The Unconstrained Sleep Monitoring System for Home Healthcare using Air Mattress and Digital Signal Processing

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공기 매트리스와 디지털 신호처리를 이용한 홈헬스케어용 무구속 수면 모니터링 시스템

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Abstract

For home healthcare, the unconstrained measurement of physiological signal is highly required to avoid the inconvenience of users. The recording and analysis of the fundamental parameters during sleep like respiration and heart beat provide valuable information on his/her healthcare. Using the air mattress sensor system, the respiration and heart beat movements can be measured without any harness or sensor on the subject's body. The differential measurement technique between two air cells is adopted to enhance the sensitivity. The balancing tube between two air cells is used to increase the robustness against postural changes during the measurement period. The meaningful frequency range could be selected by the pneumatic filter with balancing tube. ECG (Electrocardiography) and respiration sensor (plethysmography) were measured for comparison with the signal from air mattress. To extract the heart beat information from air pressure sensor, digital signal processing technique was used. The accuracy for breathing interval and heart beat monitoring was acceptable. It shows the potentials of air mattress sensor system to be the unconstrained home sleep monitoring system.

I. INTRODUCTION

When we say the non-invasive measurement methods in medicine, it has advantages in minimal pain (sometimes no pain) than invasive measurement like catheterization or biopsy examination. Ultrasound imaging and many kinds of electric potentials as ECG (electrocardiography for the heart) and EEG (Electroencephalography for the brain) are the typical non-invasive measurement techniques. But the non-invasive measurement method makes the inconvenience in monitoring of healthcare status in daily life. This inconvenience makes long term monitoring impossible. The concept of non-intrusive measurement or unconstrained measurement of physiological signal has stronger condition as there should be no additional sensor or harness on body surface of subjects. So the condition of unconstrained measurement is essential in home healthcare and ubiquitous healthcare solution.

As the obese population is growing rapidly, the need of sleep monitoring device is also increasing. Even though polysomnography (PSG) is the standard sleep analysis method in hospitals, it is too complex to be used in the home. The portable devices also need electrodes or sensors on the body surface [1]. In this paper, the unconstrained measurement technique was used to monitor the respiration and heart beat movement during sleep. The respiration, heart beat are the fundamental physiological signals that are needed for sleep analysis. For the purpose of unconstrained monitoring, there have been several trials until now. Tanaka [2] suggested a phonocardiogram sensor on the bed and Static Charge Sensitive Bed (SCSB) was also introduced by measuring the changes of static charge by the movement of respiration [3]. Even with these trials, there is no leading method that is stable, accurate, and economic until now.

There have been the studies using air mattress [4-6]. The respiration and heart beat movement add pressure to the air cell, which changes the pressure in the air mattress. In the measurement using air mattress, the most difficult point is to pick up the small signals of the respiration and heart beat movements from the large signals those are associated with motion artifacts and body weight. Normal air pressure sensor has its limited operating range and the sensitivity. In order to solve this problem, the balancing tube was connected between two air cells which can be the frequency selective filter in pneumatic method [7].

In this paper, the principle of the measurement and the experimental validation of its effectiveness in various situations

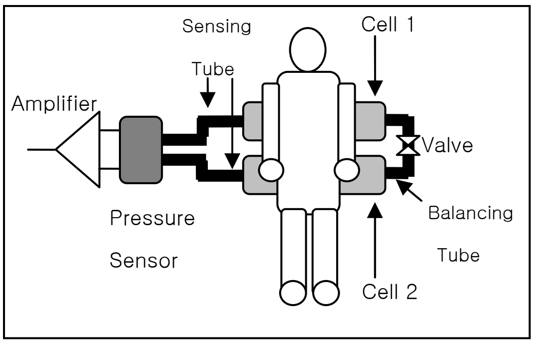

Fig. 1. The air mattress sensor system with balancing tube

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were summarized.

II. METHODOLOGY

A. Measurement Principle

As shown in Fig. 1, when a subject is lying on the air mattress, any movement including respiratory effort, heart beating and postural changes make change the air pressure inside the air cells. To enhance the sensitivity, the differential measurement technique was used as shown in Fig. 1. The pressure by the body weight can be regarded as the static pressure during the measurement. By measuring the differential pressure in remote device with tubes (sensing tubes in Fig. 1), we can record the respiratory and the heart beat movement in pneumatic method. One of the advantages of the differential measurement is to reject the common mode artifacts that are not related with respiratory and heart beat movement like body weight and environmental noise.

In previous study [7], this measurement system was modeled as the band pass filter which can reject the dc component (body weight) and high frequency component.

$$R_2 C_2 \frac{dp_{c2}}{dt} + p_{c2} = p_{c1} \qquad (1)$$

$$R_1 C_1 \frac{dp_o}{dt} + p_o = p_{cd} \qquad (2)$$

R_1 and C_1 are the air resistance and capacitance of sensing tube R_2 and C_2 are the air resistance and capacitance of balancing tubes. p_{cd} is the pressure difference between two air cells(p_{c1} , p_{c2}) and p_o is the pressure that is delivered to the transducer. The lower cutoff frequency of pass band can be adjusted by rotating the opening area of the balancing tube. The respiratory and heart beat movement can be described as the linear combination of sinusoidal waves with small amplitudes. The balancing tube has high resistance and small capacitance. It is able to block the air flow for very low frequency components between two cells. With this balancing tube, after the postural changes, the operating point of differential pressure returns around zero level automatically.

B. Analysis algorithm

To extract the quantitative information from air mattress system, we have to calculate the heart beat interval and respiration interval. In this study, Pan&Tompkins algorithm [8] was used to detect QRS complex from ECG signal. The respiration and heart beat signals from air mattress have quite different properties from those of ECG. So modification of the algorithm is required to detect certain feature points from the measured waveform.

At first, one epoch of 30s was checked whether there was

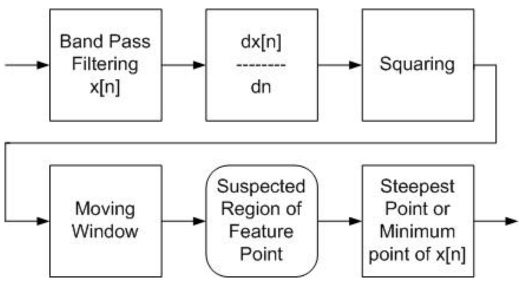


Fig. 2. The flow chart to localize the feature points in semi-periodic waveform.

Fig. 3. The sensor system using air mattress

postural change or big movement during sleep. In this case, the calculation of physiological parameters is impossible. Based on high gain of its measurement system, bigger movement than respiration effort makes saturation in one direction (maximum value or minimum value). We can mark easily whether a certain epoch has movement event or not. If there was no big movement, the signal is separated into respiration and heart beat with frequency selective filter. The power spectrum of respiration signal from air mattress is mainly distributed in lower frequency band (< 1Hz). And the largest peak in one heart beat complex has the frequency from 1 to 15 Hz. As a pre-processing, there should be band pass filter for each purpose. In this study, 4^{th} order Butterworth filter was used with software. Then the filtered signal is derived and squared to localize the peak in the waveform. With the time location of the peaks, the breathing rate and heart rate are calculated. The Fig.2 shows the procedures for this algorithm.

C. Implementationand Measurement Experiment

As shown in Fig. 3(a), the air mattress system with 20 air cells was constructed. In this experiment, the two cells that are located on the backside of chest and abdominal region were chosen where we could obtain the large respiration signal than the other locations. The other air cells in Fig. 3(a) are to support the body in comfortable way. The cells are in the form of a cylinder with the diameter of 110mm, which was made from a polyurethane sheet, and air was filled at 10 kPa in the beginning. We connected the air cells and sensors that are assembled on the circuit board with the silicone tube with the inner diameter of 4mm, an outer diameter of 8mm, and a length of 1.0 m. The length of the balancing tube was 0.5 m. In the middle of the balancing tube, there is a rotational valve that can control the open area precisely (Fig. 3(b)). NPC-1210 (100mVolt/5psi) from Luca NovaSensor® is used for pressure transducer. The analog signal was sampled at 200 Hz and digitized into 16 bits with Biopac Inc. To test its validity for human body, a male subject (67Kg, 36 years old) slept over the mattress through the night. Together with the air mattress sensor, the traditional electrocardiography (Biopac Inc.) and nasal airflow (Biopac Inc.) and respiration effort (resistive type, Biopac Inc.) were measured simultaneously to compare as standard method.

III. RESULTS

A. Measurement in qualitative view of waveforms

Fig. 4 shows the measurement results from human body with the air mattress sensor system. Fig. 4(a) is the signal from the pressure sensor, which measures the pressure change in the air mattress system with a balancing tube. This figure shows clearly the respiration movement, which can be confirmed by comparing it with Fig. 4(b) that is the direct measurement of nasal air flow using a thermistor below the nose hole. Fig. 4(c) is the band pass filtered waveform in the range from 1 to 15 Hz. In order to extract the heart beat movement from the respiration movement, a digital filter (4^{th} order Butterworth filter) was applied to the signal (a). The heart beat movement could be extracted from the air mattress system. The heart rate can be detected using the waveform of Fig. 4(d) which is the first derivative of Fig. 4(c). Fig. 4(e) is the conventional ECG recording. As a result, Fig. 4 shows that the suggested air mattress sensor system with a balancing tube can be used as one of the unconstrained monitoring of cardio-respiratory signals for sleep analysis.

B. Results of the analysis algorithm

As explained in II.B, after the measurement of signal, the useful parameter can be calculated by applying the feature point detection algorithm. Respiration interval (inter-breathing-interval) and heart beat interval (similar to R-R interval in ECG) are the most fundamental parameter for further analysis. Fig. 5 shows the respiration signal that is measured by air mattress system. Fig. 5(c) shows respiration intervals that were calculated from (a) and (b) for comparison. It shows that the respiration intervals those were calculated with air mattress are equivalent with the signal that was from the conventional sensor system.

Fig. 6 shows the heart beat signal that is measured by air mattress system for 20 seconds. Fig. 6(a) is the control signal that is measured by the conventional ECG. The cross marks shows the detected reference feature points to calculate R-R interval. In this algorithm, the steepest slope points in R-S segment were chosen. The Fig. 6(b) is the band pass filtered (pass band is 1Hz~15Hz) signal from air mattress. The points where the circles are located in Fig. 6(b) indicate the points where the feature points are. Fig.6(c) is the comparison between two methods. It shows that the heart beat intervals that were calculated with air mattress is very close to those from ECG.

C. Accuracy Analysis

Fig.7 (a) shows the comparison data of the inter breath intervals those were calculated from standard respiration sensor and from air mattress. The respiration rate has high correlation (correlation coefficient = 0.981) with the signal from standard sensor. The SD (standard deviation) is 0.1156 second that is sufficiently small to monitor the breathing activities. Fig.7 (b) shows the comparison data of the heart beat intervals those were calculated from standard ECG and from air mattress. The heart beat intervals from air mattress and R-R intervals from ECG has also high correlation coefficient of 0.8516. The SD (standard deviation) of the difference between two methods is 10 ms. The differences come from the methods to pick up the feature points in waveform to calculate rate.

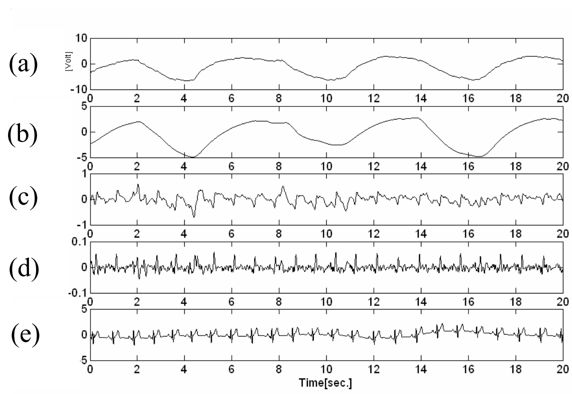


Fig.4. The waveforms from air mattress and the conventional methods. All of the horizontal axes are the time in second, and all of the vertical axes are the amplified voltage outputs from each electrode and sensor. The meaning of each waveform is described in the text.

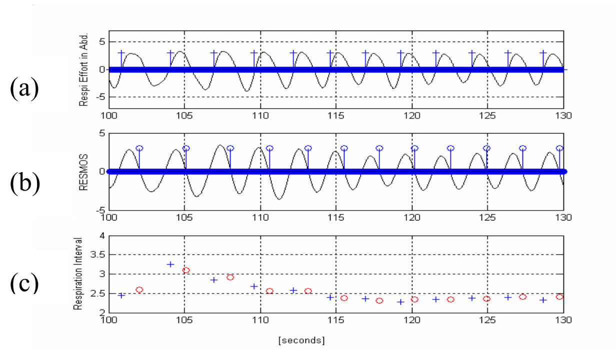


Fig.5 Calculation of inter-breathing interval (a) Respiration signal as control signal that is measured by the resistive type respiration sensor belt (standard method) (b) The low pass filtered (*fc*=1Hz) signal of air mattress (c) The instantaneous respiration interval that were calculated from (a) and (b)

D. Sleep monitoring

Fig.8 (a) shows the respiration intervals during sleep for 6 hours. After dividing into 720 epochs (1 epoch is 30 seconds, 720-epochs are 360 minutes), average breathing interval was calculated. The circles in the graph indicate the movement epoch. Fig.8 (b) shows the change of heart beat intervals that were calculated from the air mattress signal. In Fig.8, the initial 20 minutes was excluded because there were large body movement before falling asleep. Clearly we can see the variability of heart rate that might be useful to analyze the quality of sleep.

IV. DISCUSSION & CONCLUSION

An air mattress sensor system was used to detect minute movements due to respiration and heart beat without any electrode or sensors attachment on the subject's body surface. The differential measurement of two air cells was done to increase the sensitivity of sensor system. A balancing tube concept was adopted in order to increase the robustness against postural changes during the measurement. The potential of applications in unconstrained sleep analysis was examined by measuring the various sleep postures and basic analysis of the waveforms. With digital signal processing methods, the physiological parameters as respiration intervals and heart beat

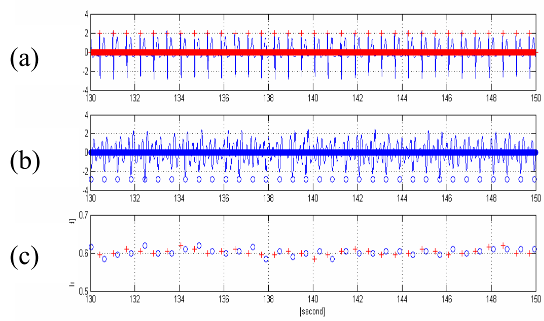
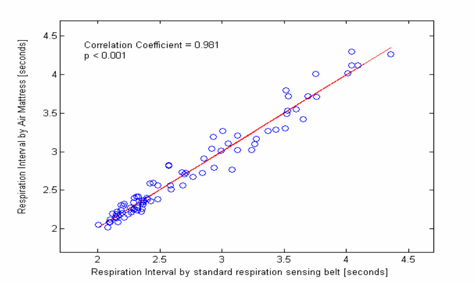
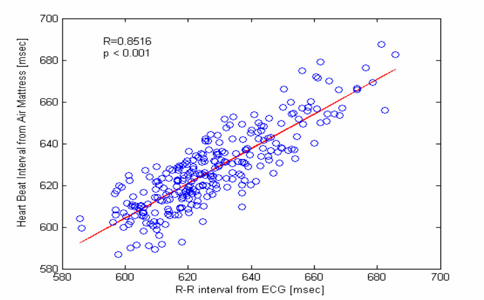


Fig.6 Calculation of heart beat intervals (a) ECG signal (standard) (b) The band pass filtered(pass band is 1 Hz ~ 15 Hz) signal from air mattress (c) Heart rate that were calculated with (a) and (b)



(a) Inter-Breathing Intervals between standard

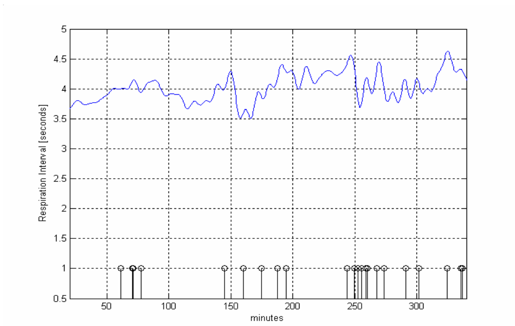


(b)Heart Beat Intervals between the standard method (RR

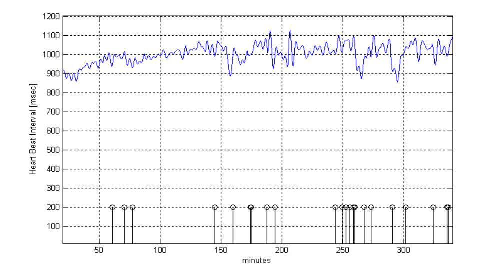
Fig.7 Accuracy analysis of physiological parameters

intervals and its average in each epoch can be calculated accurately. The comparison with conventional method was shown.

In the future, it is needed to analyze the waveforms in the various conditions as well as with various subjects including patients and neonates for sudden infant death syndrome where there is no effective monitoring method available. Also to



(a) Inter-Breathing Intervals during. The circles



(b) Heart Beat intervals. The circles indicate the

Fig.8. The physiological parameters during 6-hours sleep

develop this system to effective monitoring device, intelligent and robust algorithm to calculate many parameters should be investigated.

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