URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Unobtrusive Respiratory Monitoring of Sleeping Subjects by Multiple Bioradars

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Abstract

The development of effective personal non-contact methods for detecting sleep disorders, which may precede different health problems, is an up-to-date task of modern medicine. As was shown in recent studies, it is possible to detect sleep disorders by means of bioradar. However, the problem of view dependency of the radar-based sleep monitor performance needs to be overcome. In the present paper we presented a two-transceiver system and a signal processing algorithm for obtaining information about sleeping person respiratory rates at different positions of a human body during sleep. The proposed system was tested in a sleep laboratory of Almazov National Medical Research Centre with the participation of 5 volunteers. The performance of the proposed algorithm was estimated by comparison with a full-night polysomnography data. The achieved results showed that the designed two-channel bioradar system proved to be more accurate and robust than a single bioradar. The results might contribute to extension of bioradar sleep monitoring technology.

1 Introduction

A restorative sleep is vital for maintaining a person's physical and psychological health. However, the increasing pressure and speed of everyday life leads to lack of sleep and decreasing its quality. Insufficient sleep duration and poor sleep quality can result in heart disease [1, 2], depression [3], obesity [4], diabetes mellitus [5], and neurodegenerative diseases [6, 7]. Even one sleepless night might result in changes of immune responses [8].

During the last year because of COVID-19 pandemic researchers in sleep medicine have paid even more attention to sleep quality because of its immunomodulating effect and correlation of COVID-19 severity and sleep quality [9, 10].

The standard method in sleep diagnostic is polysomnography (PSG). It requires the patient to be tested in a specialized laboratory environment. Moreover, a few dozens contact sensors and electrodes need to be attached to the subject's body. Therefore, undergoing PSG may cause difficulties in falling asleep and have negatively impact sleep quality. Therefore, the problem of creating accurate and reliable unobtrusive methods for detecting and monitoring various sleep disorders and estimating sleep quality remains relevant at the moment, that will be able to provide natural conditions during sleep.

One of these methods is bioradiolocation [11], which detects movements of the human body surface and thus allows monitoring human respiratory and movement patterns during sleep without an physical contact to the body. There are a few papers to date describing monitoring sleep stages and detection sleep breathing disorders of subjects based on the analysis of respiratory patterns by means of bioradar (BRL). It should be noted that different groups of researchers are testing BRLs for different positions of the device relative to the subject: above or below the bed [12, 13], on the left or right side [14, 15].

As it is known from physiology, the amplitude of the chest movements caused by breathing in different directions can differ significantly. As a consequence the amplitude of the detected by a BRL signal depends on the orientation of the BRL toward the subject and reaches maximum for a frontally oriented BRL. So, since the subject position changes during sleep, then the optimal position of the BRL also will change. This results in decreasing quality of the received BRL signal, if the subjects orientation becomes not optimal.

To overcome this problem, in the present paper we propose the combined use of two BRLs oriented relative to the sleeping subject at different angles, that would make it possible to create a more robust system for assessing the breathing rate during sleep.

2 Experiments and Methods

In the present paper we used BRL data of five subjects, who underwent a polysomnography study at Almazov National Medical Research Centre (St. Petersburg, Russia) in 2020. The characteristics of each subject are listed in table 1. Experimental study was approved by the Ethical Committee of Almazov National Medical Research Centre. Prior to the experiment each subject gave his/hers written consent.

Table 1. Subjects Characteristics

Volunteer	1	2	3	4	5
Age, years	52	77	63	35	24
Gender	m	m	m	m	m
BMI, kg/m^2	27.4	26.2.6	34.0	30.0	21.0
PSG record duration, min	564.0	728.8	579.2	493.1	458.0
AHI, events per hour	2	9	81	6	3

During the experiments, two BRLs were used to record sleeping volunteer vital signs simultaneously with PSG. The full-night PSG monitoring was performed using Embla N7000 system (Natus Neurology Inc., USA). As BRLs we used BIORASCAN-24 devices designed at Remote Sensing Laboratory at Bauman Moscow State Technical University. They utilise continuous wave of 24 GHz as a probing signal and provide two quadrature signals (I and Q) as outputs. The design of the BRL was described in [15]. We set different probing frequency for each BRL to prevent their signals interfering while used simultaneously. The technical characteristics of both BRLs used in this paper listed below:

- Probing frequency: 24.0 and 24.1 GHz;
- Detecting signal band: 0.05–20 Hz;
- Beam aperture: 80/34 °;
- Sampling frequency: 50 Hz;
- Radiated power density: <3 μW/cm^2;
- Size: 95x75x45 mm.

The BRL # 1 was located at 1.2 m above the floor at a distance of approximately 1.5 m to the left from the sleeping volunteer. Another BRL was attached to the wall to the right from the couch 1.6 m above the floor and was pointed to the couch. Both BRLs were pointed to the volunteer's thorax (Fig. 1).

Recordings of both PSG and BRL signals were started by the somnologist in the evening and stopped the following morning. The classification of all sleep events in the PSG record and estimation of apnea-hypopnea index (AHI) were done by a somnologist according to recommendations of the American Academy of Sleep Medicine [16]. The internal clocks of the PSG and BRL computers were synced, that allowed using of PSG data as a ground truth.

Figure 1. Photo of the experiment.

3 Data Processing

The BRL signal processing algorithm consisted of the following stages:

- Demodulation. For each BRL we extracted the phase of the I and Q quadratures using an arctangent demodulation.
- Filtration. The phase signals for both BRLs were filtered using 5th order Butterworth filter with cutoff frequency of 0.05 and 0.5 Hz.
- Movements Detection. Subjects movements during the sleep results in BRL signals artefacts with amplitude much higher that the one for periods of motionless sleep. Thus, during the movement artifacts the respiratory rate (RR) cannot be estimated correctly. Therefore, all intervals of BRL signals with movement artifacts should be excluded from further analysis. To do so, we detected each artefact using the algorithm proposed in out previous work [17] and split the record to inter-artefact intervals (IAI).
- Respiratory Rate (RR) Estimation. For each IAI we calculate respiratory cycle duration as the time interval between adjacent local maximums.

4 Results

To estimate the accuracy of the proposed algorithm we compared the RRs calculated for every 30 s epoch using BRL signals with the same parameters for the one of PSG channels (the abdomen belt of respiratory inductive plethysmography, which is standard contact method for respiratory pattern registration). The obtained RRs were compared for each of 5 subjects. The performance of the proposed algorithm was estimated using accuracy and mean absolute error.

The two metrics were calculated for each of two BRLs separately with and without regard to the subjects position during sleep (Tables 2 and 3, respectively). As it can be seen from the Table 3 there is no answer which of two BRLs positions is optimal: for subject # 2 the BRL #1 provided more accurate RR estimation, while for remaining 4 subjects the results are opposite.

Moreover, we proposed an additional way of RR estimation using data for both BRLs in conjunction. For each 30 s epoch we chose from the RR estimates for two BRLs the one closest to the mean overnight RR for the subject. As it can be seen from Table 3, using data for BRLs #1 and #2 simultaneously for RR estimating results in better results than for these BRLs separate usage.

Table 2. Results of Respiratory Rate Estimations

Sub. #	BRLs #	Body position and accuracy, %		
		Left	**Supine**	**Right**
1	**1**	92.0 ± 11.2	90.9 ± 12.2	91.8 ± 10.5
	2	94.3 ±12.1	94.2 ± 11.8	95.4 ± 9.4
	1&2	94.6 ± 9.4	95.3 ± 7.4	94.6 ± 7.7
2	**1**	67.4 ± 27.1	-	93.4 ± 12.6
	2	73.3 ± 25.6	-	92.0 ± 11.1
	1&2	71.4 ± 23.9	-	94.4 ± 8.9
3	**1**	68.9 ± 18.3	83.5 ± 22.2	84.1 ± 19.5
	2	72.4 ± 19.9	86.4 ± 17.9	82.1 ± 20.0
	1&2	71.3 ± 18.0	87.8 ± 15.7	85.0 ± 16.4
4	**1**	93.9 ± 10.8	89.9 ± 15.6	-
	2	92.7 ± 15.5	93.5 ± 11.7	-
	1&2	93.9 ± 10.6	95.4 ± 7.8	-
5	**1**	88.3 ± 16.4	90.7 ± 13.4	80.9 ± 14.1
	2	89.9 ± 15.0	92.2 ± 11.5	88.4 ± 8.2
	1&2	90.5 ± 16.4	93.6 ± 9.0	88.4 ± 8.2

Table 3. Results of Respiratory Rate Estimations

Subject #	BRLs #	Accuracy, %	Mean Abs. Error
1	**1**	91.7	0.33
	2	94.2	0.21
	1&2	94.8	0.21
2	**1**	91.2	0.41
	2	90.4	0.45
	1&2	92.5	0.38
3	**1**	82.0	0.84
	2	84.6	0.74
	1&2	85.5	0.75
4	**1**	92.3	0.31
	2	93.0	0.26
	1&2	94.5	0.22
5	**1**	89.7	0.47
	2	91.2	0.40
	1&2	92.4	0.35

5 Conclusion

In the present paper we presented a two-transceiver system and a signal processing algorithm for obtaining information about sleeping person respiratory rates at different positions of a human body during sleep. The proposed system was tested in a sleep laboratory of Almazov National Medical Research Centre with the participation of 5 volunteers undergoing sleep study, both health and with sleep–disordered breathing. The performance of the proposed algorithm was estimated by comparison with a full-night polysomnography data. The achieved results showed that the designed two-channel bioradar system proved to be more accurate and robust than a single bioradar.

The study has some limitation because the algorithm was tested on data of 5 subjects only. Two of them were healthy and three had mild to severe obstructive sleep apnea.

In further studies, we are planning to expand the dataset, include data of subjects not only with sleep breathing disturbance but with other sleep disturbances. Nevertheless, this study is an important step on the way of creating a robust view-independent bioradar system for assessing the breathing rate during sleep.

6 Acknowledgements

The research was supported by the grant of Russian Foundation for Basic Research No. 18-29-02013.

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