Application of step-frequency radars in medicine

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ABSTRACT

The paper summarizes results of step-frequency radars application in medicine. Remote and non-contact control of physiological parameters with modern bioradars provides a wide range of possibilities for non-contact remote monitoring of a human psycho-emotional state and physiological condition. The paper provides information about technical characteristics of bioradars designed at Bauman Moscow State Technical University and experiments using them. Results of verification experiment showed that bioradars of BioRASCAN type may be used for simultaneous remote measurements of breathing and heart rate parameters. In addition, bioradar assisted experiments for detecting of different sleep disorders are described. Their results proved that method of bioradiolocation allows correct estimation of obstructive sleep apnea severity compared to the polysomnography method, which satisfies standard medical recommendations.

Keywords: Bioradiolocation, bioradar, remote sensing, contactless vital signs monitoring, sleep monitoring

1. INTRODUCTION

Bioradiolocation is a modern sensing technique giving the opportunity to detect persons remotely even behind opaque obstacles, not applying any contact sensors. It is based on radar signal modulation by oscillatory movements of human limbs and organs. Electromagnetic wave reflected from human body obtains specific biometric modulation, which is not present when interacting with motionless objects. The main factors of such signal changes are heartbeat; contractions of vessels; movements of limbs; reciprocal movements of chest wall and abdomen areas caused by breathing. Patient's physical activity and medical state determines the values of these fluctuations. Bioradiolocation have a variety of potential areas of application: military, law enforcement, medicine, etc. A detailed list of these areas is given below.

- Terrorists and hostages localization inside the buildings during counter-terrorism operation[1,2]. These are a few commercially available bioradars for this application[3,4], however these devises have several limitations which till now have not been overcome, the most serious one is a high attenuation of bioradar signal while propagating through wet or reinforced concrete walls.
- Disaster medicine. Bioradars are used for detection of live humans under debris of destroyed buildings after natural disasters or technical catastrophes[5,6]. The most serious challenge lies in multipath propagation of bioradar signal. So far, to reduce the level of false alarms in this case all dismantling work should be stopped for the period of searching with the bioradar. The same technique may be applied during fire emergency search[7].
- Battlefield triage[8]. The application of bioradar could help in distinguishing between wounded and dead person and thus establish the order of evacuation and treatment priority.
- Transportation safety (examination of transport containers for revealing illegal persons and intelligent crossing the border[1]).
- Remote diagnostics of psycho-emotional state during latent or open checks in criminal investigations or at checkpoints[1].
- Remote speech detection[9].
- Contactless registration of heartbeat and breathing parameters for burnt patients and for patients for whom contact sensors cannot be applied[1,2,10].

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- Sleep medicine. Bioradars are supposed to monitor respiration and heartbeat pattern during night sleep and thus diagnose sleep apnea syndrome[11]. In case of newborns it is possible to use this method for detection of Sudden Infant Death Syndrom[12], which would help to apply early actions in case of it.
- Estimation of vessel elasticity from pulse-wave velocity for revealing patients predisposed to cardiovascular disease[13].
- Smart homes. One can use bioradars for monitoring movement activity of elderly subjects at home[12].
- Tumor tracking in radiation therapy[12].
- Laboratory animals locomotor activity monitoring[14].

There are several challenges in achieving reliable registration of respiration and heart rate parameters in practice by means of radar. Among them are: clutter caused by surrounding objects and multipath propagation, movement artifacts with amplitude much bigger than useful signal and problems with isolation of respiration and heartbeat signals in case of prolonged monitoring.

That is why noncontact control of vital signs by means of bioradar is a challenging task and requires development of adaptive algorithms for effective informative components extraction from bioradar signals, as well as implementation of procedures aimed to improve the stability of estimates calculations for such physiological parameters as respiration and heart rate. By applying the rejection of all approach-zero frequencies from the bioradar signal reflected from local objects it is possible to suppress clutter caused by surrounding objects[15].

2. APPARATUS AND METHODS

At Bauman Moscow State Technical University (BMSTU) method of bioradiolocation has been studied since 2002. Primarily a modified ground penetrating radar (operating frequency is 1.6 GHz) was used. The experimental results showed that sensitivity of the bioradar modification applied needs to be increased. It was also proposed to use not monochromatic but multi-frequency probing signal. The main advantage of wideband and UWB signals over monochromatic signals in probing live objects is that the field under observation can be divided into distance cells; which allows measuring the distance to a target and rejection of clutter caused by background objects. That is why in 2006 multi-frequency bioradar BioRASCAN was designed. At present, it has two modifications BioRASCAN-4 and BioRASCAN-14 (Fig. 1a and b respectively) operating in different frequency ranges. Table 1 presents their technical characteristics.

(a) (b)

Figure 1. BioRASCAN-4 (a) and BioRASCAN-14 (a).

As it is known, the sensitivity of short-range radars is increasing with the probing frequency value; however, attenuation of the probing signal in the media has the same dependence on the frequency. Therefore, details of a bioradar practical application determine choice of BioRASCAN-4 or BioRASCAN-14 in each case. For example, in monitoring of human vital signs in sleep BioRASCAN-4 is preferable, whereas for evaluating of small laboratory animals' movement activity BioRASCAN-14 shows better results.

Since 2006 a number of bioradar-assisted experiments were carried out at BMSTU, their details are given in Section 3.

Table 1. Technical characteristics of BioRASCAN radars.

	BioRASCAN-1	BioRASCAN-4	BioRASCAN-14
Number of frequencies	1	16	
Operating frequency band, GHz	1.6	3.6-4.0	13.6-14.0
RF output, mW	<10	<3	
Gain constant, dB	20		
Detecting signals band, Hz	0.03-3.00	0.03-5.00	0.03-10.00
Dynamic range of the detecting signals, dB	60		
Size of antennas block, mm	200x120	370x150x150	120x50x50
Sensitivity, mm	2.5	1.0	0.1

3. BIORADAR ASSISTED EXPERIMENTS

3.1 Verification of respiration and heartbeat patterns obtained with bioradar

Firstly, we compared estimates of respiration and heartbeat rates measured with bioradar and clinically applied methods to prove that the former is feasible for simultaneous remote measurement of before-mentioned parameters. Extraction of respiration and heartbeat patterns from the received bioradar signal was performed with purpose-written algorithms, using the MATLAB software package (MATLAB R2012b; The MathWorks, Inc; USA).

At present, the golden standard method for respiratory efforts monitoring is respiratory plethysmography, which was used during feasibility study of bioradar BioRASCAN-4 for respiration pattern monitoring. We compared bioradar and respiratory plethysmography data during parallel registration of respiratory movements in both time and frequency domains using cross-correlation and spectral methods[16]. Fig. 2 presents photo of the experiment.

Figure 2. Comparison of bioradar and respiratory plethysmography data.

The constructed correlation field for couple of signals recorded with both methods indicated strong positive linear relationship between breathing rate values registered simultaneously with bioradar and respiratory plethysmograph. The obtained values of cross-correlation coefficients, ranging from 0.84 to 0.94, indicate linear relationship between bioradiolocation and plethysmography signals in time domain.

The calculated estimates of cross-spectrum effective width for all the couple of signals realizations revealed the fact that the main cross-power spectral density of signals is concentrated in the narrow frequency range of external respiration activity parameters registration. Thus, bioradar and abdominal respiratory plethysmography belt signals are almost linearly related in both time and frequency domains. So by the experiments it was proven that bioradiolocation should be considered as reliable and correct approach for non-contact remote monitoring of external respiration activity parameters.

For verification of heartbeat frequency estimated by mean of BioRASCAN-4 we utilized ECG, which is a standard method for monitoring of heart electrical activity. 103 adult examinees (36 males and 67 females, 20 ± 1 years (mean ± S.D.)) participated in the study, for each of them bioradar and ECG signals were recorded (duration of one record was 1 min). During the experiment, an examinee sat in relaxed pose in front of the bioradar at the distance of 1 m from antennas. Values of heartbeat rate for contact and non-contact methods were compared, which showed that estimates made by each method are agreed with confidence level of $p = 0.95$.

Thus, the feasibility of bioradar BioRASCAN-4 application for simultaneous remote measurements of breathing and heart rate parameters was proven.

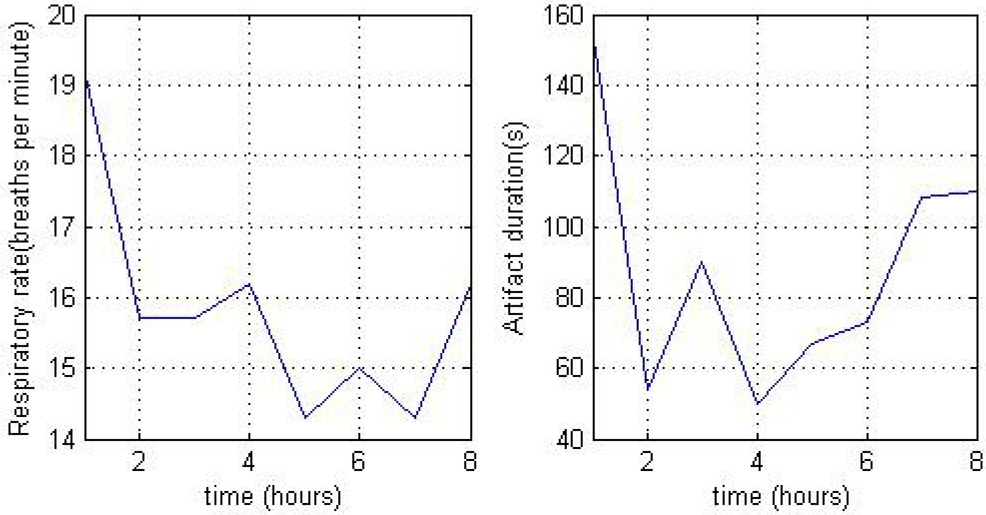
3.2 Bioradar in Sleep Monitoring

The most promising area of bioradiolocation application in medicine is somnology, where we propose to use bioradar technique for detecting of different sleep disorders. The main advantage of the method in case of monitoring vital signs of sleeping people is that it does not require application of any contact sensors and thus does not disturb the sleep of the examinee. On the contrary, a golden standard method for sleep monitoring (polysomnography) uses of several dozens of contact electrodes and sensors, which may be an additional stress factor for sleep laboratory patients and hence worsen the sleep quality.

In 2009 we started to investigate the possibility of bioradar application in sleep medicine for remote monitoring of movement activity, respiration and heartbeat patterns. During preliminary tests, bioradar signals were recorded for the whole night sleep. The experiments were used for developing and testing of sleep monitoring procedure by means of bioradar and appropriate data processing algorithm.

As a result the bioradar experiments were included into the scientific program of the International research project MARS-500 (simulation of prolonged isolation during a manned flight to Mars), which was conducted by Institute for Biomedical Problems of Russian Academy of Sciences from June 2010 to November 2011[17]. An ethical committee approval and informed consent from all the crewmembers were obtained before the start of the experiment. The crew of MARS-500 had been trained to perform bioradar experiments before the start of the prolonged isolation. During the project MARS-500, seven series of bioradar experiments were conducted for each of six crewmembers. The results revealed that it is more convenient to use values of the interested parameter average per hour to analyze its dynamic during full night sleep. Fig. 3 presents the results of the experimental data recorded for one of MARS-500 crewmembers.

The processing of experimental data revealed the individual characteristics of sleep latency and sleeping of crewmembers. Some of them has longer period of falling asleep and more restless sleep, others on the contrary fall asleep faster and have more calm and regular breathing pattern during sleep time. For none of the crewmembers any clinically significant sleep disordered breathing episodes were registered, however episodes of hypopnea in bioradar signals were detected, which is normal for practically healthy people.

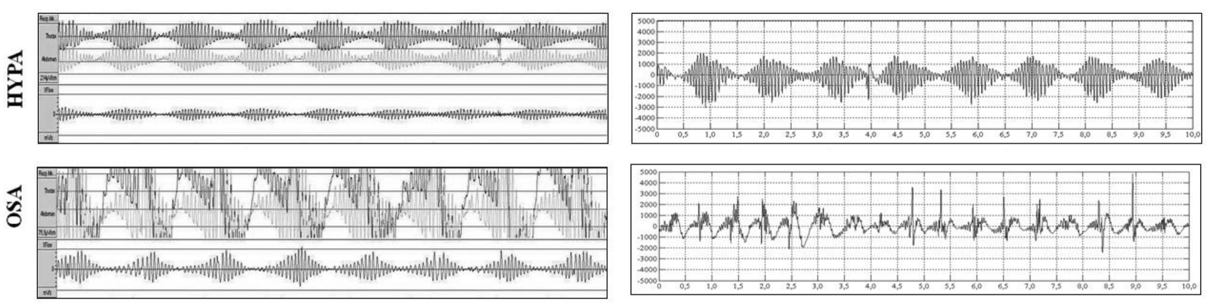


(a) (b)

Figure 3. Dynamic of respiration rate (a) and movement activity (b) during full night sleep registered by BioRASCAN.

On completing MARS-500 bioradar assisted sleep experiments were continued on the base of Sleep Laboratory of "Almazov Federal Heart, Blood and Endocrinology Centre" (St. Petersburg, Russia). Their purpose was to estimate the quality of bioradar monitoring in noncontact screening diagnostics of obstructive sleep apnea syndrome compared with standard polysomnography method, which satisfies standard medical recommendations. In the experiment 15 volunteers aged 21 to 62 years, with the body mass index varying from 18.4 to 57.7, participated with the following OSA severity by the apnea-hypopnea index (AHI): severe for 4 test subjects, moderate for 1 subject, mild for 1 subject, and 9 test subject was almost healthy. For subsequent verification of bioradar signals full night polysomnogram records were collected in parallel with Embla N700 system application.

Bioradar signals with typical forms for the sleep disordered breathing episodes were analyzed. They are visually similar to the correspondent signals registered by abdominal belt sensors within the framework of the complete polysomnography research (Fig. 4).



(a) (b)

Figure 4. Hypopnea (HYPO) and obstructive sleep apnea (OSA) respiratory patterns recorded by Embla N700 (a) and BioRASCAN-4 (b).

While estimating the quality of bioradar monitoring in non-contact screening of obstructive sleep apnea sensitivity value of 71 % were obtained with the prognostic value of positive decision 75 % of the sleep disturbance presence. The results should be considered satisfactory, as for each test subject the AHI score was in the same range of thresholds for determination of the of obstructive sleep apnea severity compared to the polysomnography method.

4. CONCLUSION

At present on the base of Almazov Federal Heart, Blood and Endocrinology Centre bioradar assisted experiments are continued, during which bioradar data recorded simultaneously with full-night polysomnograms for patients not only with sleep breathing disturbances, but also with insomnias. These experimental data are planed to be used for studying the possibility to distinguish REM and non-REM sleep only by breathing pattern recorded by bioradar without applying any additional contact sensors. Furthermore, the design of bioradar assisted technique for monitoring of movement and respiration pattern of bed-patient or seniors for preventing bedsores is under consideration.

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