals were digitized by a USB compliant A-to-D converter. This A-to-D converter sampled each of the four channels (two cardiac and two respiration signals) at 150 Hz. The data were transferred 30 seconds at a time to a computer database where it was stored for later analysis. Fig. 2 shows an example of the NAPS system's pulse data from the same time period as the EKG data in Fig. 1.

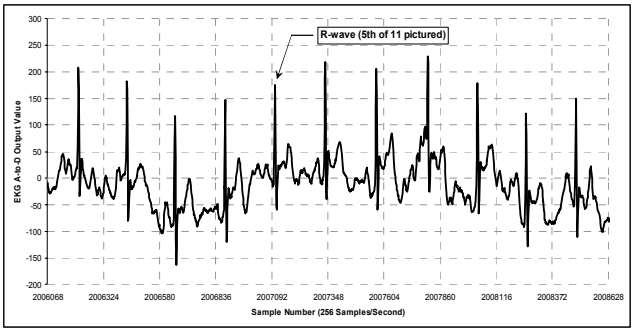

Fig. 1. Example of EKG Waveform – 10 second sample

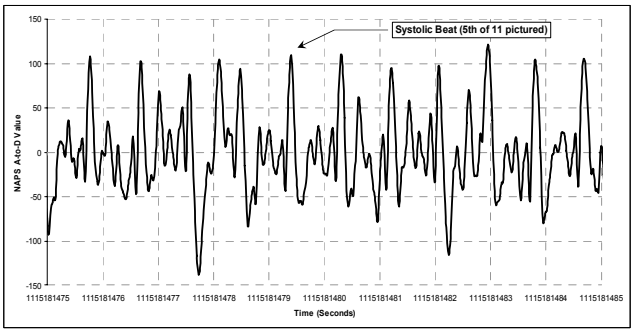

Fig. 2. Example of NAPS Waveform – 10 second sample

D. NAPS Software Analysis

The raw data acquired by the NAPS system was pre-processed using bi-directional recursive filtering to ensure that no phase shift was introduced into the filtered data while smoothing, unlike a typical moving average approach. The analysis to yield heart rate data averaged over thirty-second epochs was fully automated by an algorithm developed by this author. Two different methods were used to detect the position of the systolic portion of each BCG wave. The first involved simple derivative and threshold peak detection while the second looked for changes in the direction of relative trough position. The latter technique was performed with varying upper limit levels for the heart rate to enable selection of consistent and accurate data. By using this technique, a heart rate is computed in a similar way to counting R-R intervals of an EKG. Instantaneous heart rate was reported on a beat-by-beat basis for each epoch and the median was used as the heart rate for that epoch. This ensured eliminating the influence of outliers on the average data. Iterative and statistical selection was employed to choose the highest quality, most consistent data available for each epoch. Specifically, the algorithm generated a quality score based on instantaneous heart rate consistency on a beat-by-beat basis, clustering of data near the average, and the percentage of beats obtained during the epoch. If excessive movement was present or exceedingly low quality data was reported during a specific epoch, no heart rate data was reported. To prevent large errors, mostly due to movement artifacts, we implemented an automated correction method that selected a heart rate closer to the rest of the recorded values in the selected three-minute set. This correction scheme was applied in cases where only one of the heart rates computed out of the six thirty-second epochs in the three-minute data set was much higher or lower than the average, or if one was extremely below the average while another was extremely above the average. This only occurred in 10 of the 480 cases (2%). Parameters of the automated heart rate algorithm were optimized over the first 27 subjects and tested over the last 13 subjects.

The respiration analysis was partially automated to detect and align breaths recorded by the two compliant force-coupled pads of the NAPS system. Additionally, the algorithm normalized the three-minute block of breathing data based on the average amplitude obtained from each pad. We examined the clinical and research definitions of breathing events during sleep, as recently defined by the American Academy of Sleep Medicine [10], to provide physiological basis in setting the NAPS system's criteria for establishing apneas and arousals. These criteria were then applied to the breathing signals to automatically classify each breath as possible movement/arousal class (amplitude over 140% or containing a minimum amount of postural movement) or possible apnea class (amplitude under 75% or gaps in the signal with minimal postural movement present). Breaths were examined for a potential arousal or apnea based on the class to which they were assigned. Phase change and relative amplitude of the two breathing signals were also examined and scored automatically. During normal breathing, the two signals should be closely matched in terms of phase as well as normalized amplitude around 100%, which is not the case during an apnea or arousal. An automated scoring system was established to characterize the severity of contributing factors. The manual portion of the algorithm involved applying a set of rules for marking apneas and arousals based on the scoring system and classification of breaths. Minor exceptions were also applied including extended movement during an apnea class breathing segment being marked as an arousal or allowing extended gaps that sometimes occurred between or during epochs to contribute to apnea class breathing segments. The latter provided a way to detect apneas even if they occurred over multiple epochs or were central in nature. Parameters of the apnea/arousal algorithm were optimized over the first 27 subjects and tested over the last 13 subjects.

III. Results & Discussion

A. Average Heart Rate Value Calculation

The NAPS average heart rate was highly correlated with the EKG average heart rate ($r = 0.972$, $p < 0.0001$) as shown in Fig. 3. The NAPS System failed to produce an average heart rate for an epoch 10.6% of the time where the majority of those were due to movement artifacts. Of the detected heart rates, 80.0% were at or below the standard error of ±2.54 beats per minute (BPM). The standard error for the delta sleep portion of the data was ±2.20 BPM while the standard error for the segments with at least one apnea present was ±2.83 BPM. This is due to the increased movement and breathing anomalies that occur during and immediately following apneas and arousals, which can adversely affect the NAPS heart rate signal quality.

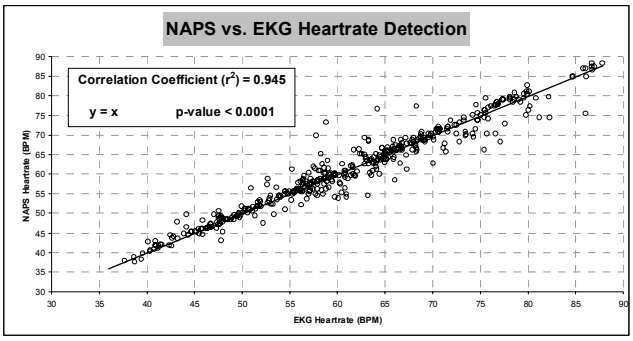

Fig. 3. NAPS vs. EKG Average Heart Rate

B. Apnea and Arousal Detection

Using 2-way contingency comparisons, we compared apneas and arousal events detected with the NAPS system to those detected with polysomnography. We did not discriminate between central and obstructive apneas and included all hypopneas as well. Overall, we achieved a sensitivity of 89.2% and specificity of 94.6% in the detection of apneas with a kappa correlation coefficient of 82.8%. The kappa correlation was chosen since the technician scored polysomnography data is also subject to errors. Moreover, we obtained a sensitivity of 77.3% and a specificity of 96.2% in the detection of arousals with a kappa of 73.0%. In examining the aggregate detection of apneas by computing an AHI for the four hours of data, we found strong agreement between the NAPS system (33.8) and polysomnography (32.5). Similarly, we computed an arousal index that also showed agreement between the NAPS system (16.8) and polysomnography (16.5). Additionally, standard errors of ±9 seconds in detecting the start time of apneas and ±7 seconds for arousals were attained. Finally, the average length of apneas and arousals were closely matched to their respective polysomnography values (1% error in average apnea length, and 4% error in average arousal length). The results presented here show that the NAPS system not only detected the right number of events, but also exhibited high timing alignment of events as compared to polysomnography.

IV. Conclusions

The average heart rate and apnea/arousal events were captured with a high degree of accuracy across a wide variety of subjects. These preliminary results demonstrate the effectiveness of the NAPS system as compared to conventional polysomnography. They also suggest that high quality sleep assessment can be performed by our passive and portable system, which make it an excellent candidate for home use.

V. Future Directions

The next step in the development of the NAPS system will be to fully automate the algorithm and perform the full night analysis on each of the 40 study subjects. We will run the developed algorithms on the remainder of the collected data sets (as a validation data set) to provide a full validation of the NAPS system against polysomnography. Moreover, we will explore the NAPS system's ability to identify sleep stages.

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