Original Research

Wireless Portable Electrocardiogram and a Tri-Axis Accelerometer Implementation and Application on Sleep Activity Monitoring

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Abstract

Night-to-night variability of sleep activity requires more home-based portable sleep monitoring instead of clinical polysomnography examination in the laboratory. In this article, a wireless sleep activity monitoring system is described. The system is light and small for the user. Sleep postures, such as supine or left/right side, were observed by a signal from a tri-axis accelerometer. An overnight electrocardiogram was also recorded with a single lead. Using an MSP430 as microcontroller, both physiological signals were transmitted by a Bluetooth chip. A Labview-based interface demonstrated the recorded signal and sleep posture. Three nights of sleep recordings were used to examine night-to-night variability. The proposed system can record overnight heart rate. Results show that sleep posture and posture change can be precisely detected via tri-axis accelerometer information. There is no significant difference within subject data sets, but there are statistically significant differences among subjects, both for heart rate and for sleep posture distribution. The wireless transmission range is also sufficient for home-based users.

Key words: *sleep posture, portable polysomnography, ECG, accelerator*

Introduction

Sleep disorders are common and the number of patients reporting this problem is on the increase in modern industrialized societies. There are many kinds of sleep disorders, such as insomnia, obstructive sleep apnea (OSA), narcolepsy, rapid eye movement (REM) sleep behavior disorder, and restless legs syndrome.[1] Patients, especially older adults, often complain of one of the following: waking too early and not feeling rested, having trouble falling asleep, daytime napping, and multiple nocturnal awakenings. They also experience an increased percentage of time spent in the light-sleep stage and a decreased percentage spent in deep-sleep stages.[2]

The standard sleep examination is based on polysomnography (PSG), with two electroencephalogram channels, electrooculogram, chin electromyogram (EMG), airflow, respiratory effort, oxygen saturation (SpO2), and EMG for leg movement and operated by a trained physician.[3] PSG examination is a time-consuming examination with an overnight test in the laboratory. Also, patients will be on a waiting list for PSG examination for 3–6 months. Therefore, an alternative approach is needed, such as portable monitoring for home-based diagnosis with fewer measurement variables, and, thus, no waiting time for sleep examination.

A major requirement for a portable sleep monitoring unit is small-size, less equipment than PSG, and easy operation in a home environment. There has been much research devoted to portable sleep monitoring systems.[4] The American Sleep Disorders Association's Standards of Practice Committee has developed portable recording devices with practice parameters intended to diagnose OSA and guide the clinicians in their appropriate use.[3] Portable monitors are classified into three levels (Level II, III, and IV) with decreasing measurements of sleep and respiratory variables. Three or more respiratory channels and heart rate generally without sleep staging either attended or unattended is Level III. Littner[5] reviewed the use of Level III PSG in the laboratory and combined in the home and laboratory. The Portable Monitoring Task Force of the American Academy of Sleep Medicine also makes some recommendations for the use of portable monitoring devices for OSA.[6] They thought a portable monitoring device may be used as an alternative to PSG for the diagnosis of OSA in patients with a high pretest probability of moderate to severe OSA and should, therefore, be used under some restricted guidelines and medical requirements. The other major advantage of a portable device in home monitoring is to reduce the night-to-night variability in sleep-disordered breathing that was a confounding factor in assessing treatment outcomes.[7]

Portable sleep monitoring systems are now widely applied in sleep disorder detection, such as OSA syndrome.[8] OSA is a respiratory disorder that occurs during sleep. Patients suffering from OSA hold their breath for periods exceeding 10 s when sleeping, with greater effort breathing out being subsequently needed to overcome the partial or total collapse of the upper airway. Previous research has attempted to develop portable OSA detection systems, and electrocardiogram (ECG) is one of the promising signal variables for portable PSG, especially for OSA detection. Heneghan et al.[9] developed an automated OSA detection algorithm and tested it with 92 subjects exhibiting apnea-hypopnea indices thresholds below 5 and >15. The automated algorithm achieved positive and negative likelihood ratios of 2.16 and 0.08, respectively. There has also been a lot of research on the use of heart

rate variability (HRV) and cardio-respiration variables to estimate the sleep state of patients with OSA.[10–12]

A complementary metal oxide semiconductor (CMOS) accelerometer was designed, in which the capacitance was sensitive to gravitation change. x-, y-, and z-axis gravitation was measured simultaneously, and the three axis changes reflected in the output voltages. A tri-axial accelerometer is widely used for physical activity detection.[13–15] Yang and Hsu[16] developed a physical activity monitoring system based on tri-axial acceleration signals. They can monitor the posture transition between standing, sitting, and lying down. Still postures and dynamic movements, such as walking and fall recognition, were also detected with high sensitivity and specificity. A tri-axis activity sensor was also used for sleep activity estimation. Sleep activity can be measured by sleep posture variation. There are several articles that discuss sleep activity and sleep disorders. Foo and Lim[17] developed a simple and portable home screening monitor for sleep-disordered breathing in children, with an accelerometer being used as a motion artifact detector. Yoshimi et al.[18] examined the muscle activities and mandibular movement patterns during sleep bruxism, with the aid of EMG and an accelerometer. Posture change during sleep is an important factor in sleep quality, and Lee et al.[19] have investigated the effect of sleep position on surgical outcomes in patients with OSA. They found that without appropriate corrections based on the change of sleep position, the fluctuation of sleep position in each PSG might confound surgical outcomes in patients with OSA. Therefore, a tri-axis accelerometer was also integrated into this study. Kawada et al.[20] revealed that there was significant negative relation between sleep time and sleep activity, as before or after sleep became clear in rotating shift workers. Mador et al.[21] showed that overall activity was significantly less in patients with Chronic Obstructive Pulmonary Disease than in normal subjects. The accelerometer sensor was also used for screening of sleep apnea-hypopnea syndrome.[22] Yang and Hsu[23] reviewed accelerometer-based motion detectors. In their study, SenseWear Armband (BodyMedia Inc.), a commercial product, combines a dual-axial accelerometer to measure motion and multiple sensors to measure skin temperature, heat flux, and galvanic skin response. This system also reports sleep duration by accelerometer output. Therefore, sleep posture is also an important reference to monitor sleep activities.

Other biomedical signals have also been applied to portable sleep monitoring systems, such as snoring[24] and oximetry.[25–27] A commercial portable sleep monitoring system has been developed,[28] which monitors breathing movement, nasal and oral air flow, position, snoring, blood oxygen saturation, and heart rate. A novel pressure detection sensor has also been developed. Cheng et al.[29] developed conductive mats to monitor the sleep activity and evaluate the sleep/awake states for home usage. They achieved good performance with their design and also proposed a decentralized home telehealth system to support this sleep monitoring system.

A wireless body sensor network with a low-cost, low-power, noninvasive, and unobtrusive system can be a useful device to monitor human physiological responses,[30] and it would also be useful for home-case based biomedical signal monitoring and signal transmission.[31–33] Among the transmission media, Bluetooth is one of the promising tools.[34,35] In a previous study,[36] a personal digital assistant (PDA) embedded Bluetooth transmission system was established, with a satisfactory result.

The aim of our study was to propose a novel portable device combined with ECG and tri-axis activity and to monitor sleep activities. Embedded Bluetooth transmission and a sleep activity diction algorithm were also developed. This portable sleep monitoring system was tested in a home-care environment. Simulated sleep posture change experiments and overnight sleep examination were carefully handled. Compared with previous studies, this system was more compact and user friendly. This system was also used to examine the night-to-night variability for overnight monitoring of the home condition.

Hardware Architecture

The structure of this portable and home-based sleep monitoring and posture detection system is illustrated in *Figure 1*. This system is based on the microcontroller MSP430 as the core structure. The ECG and accelerator signals were achieved as follows: the ECG was recorded from electrodes attached to the subject's chest and transmitted to the amplifier circuit. At the same time, the tri-axis accelerometer sensor was also attached to the chest to measure acceleration due to posture change. Both biomedical signals were passed from sensors to the MSP430 and converted to a digital signal through an analog-to-digital converter (ADC)12, embedded in MSP430. Digital signals were transferred to a Bluetooth chip and transmitted wirelessly to a remote server. A Labview-based interface system was used to receive the Bluetooth transmitted signal and also used as a real-time signal display and storage. Detailed information on each component is described next.

SENSORS AND AMPLIFIERS

There were two signal sensors, one for ECG and the other for the tri-axis accelerometer. The raw ECG signal is a low-amplitude signal and, therefore, needs to be amplified. A traditional operational amplifier (OP) was used to enhance the signal, with a differential input and common mode noise reduction. In this study, an op-amp (National Semiconductor, LM324) with a gain of 500 was used. The op-amp was also used in the design of a filter, in which there was a low-pass filter with a cut-off frequency of 40 Hz, followed by a high-pass filter with a cut-off frequency 0.5 Hz. The high-pass filter was used to remove the direct current (DC) offset and baseline wandering, whereas the low-pass filter was used to reduce high frequency (HF) noise and to avoid aliasing.

The other sensor in this system is the tri-axis accelerometer with a Kionix KXM52-1050 sensor. The three-axis CMOS output voltage and the ECG output voltage were transferred to the MSP430 chip.

POWER

Power is an important issue for a biomedical measurement system. A high-capacity power supply is required for a home-care based device. The power source is also expected to be rechargeable, of small size, and be able to provide a stable voltage. The system was equipped

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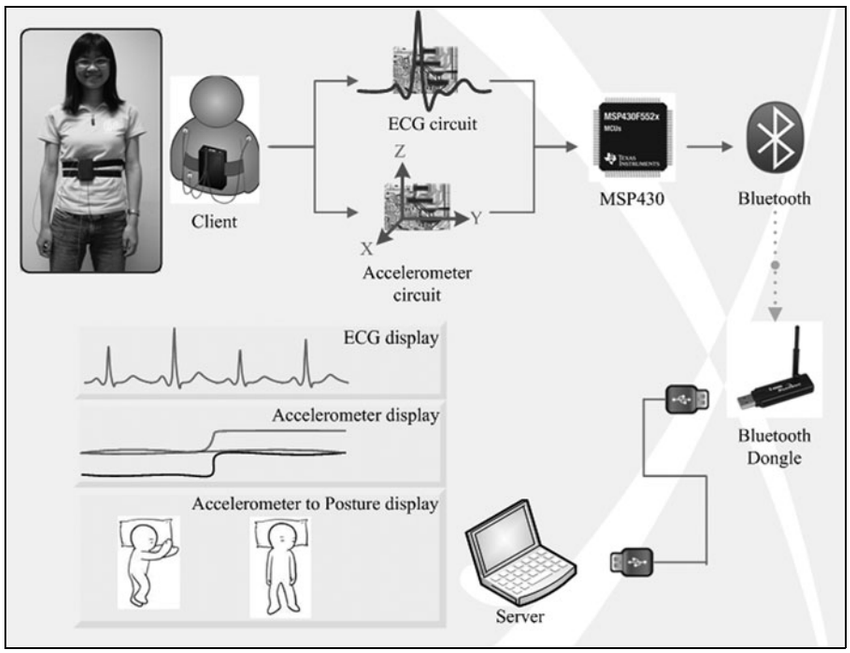


Fig. 1. Structure of portable sleep monitoring and posture detection system.

with BLB-2 lithium battery, with a capacity of 830 mA, and output voltage of 4.2 V. A regulated power circuit was used to support the power supply and avoid instability, which is the major reason for unstable working conditions in such a system. The single power source, a 4.2 V lithium battery, was applied to a power regulator chip, IC 7585-3.3T, produced by Addtek Company. This provided a 3.3 V stable working voltage for the microchip and the other circuits in the system.

MSP430 MICROCONTROLLER

The core of the system is the microcontroller MSP430F169 chip from Texas Instruments. The advantage of the MSP430 is that it is a low-power consumption device needing a working voltage between 1.8 and 3.6 V. and a working current of 330 μA when operated at 1 M Hz and 2.2 V. This device has an embedded 12-bit ADC. Due to the properties just mentioned, the MSP430 is a popular device, especially for biomedical signal acquirement systems.[37] A timer in the MSP430 F169 chip was used to enable the ADC to acquire four channel signals, one from ECG and the other three from the tri-axis accelerometer. These digitized signals pass through universal asynchronous receiver/transmitter (UART) to the Bluetooth transmitter.

BLUETOOTH CHIP

Bluetooth was chosen as the wireless transmission interface in this study as a consequence of its low cost and low-power radio frequency transmission. A Bluetooth chip made by the CSR Company with type number MB-C04 was used. This Bluetooth chip is energy saving and has a high transmission capacity of 1 megabits per second. It is also easy to integrate into the low-level circuit requirements. The transmission range was limited to within 10 m; but this is still a very powerful wireless transmission tool in terms of the requirements of a home environment.

USER INTERFACE

A remote personal computer (PC) receives the Bluetooth-transmitted data and connects to the host PC through UART. A Labview-based user interface was designed to collect the data package from the Bluetooth device and display the ECG and accelerator signal on a monitor. Six posture patterns were determined online from accelerator signals. Sleep posture was also displayed in real time in the Labview interface. Offline signal analysis was performed, and the data were saved by Labview in a text file format.

Hardware Performance Examination

The hardware system performance was carefully examined, and each component is described in the following subsections.

ECG CIRCUIT

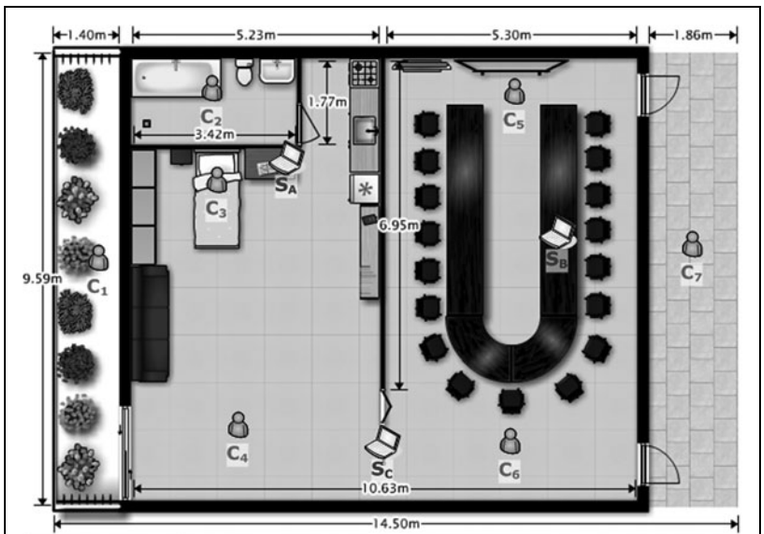
Three aspects of the ECG amplifier were examined. The first was the amplifier gain. Compared with a standard ECG from an ECG simulator (BC-Biomedical PS-2210), the output from the ECG amplifier showed a voltage gain of 500. The second aspect was the common-mode rejection ratio (CMRR) for the ECG amplifier. A higher CMRR value means a higher required signal performance. The CMRR was 76 dB for this ECG amplifier. The third specification was frequency response. With a 10 mV sinusoidal signal input with a frequency range of 2 to 10,000 Hz, the output signal voltage was used to estimate the gain function under each frequency. The frequency response of the ECG amplifier revealed a band-pass filter spectrum range between 0.5 and 40 Hz, thus meeting the original design specifications.

ECG SIGNAL

The ECG waveform accuracy of ECG amplifier output was also examined. A signal from the ECG simulator (BC-Biomedical PS-2210) was used to compare the accuracy with Bluetooth transmission. The simulated ECG was shown on the Labview interface (ECG amplifier output) and scope (original ECG) simultaneously, and there was no visual waveform distortion. Also, comparing the real ECG acquisition performance with the commercial ECG amplifier (Iworx ETH-256), the ECG output on the Labview interface was also similar to the commercial ECG amplifier, MSE is 0.002504. Both tests indicated that the ECG amplified circuit and the Bluetooth transmission system reliably showed ECG signal.

TRI-AXIS ACCELEROMETER SIGNAL

The tri-axis accelerometer was attached to the user's chest. In the Labview interface, the three axis accelerometer voltages were displayed



Server Position	Client Position						
	C_1	C_2	C_3	C_4	C_5	C_6	C_7
S_A	O	O	O	O	O	O	X
S_B	X	O	O	O	O	O	O
S_C	O	O	O	O	O	O	X

Fig. 2. Bluetooth transmission range test in the house environment.

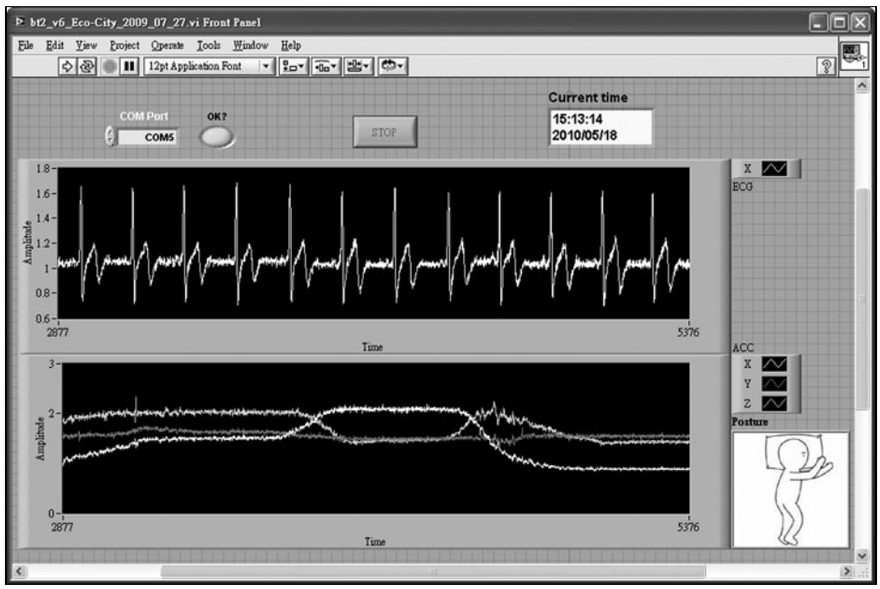


Fig. 3. Complete Labview interface with ECG and tri-axis accelerometer information. Real-time heart rate and estimated sleep posture were also shown on the board.

simultaneously. To mimic the sleep posture variation during sleep, six standard still postures for sleep, denoted as P1–P6, and a walking state were defined as follows:

P1: sit on the bed.

P2: supine with face up.

P3: lie on the left side.

P4: lie on the right side.

P5: lie face down.

P6: lie partially off the bed in a falling position, but with hand support.

W: walking and not on the bed (people may get up and walk to the restroom during the sleeping period).

Distinct sleep postures had distinct accelerator voltages. This system can show the sleep posture and posture change duration precisely.

BLUETOOTH TRANSMISSION RANGE TEST

To test the Bluetooth transmission range in the house environment, a subject with the system in place lay in the bedroom. The Bluetooth receiver was located at three test locations around the house, and seven user positions were examined. The overall Bluetooth transmission test result is shown in *Figure 2*. Results showed that when the receiver is located in the same room, it can work very well. Although there is a 10 m transmission limit for Bluetooth, it is acceptable for home-care use.

COMPLETE CIRCUIT SYSTEM AND USER INTERFACE

The complete system size of the circuit module was $3.9 \times 5.8 \times 2.3$ cm, weight 98 g, and battery life 18 h. The battery cell was almost the same size as the circuit. The complete Labview interface containing ECG and tri-axis accelerometer information is shown in *Figure 3*. The following study was based on this system to investigate overnight sleep activities.

Signal Processing Algorithms

ECG PREPROCESSING AND HRV ESTIMATION

The ECG signal was recorded with a sampling frequency of 250 Hz and processed offline to extract HRV information. Consecutive block computations with a window size of 5 min were chosen for preprocessing. Raw ECG was passed through a low-pass filter and a high-pass filter to remove baseline wandering and muscle contraction noise. An ECG pattern R peak detection algorithm based on Tompkin's was applied to extract the R peak of each ECG beat.[38] Time domain HRV features, such as heart beat per minute (BPM), standard deviation of RRI (SDNN), and root mean square of successive differences of RRI (RMSSD), were extracted with the interval between R peak in each heart rate beat (RRI) information. A 1,024-point fast

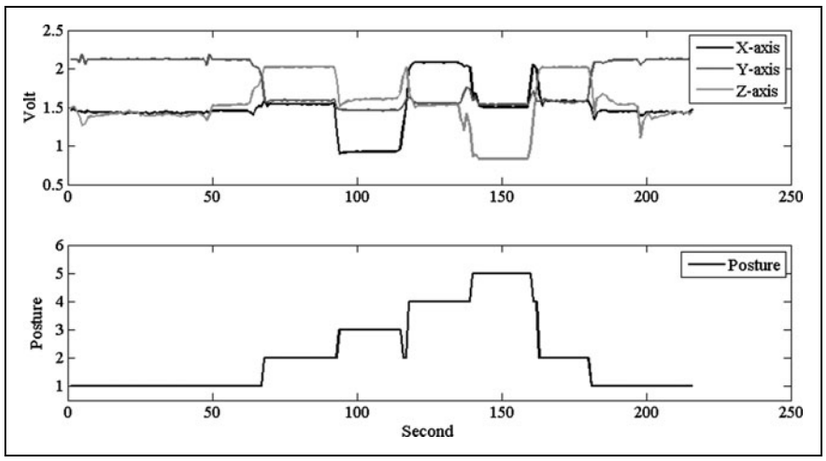


Fig. 4. The three-axis accelerometer voltage, $V_1(t)$, $V_2(t)$, and $V_3(t)$, under different sleep postures.

Fourier transform was applied to the HRV signal with normalization and re-sampling at 4 Hz. Spectrum features were obtained separately in different frequency ranges, such as low frequency power (0.04–0.15 Hz), HF power (0.14–0.4 Hz), and the ratio of low frequency to HF.

SLEEP POSTURE DETECTION BY TRI-AXIS ACCELEROMETER

The voltages of x-, y-, and z-axis in the accelerator were denoted as $V_1(t)$, $V_2(t)$, and $V_3(t)$. Different postures experienced different gravitation force on these three axes; therefore, a specific sleep posture can be detected via the absolute and relative gravitation voltage among the three axes. Upper and lower thresholds, L1 and L2, were determined empirically by accelerator voltage output under different postures, as shown in *Figure 4*. In this study, $L1 = 1.8$ and $L2 = 1.2$ and the value of L1 and L2 were specific for the accelerator type. The sleep posture was then determined by the following formula in *Table 1*:

$$\overline{V}_i = \frac{1}{M}\sum_{k=0}^{M-1} V_i[n-k], M = f_s \text{ where } i = 1, 2, 3$$

STATISTICS

The night-to-night variability of RRI for each subject was evaluated by one-way analysis of variance; whereas the night-to-night variability of posture percentage distribution for each subject was evaluated by Chi-square analysis. A significance threshold of 0.05 was required.

Overnight Sleep Monitoring

The other test for the system is overnight sleep monitoring. Four volunteers were involved (undergraduate students, all men), and each volunteer recorded for three nights to examine night-to-night variability. Subjects were labeled A, B, C, and D. The first night examination of subject A was labeled as data A1. Each volunteer gave their consent and discussed the applicability before and after recording. The overnight ECG and sleep posture variation chart was drawn and compared for three nights.

Results

OVERNIGHT SLEEP MONITORING

The main purpose of this study is to provide a portable and useful sleep monitoring system. The overnight heart beat information is important for further sleep staging and sleep disorder diagnosis. *Figure 5* demonstrates the overnight sleep posture variation and corresponding heart beat intervals of subject A. The main sleep posture of subject A is P2 (supine with face up), which accounts for 80%, 62%, and 55% of total sleep time, on each of the three nights, respectively. The average overnight heart beat interval of subject A was around 0.83/s (BPM = 72.3) to 0.93/s (BPM = 64.5), which also met with the regular sleep condition. Significant RRI

Table 1. Sleep Posture Detection Condition by Tri-Axis Accelerometer Voltage and Corresponding Comic Posture Display

POSTURE	P1	P2	P3	P4	P5	P6
Condition	$\overline{V}_2 \geq L_1$	$\overline{V}_3 \geq L_1$	$\overline{V}_1 \leq L_2$	$\overline{V}_1 \geq L_1$	$\overline{V}_3 \geq L_2$	$\overline{V}_2 \leq L_2$
Comic posture display						

Meaning of posture notation, P1, sit on the bed; P2, supine with face up; P3, lie on the left side; P4, lie on the right side; P5, lie face down; P6, lie partially off the bed in a falling position, but with hand support.

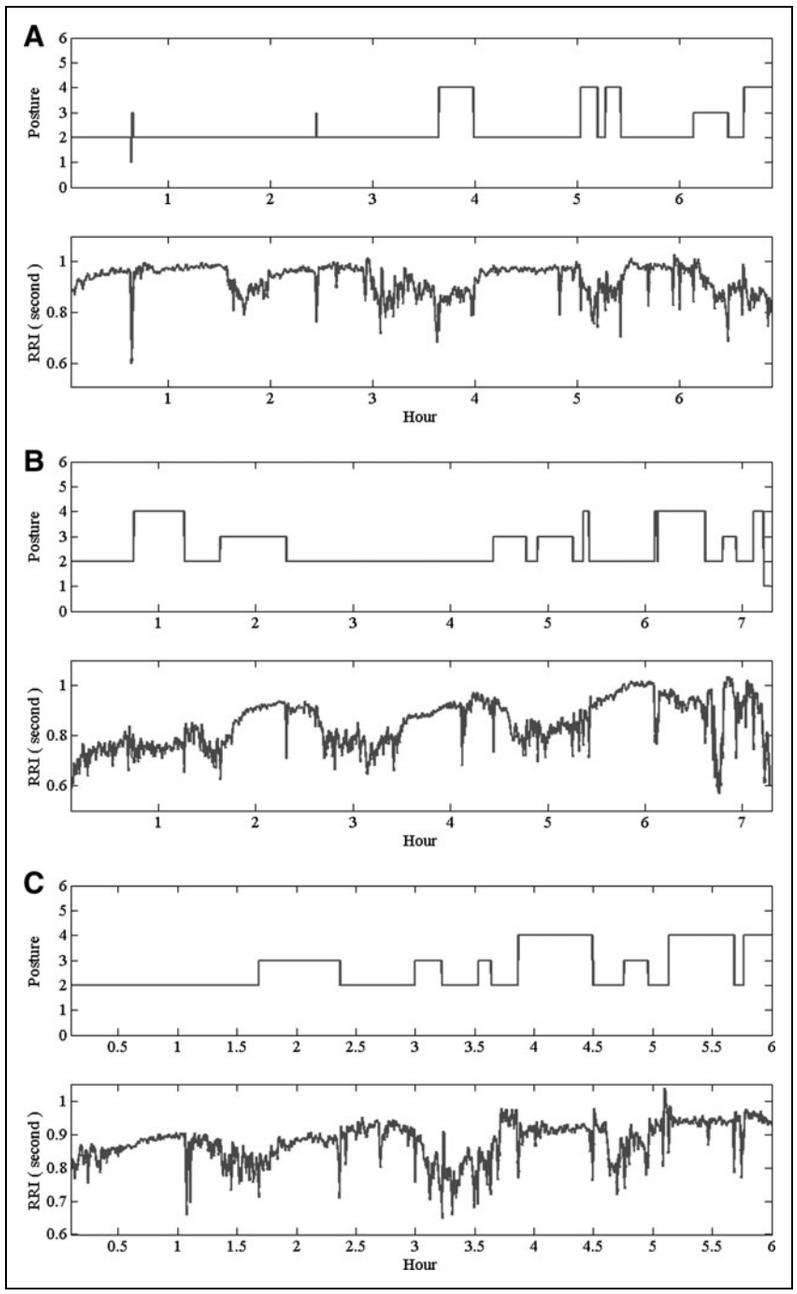


Fig. 5. Overnight sleep posture and heart beat variations of subject A at three nights (**A**: A1, **B**: A2, **C**: A3). The upper figure is posture determined by tri-axis accelerometer, and the lower figure is the corresponding heart rate interval sequences.

decreasing is often at the time of posture change, such at 0.6 h of *Figure 5A*. The change of posture may interfere with ECG recordings with massive noise and lead to false heart beat identification.

The overnight RRI statistics and posture distribution of the four subjects are listed in *Table 2*. The average RRI of subject B ranged from 0.93 to 0.98/s (BPM = 64.5–61.2), and the major sleep postures were P2 and P3. The RRI of subject C ranged from 1.0 to 1.06/s (BPM = 60–56.6), with the major sleep posture being P2. Subject D only recorded two nights successfully, and the third night's data was deleted due a loose electrode contact. The average RRI of subject D ranged from 0.99 to 1.03/s (BPM = 60.6–58.2), and the major sleep posture was P2. It is obvious that P2 (supine with face up) was the main sleep posture for most subjects. Chi-square results showed that there were significant differences of sleep posture proportion among three nights for all four subjects. Therefore, it is a night-to-night variability on sleep posture distribution. One-way analysis of variance results also showed the significant difference on each subject's RRI distribution among different nights.

Discussion

The system described in this article can be confidently used for overnight sleep monitoring. Previous studies have used a PDA system as a Bluetooth signal transmission system; now, we demonstrate an embedded circuit with a Bluetooth chip and MSP430 as a portable system, which is lighter and more convenient for the user. The wireless transmission range has been found to be sufficient for home users, even when they may get up and walk to the washroom or kitchen. The next door range is also detectable by the system, and data recording is consistent.

The aim of this study is not to develop a commercial portable sleep monitoring system; therefore, it is not an important issue to fit American Academy of Sleep Medicine classification category. This system is an improvement of previous work.[36] New added sensors, tri-axis activity, can provide sleep posture change and related information. More compatible and wireless systems can be beneficial for practical home users. Not limited to bed site monitoring as in the clinical lab, walking around the bed to the neighbor's room at night is still to be considered.

The night-to-night variability consisted of posture distribution and sleep staging performance. The respiratory disturbance index (RDI) for some patients with sleep disorder, such as those with OSA, may also vary on different nights. *Table 2* also showed significant variation on heart rate and posture distribution among three nights. Clinical sleep examination is only night PSG examination. Phenomena of night-to-night variability will challenge diagnosis reliability of clinical sleep examination. A PSG examination in the lab may ignore the night-to-night variability and have some diagnostic bias with a single night's sleep examination result. Therefore, this portable sleep monitoring system is important to measure the "real" sleep activity. It is very

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Table 2. Statistics of RRI and Sleep Posture Distribution of all Subjects with Overnight Sleep Recording

DATA	RRI (S)	*P*-VALUE	P1%	P2%	P3%	P4%	P5%	P6%	*P*-VALUE OF POSTURE
A1	0.93 (0.07)	<0.01	1	80	5	14	0	0	<0.001
A2	0.83 (0.11)		1	62	21	16	0	0	
A3	0.87 (0.08)		1	55	20	24	0	0	
B1	0.98 (0.09)	<0.001	0	52	45	3	0	0	<0.05
B2	0.93 (0.08)		0	63	37	0	0	0	
B3	0.95 (0.09)		0	50	50	0	0	0	
C1	1.00 (0.15)	<0.01	12	51	5	32	0	0	<0.001
C2	1.06 (0.11)		1	74	10	15	0	0	
C3	1.02 (0.16)		2	80	6	10	2	0	
D1	1.03 (0.08)	<0.01	0	40	23	37	0	0	<0.01
D2	0.99 (0.09)		20	58	8	14	0	0	

The unit of RRI is second and represented as mean (standard deviation). Posture distribution is represented as the posture occupation time percentage to total sleep time. Chi-square test was used for night-to-night intraposture variation. One-way analysis of variance was used for night-to-night intra-RRI variation testing. RRI, interval between R peak in each heart rate beat.

useful for diagnosis decisions and after diagnosis monitoring, such as for a continuous positive airway pressure (CPAP) user.

The accelerator is widely used for posture detection, especially for a body falling detection system, and is now used for sleep posture detection. The advantage of the accelerator for posture detection is the simple criteria of being able to identify posture. Real-time posture identification is now very easy. Some patients with sleep disorder may change their posture more frequently than usual. Consequently, sleep posture information is important for further diagnosis. In this study, the overnight sleep posture distributions were well demonstrated. Most subjects' dominant posture is supine (p2). Their other time is spent in side sleep posture, such as P3 and P4.

ECG data were also collected using this system. The overnight RRI sequence was observed, which is useful for sleep monitoring such as in sleep staging and OSA detection. The average RRI of each subject was quite similar; that means there were no intradifferences between subjects, but there were some interdifferences.

This system has many advantages. However, it is with some limitations. First limitations are the wireless transmission range. Battery time within 18 working hours is a main limitation of this system. Users had to recharge the battery every day. The wireless transmission may be broken if the subject moves to a room where the transmission needs to penetrate several walls. Although this system uses a motion noise reduction algorithm signal, collection may, in fact, be disturbed due to motion noise. An advanced adaptive signal processing algorithm to remove the motion artifact is beneficial to improve the signal collection quality. The comfort of the user is also of concern, and a smaller system will be more welcome.

In the future, more clinical data need to be collected to confirm the applicability of the proposed system.

Conclusion

A light and portable sleep activity monitoring system consisting of good design and application was developed. Overnight ECG and sleep posture were estimated. Posture was derived from real-time tri-axis accelerometer data. Night-to-night variability on subject sleep information was also considered. Intradifferences of heart rate and posture distribution were insignificant compared with interdifferences between subjects. Bluetooth transmission is beneficial for some walking and movement. This model is appropriate for home-based sleep monitoring and can be potentially useful for sleep monitoring of patients with some sleep disorders.

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Disclosure Statement

No competing financial interests exist.

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