Bioradiolocation: Methods and Applications

Lesya Anishchenko[1], Maksim Alekhin[1], Sergey Ivashov[1], and Maxim Ryzhii[2]

[1] Remote Sensing Laboratory, Bauman Moscow State Technical University, Moscow, Russia
{anishchenko,malekhin,sivashov}@rslab.ru
[2] University of Aizu, Aizu-Wakamatsu, Japan
m-ryzhii@u-aizu.ac.jp

Abstract. Remote and non-contact control of physiological parameters with modern radiolocation means application provides a great amount of possibilities for non-contact remote monitoring of human psycho-emotional state and physiological condition. The practical significance of bio-radiolocation monitoring applications is especially urgent for rescue services and law enforcement bodies, as well as for medicine, particularly, in somnology. The paper presents the experimental results of step-frequency modulated bioradar usage for wide range of medical applications.

Keywords: Bioradiolocation, non-contact monitoring, breathing and heart rate monitoring, movement monitoring, psycho-emotional state.

1 Introduction

During the last years much interest has been shown in radar methods for detecting a human subject or for examining a particular internal part of a human organism [1–13]. Detection of a human as a living object can be performed by short-range radars (bioradars), which can use microwave signals ranging in frequency, waveform, duration, and bandwidth. Potential applications of the short-range radars include:

- detection of humans under debris of destroyed buildings after natural disasters or technical catastrophes [2], [4], [11];
- detection of people and parameters of their motions inside buildings or outdoors under low-visibility conditions (because of poor weather, sight obstructions, etc.) in antiterrorist operations [1], [2], [4], [5], [8], [11];
- examination of transport containers to reveal illegal persons and intelligent crossing the border [2];
- remote diagnostics of psycho-emotional state during latent or open checks in criminal investigations or at checkpoints, as well as within ergatic systems [2];
- remote detection of verbal signals [3].

In addition, various medical applications should be mentioned:

- contactless registration of heartbeat and breathing parameters for burnt patients, newborns, etc. [1], [2], [6], [8];

T.D. Pham et al. (Eds.): ACBIT 2013, CCIS 404, pp. 10–28, 2014.

- respiratory pattern monitoring during night sleep in apnea screening diagnosis [14];
- estimation of vessel elasticity from pulse-wave velocity for revealing patients predisposed to cardiovascular diseases [12];
- laboratory animals locomotor activity monitoring [15].

The following signals are suitable for detecting of living object: continuous modulated or unmodulated microwave signals at frequencies ranging from hundreds of megahertz to tens of gigahertz; narrowband, wideband, or utrawideband (UWB) signals; and pulse signals that have no clearly defined carrier frequency [4–8], [13], [16].

Radar signal reflected from a living object acquires specific biometrical modulation, which is not present in the case of reflection from motionless local objects. This specific modulation appears due to heartbeat, pulsations of vessels, contraction of respiratory muscles and, especially, by skin vibrations in the region of thorax, abdomen and larynx, which occur synchronously with respiration motions, heartbeat and articulation [1], [2], [6]. These processes are almost periodic with typical frequencies in the range of 0.8–2.5 Hz for heartbeat and 0.2–0.7 Hz for breathing. Therefore, the delay or phase of the reflected signal is periodically modulated by oscillations of skin and internals. The modulation parameters are determined by the frequencies and intensities of respiration and heartbeat. Aperiodic modulations may also originate from small motions of body parts and articulation [3], [8].

2 Apparatuses and Methods

When probing a human body a bioradar signal is reflected from the interface boundaries with different dielectric properties which primarily depend on the percentage of blood in a particular tissue or body organ. The highest possible reflection coefficient value are obtained from the interface boundaries of air - chest and chest - lungs, as well as from the boundary of tissue - blood. The latter reflection is particularly significant for a cardiac muscle and large blood vessels.

In conditions of free tidal breathing and natural torso mobility reliable registration of respiration and heart rate parameters is a challenging task and requires development of a set 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 method to probing signals and signals reflected from local objects, it is possible to attain high sensitivity in detecting objects whose boundaries perform mechanical vibrations. According to published data, the sensitivity of radar probing in the GHz band may theoretically reach 10 nm [17]. In practice, radar monitoring of a biological object is performed against the background of reflections from local objects. As a rule, the intensity of these reflections exceeds the intensity of signals from a human object. However, reflections from biological objects can be distinguished by periodic and aperiodic modulation synchronous with the respiration and heartbeat of a person. Modulation of this type is either absent in signals reflected from local objects or has different time and spectral characteristics. This is the key point which lays the basis for recognition of signals reflected by a human person against the background reflections from local objects.

The main advantage of wideband and UWB signals over unmodulated signals in probing biological objects is that the field under observation can be divided into range bins; such a division makes it possible to measure the distance to a target and to improve its extraction from the background. Generally, different types of probing signals may be advantageous for examining living objects depending on the essence of a particular problem.

At Bauman Moscow State Technical University (BMSTU) method of bioradiolocation (BRL) has been developed since 2003. At first a modified ground penetrating radar (operating frequency is 1.6 GHz) was used. The experiments on radar sounding of heartbeat and breathing of a person through a brick wall allowed considering the task of remote diagnostics of vital signs with an application of the continuous-wave subsurface radar technically feasible [18]. The sketch of the experiment is shown in Fig. 1.

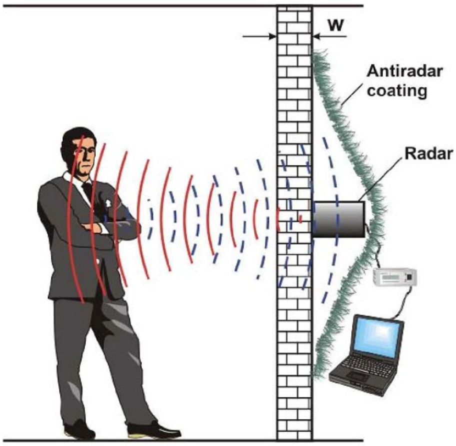


Fig. 1. The sketch of the experiment (w = 10 cm)

The results showed that sensitivity of the bioradar modification needs to be increased. It was also proposed to use not monochromatic but multi-frequency probing signal, which will allow measuring the distance to the object of the examination. That is why in 2006 multi-frequency bioradar BioRASCAN was designed. Its technical characteristics are as follows:

- Number of operating frequencies 16
- Sampling frequency 52.5 Hz
- Operating frequency band 3.6 – 4.0 GHz
- Recording signals band 0.03 – 5.00 Hz
- Dynamic range of the recording signals 60 dB

Since 2006 a number of experiments were carried out with details described below.

3 Multi-frequency Bioradar Experiments

3.1 Bioradiolocation Method in Chest Wall Motion Analysis during Tidal Breathing

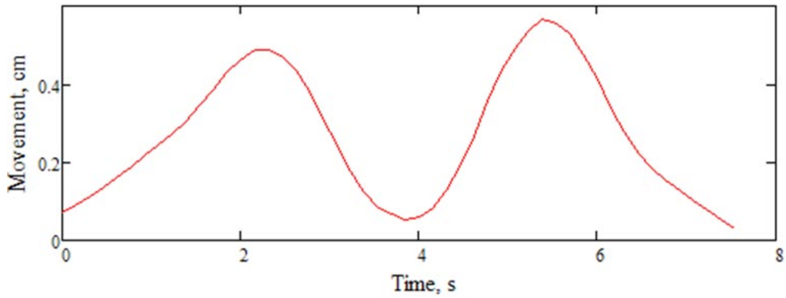
At first, an experiment was carried out to prove that designed bioradar can be used for remote monitoring of chest wall surface motion and breathing parameters [19]. During this experiment quick-shot camera and radar were applied simultaneously as it is shown in Fig. 2. On the surface of the chest wall several markers were fixed. Their displacements were recorded by the camera.

Fig. 2. Scheme of the experiment

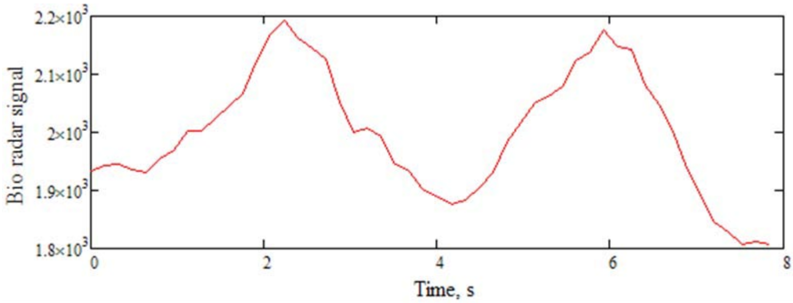
Kinematic model of the markers placed on the chest wall surface movements was taken as a basis one [5]. So the averaged horizontal projections of movement vectors of markers during tidal breathing are supposed to be known from this model. The markers movement relative to the certain central axis in the frontal plane gives the opportunity to determine the markers movements in the chest-back direction. Data obtained by both methods was compared, which revealed the fact that the highest correlation can be observed for abdominal area displacement [19] (Fig. 3).

Also a comparison of BRL and respiratory plethysmography (present golden standard method for respiratory efforts monitoring) data during parallel registration of respiratory movements in both time and frequency domains was performed on the base of cross-correlation and spectral methods [20]. Fig. 4 presents a photo of the experiment.

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 BRL and plethysmography signals in time domain.



a



b

Fig. 3. The dependences with highest correlation: a) high-speed camera method; b) bioradar

Fig. 4. Comparison of bioradar and respiratory plethysmography data

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

3.2 Human Adaptive Capabilities Estimation by Means of Bioradar

Comparative experiments for contact and non-contact methods for heart rate parameters monitoring were carried out to confirm that bioradar can be used for heart rate monitoring [21]. Sketch of the experiment is given in Fig. 5.

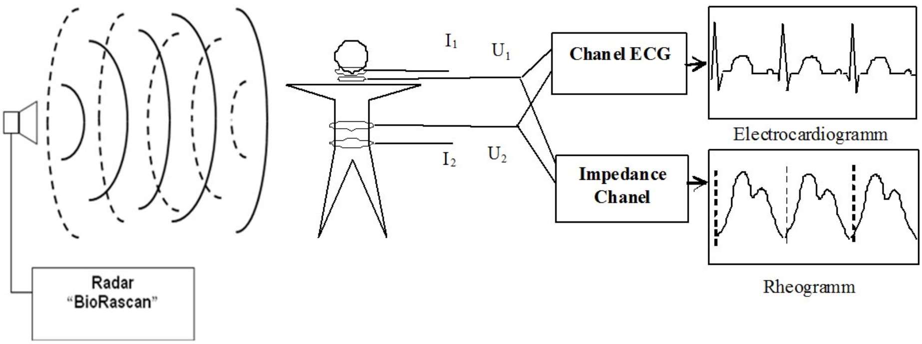


Fig. 5. Sketch of the comparative experiments for contact and non-contact methods

Respiration and heart rate parameters were simultaneously measured by contact method using rheocardiomonitor and non-contact method of BRL. 52 adult examinees participated in the experiments. For each of them bioradar and rheocardiomonitor signals were recorded three times (duration of one record was 1 min). Values of respiration and pulse frequencies for contact and non-contact methods were compared, which showed that they have good agreement (a confidence level of $p = 0.95$). Thus the feasibility of BRL for simultaneous measurements of breathing and heart rate parameters was proven.

The method of BRL can be used for monitoring of small differences in respiration and heart beat patterns. For example, bioradar can be used during Shtange`s and Hench`s breath holding test, which is widely known in medicine and is used for estimating fitness of the human cardiorespiratory system. It is used in professional selection of pilots, submariners and divers. Fig. 6 demonstrates an example of a recorded bioradar signal for this kind of test. After 1 min of holding breath involuntary traction of respiratory muscles took place because of oxygen starvation. However examinee continued holding his breathing even after this moment. The problem is that the correct duration of this test for the examinee should be estimated without the period when such involuntary traction on respiratory muscles occur (Fig. 6). Thus it was proven that usage of bioradar in such kind of tests would sufficiently improve the quality of obtained information.

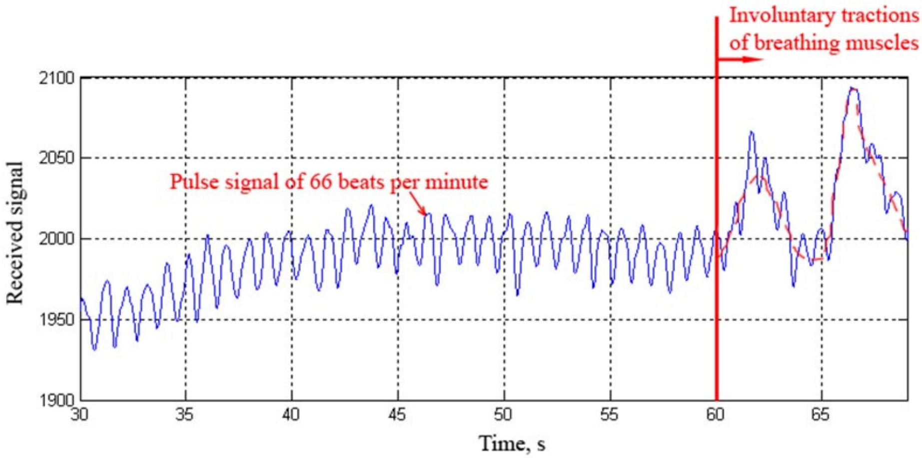


Fig. 6. Received bioradar signal for breath holding test

Also the experiments with additional stress factor were carried out to investigate the possibility of bioradar application for remote estimation of psycho-emotional state of the examinee. Ringing mobile-phone was used as a stress factor. An example of a recorded bioradar signal for this kind of test is given in Fig. 7. While the phone was ringing amplitude of chest movements caused by breathing became two times lower than was before. As for breathing frequency, its value slightly increased.

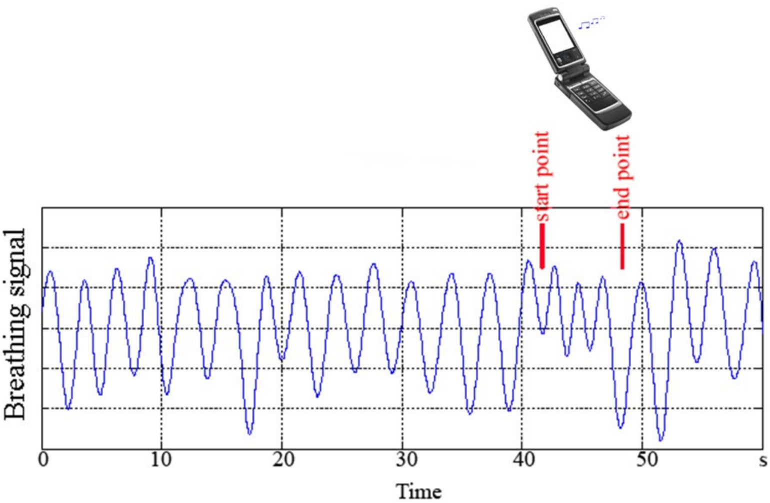


Fig. 7. Received bioradar signal for experiment with additional stress factor

To imitate stress factor of a longer duration the standard mental load test was used. During the test examinee was asked to sum inwardly 17+17+17+… Duration of the experiment was 5 minutes. In this case the mean value of respiration frequency remained almost unchanged, for a heart beat frequency this parameter slightly increased. However the variability of respiration and heartbeat frequencies changed greatly. That is why a heart beating histogram may be used as a convenient way to represent the heart rate variability changes caused by mental load. Fig. 8 shows histograms of the heart beat intervals before and after test for one of the examinees. During mental load HR increased (from 1.2 to 1.5 Hz) and heart pulse interval dispersion decreased (from 0.25 to 0.06 sec). The sample included 52 subjects (25 males and 27 females, aged 19-21 years). The analysis of experimental data showed that performing mental load leads to a statistically significant change in heart rate (a confidence level of $p = 0.80$). The changes in respiratory rate were not statistically significant.

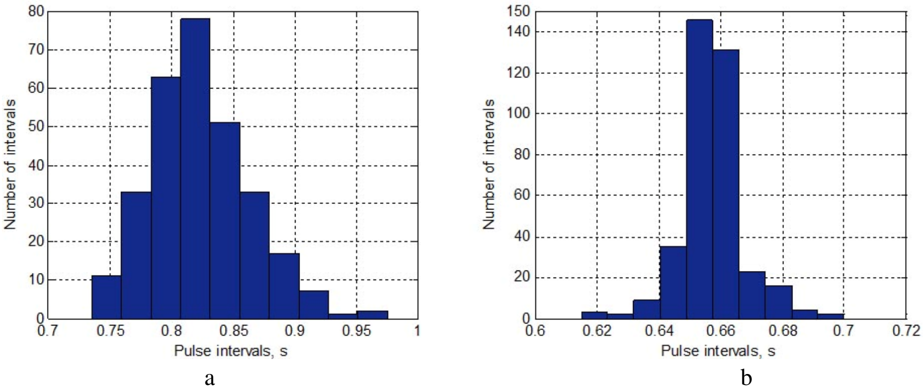


Fig. 8. Histograms on heart beat intervals before (a) and after (b) test for one of the examinees

3.3 Estimation of Changes in Breathing Pattern while Using Breathing Training Devices

In the next type of bioradar assisted experiments the possibility of BRL method application for biological feedback forming was studied. It is very important to diagnose respiratory tract diseases in time and take prophylaxis measures. It can sufficiently fasten the heeling process and even prevent development of hypoxia, bronchial asthma, etc. One of the way of training breathing muscles and prophylactics of different illnesses caused by hypoxia is based on usage of special breathing training devises, which help to normalize breathing pattern.

Special methods of training with using of these devices were developed. But control of breathing pattern changes during trainings is still important. It may help to obtain a reliable information about these changes, close biological feedback loop and thus to select particular training method not randomly but with a glance to individual response of the examinee to the trainings. The bioradar BioRASCAN was used for controlling of a breathing training device influence on breathing pattern (Fig. 9).

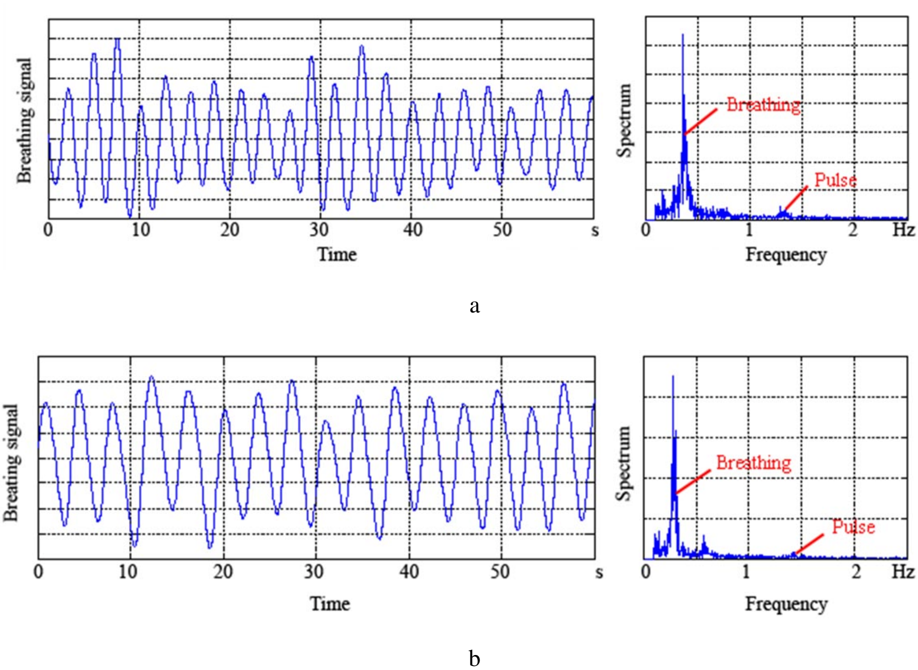


Fig. 9. Bioradar signal for steady state (a) and breathing training (b)

3.4 Automatic Sleep Disturbance Diagnostics

One of the most promising areas of BRL application in medicine is somnology (scientific study of night sleep). Due to the fact that during sleep the patient may change his position, there is a necessity to prove that respiration pattern can be remotely recorded by bioradar regardless to position of the examinee toward the bioradar antennas. That is why tentative experiments were carried out and the influence of the examinee orientation towards antennas block on the reflected signal power was studied.

During the experiments the examinee lied in one of the four positions: on the back (Fig. 10), on the left side, on the belly and on the right side. It is not a complete list of possible positional orientation of the antennas unit and examinee during sleep, but with help of it some conclusions can be made. Fig. 11 presents amplitude spectrums for all listed positions. The one which allows getting the best quality of data is when an examinee is lying on his back. In this case bioradar probing signal is emitted towards the thorax surface practically orthogonally and reflected signal power reaches the highest level. For other positions of the body the level of the received signal is also high enough to measure respiration frequency reliably (Fig. 11).

Fig. 10. Sleep monitoring experiment

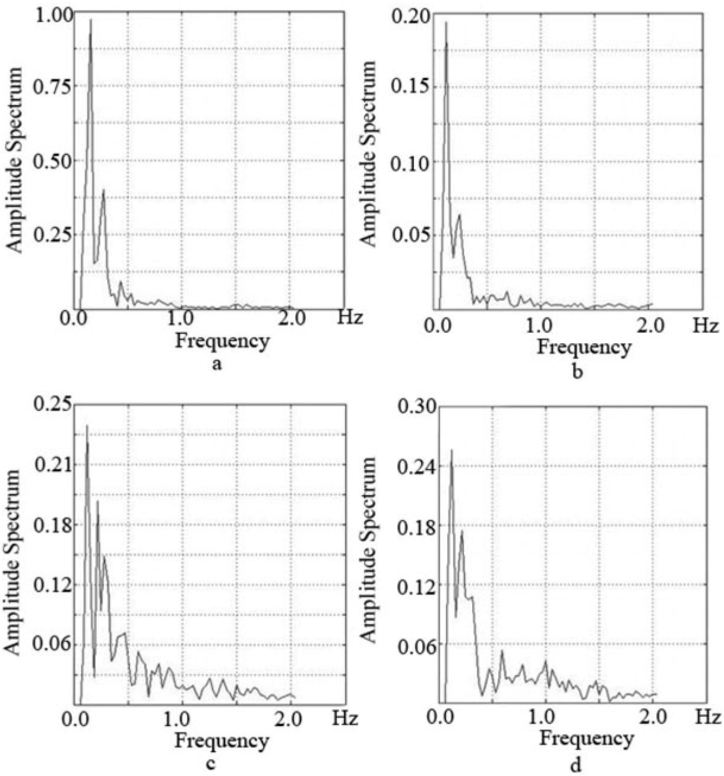


Fig. 11. Signal spectrums for different positions of the examinee: a) on the back, b) on the left side, c) on the belly, d) on the right side

The next stage of the bioradar feasibility study for somnology applications was experiment conducted on the base of BMSTU student sanatorium in 2009. Bioradar signals were recorded during the whole night sleep. 6 overnight records were collected for an adult male (aged 20 years), which was practically healthy.

Processing of the recorded signals was organized on the base of MATLAB and included several stages. First of all for baseline drift elimination bioradar signal was filtered by built-in MATLAB Butterworth digital filter with cutoff frequency of 0.05 Hz (filter order was 8). Then the intervals of movement activity were detected. It is obvious that the level of the received signal which corresponds to calm breathing and movement activity must differ greatly because of more than 10 times differences in amplitude of corresponding movements. However, the main problem in movement artifacts detecting is the fact that patient may turn from one side to another during sleep. In this case the distance between antennas and examinee and scattering cross section of the object may change. As the result level of the received by bioradar signal may also vary significantly before and after movement artifact appearance (Fig.12 a).

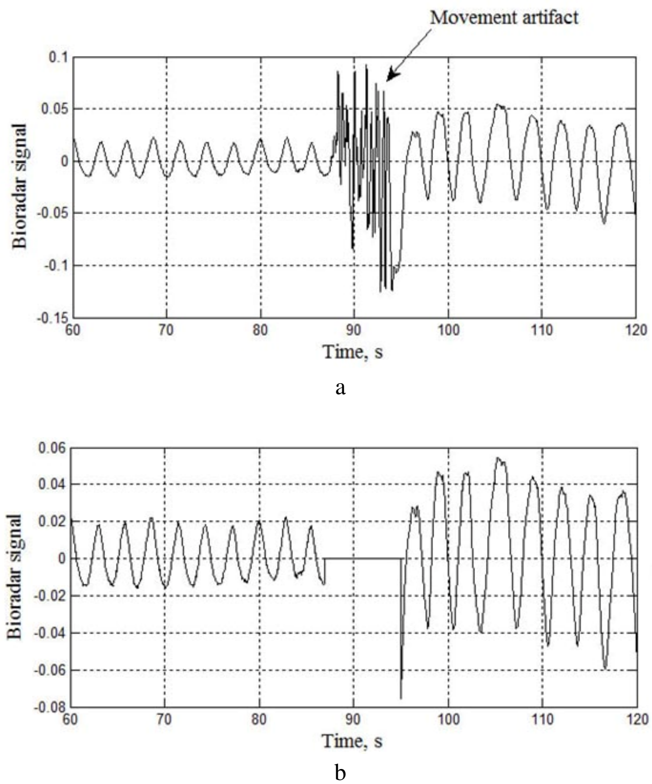


Fig. 12. Bioradar signal before (a) and after (b) movement artifact extraction

That is why it is not enough to use only signal amplitude parameters for detecting of movement artifacts. However, episodes of signal, during which movement artifacts are present, contain frequency components higher than the same parameters for episodes of tidal breathing with frequency range of 0.1-0.6 Hz, while the spectrum of bioradar signal intervals correspondent to movements contains components even higher than 1.0 Hz. These spectral differences were used in the algorithm for automated detection of movement artifact. In Fig.12 radar signal before and after movement artifacts extraction is shown (Fig. 12a and Fig. 12b respectively). Respiration frequency is estimated only for the intervals free from movement artifacts (Fig. 13). Subsequently mean values for breathing intervals are calculated for the frame of 30 seconds (Fig. 13c), following the standard recommendations for somnology data processing [22].

The presented studies 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 on the basis of Institute for Biomedical Problems of Russian Academy of Sciences from June 2010 to November 2011 [23]. An ethical committee approval and informed consent from all the crewmembers were obtained before the start of the experiment.

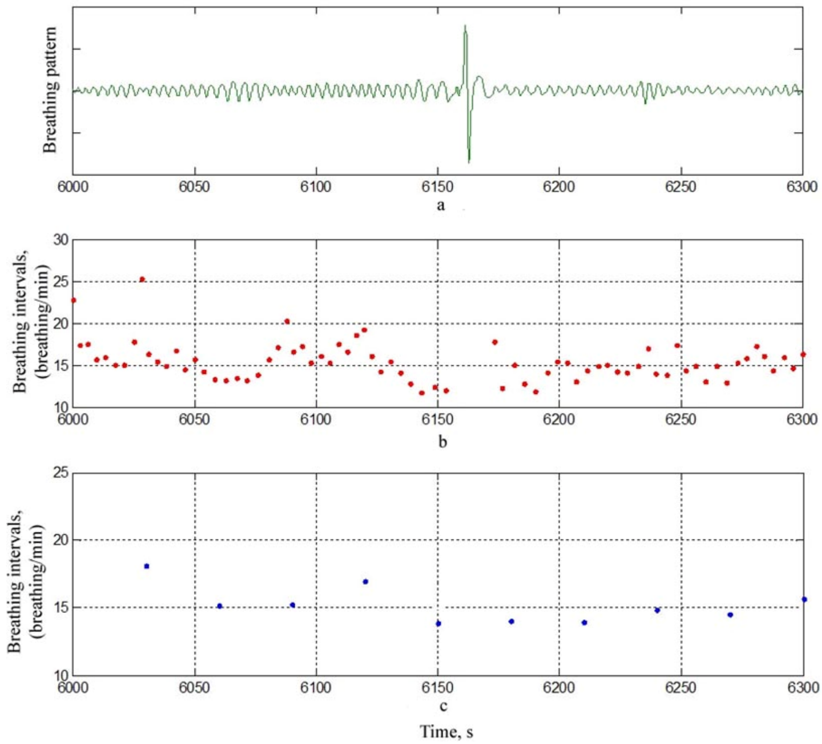


Fig. 13. Respiration frequency dynamics during sleep registered by BioRASCAN: a) breathing pattern, b) breathing intervals, c) averaged breathing intervals

The crew of MARS-500 had been trained to perform bioradar experiments before the start of the prolonged isolation. During the project MARS-500 bioradar experiments were conducted for 6 crew members. The results revealed it is more convenient to use values of the interested parameter average per hour to analyze its dynamics during full night sleep. Fig. 14 and Fig. 15 present the results of the experimental data recorded for one of MARS-500 crew members.

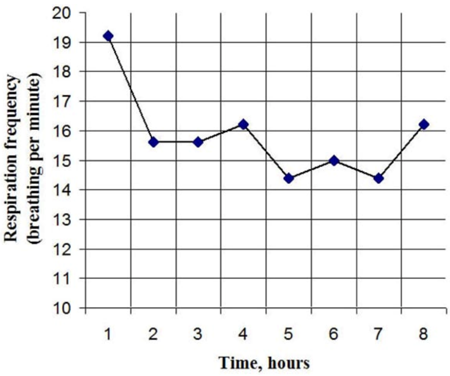


Fig. 14. Respiration frequency dynamics during full night sleep registered by BioRASCAN

In Fig. 14 it is seen that after falling asleep the value of the respiration rate of the examinee decreased from 19 to 16 breathing acts per minute, and during the last hour of sleep the respiration rate on the contrary became higher. It is known that breathing pattern and movement activity dynamics are not usually too much varied from night to night and characterize individual sleep pattern. If any changes take place they can indicate the fact that the examinee suffers from some kind of stress during the day time. So, the application of the proposed algorithm gives the opportunity to monitor the patterns of breathing and movement activity and thus detect a possible sleep disturbance caused by daytime stress.

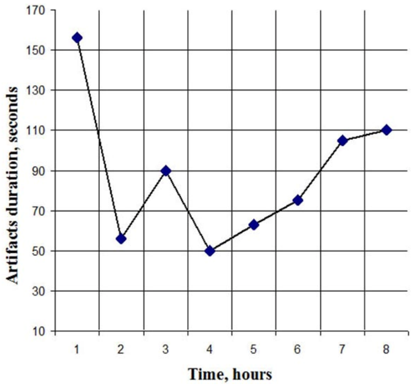


Fig. 15. Movement activity dynamics during full night sleep registered by BioRASCAN

The processing of experimental data revealed the individual characteristics of sleep latency and sleeping of crew members. Some of them have 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. Duration of sleep for each subject during the MARS-500 project changed individually, for 4 out of 6 crew members during the first three series of experiments decrease in sleep duration for more than 10 % was registered. In second half of the experiment duration no significant changes in monitored parameters (respiratory rate and the duration of movement artifacts during sleep) occurred, which indicated good tolerance of crew to the conditions of prolonged isolation. For none of the crewmembers any sleep disordered breathing episodes were registered.

The purpose of the next stage of sleep experiments with bioradar application was to estimate the quality of BRL monitoring in noncontact screening diagnostics of obstructive sleep apnea (OSA) syndrome compared with standard polysomnography (PSG) [24]. The research was conducted on the base of Sleep Laboratory of "Almazov Federal Heart, Blood and Endocrinology Centre" (St. Petersburg, Russia). In the experiment seven volunteers aged 43 to 62 years, with the body mass index varying from 21.6 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 1 test subject was practically healthy. For subsequent verification of BRL signals full night polysomnograms were collected in parallel with Embla N700 system application. The internal clock of BRL and PSG control units were synchronized.

The pre-processing procedure for the source BRL signals included the following stages:

- filtering with the fifth-order high-pass Butterworth filter with an operating frequency of 0.05 Hz corresponding to the cutoff frequency not below 0.03 Hz;
- filtering with the fifth-order low-pass Butterworth filter with an operating frequency of 5.00 Hz corresponding to the cutoff frequency not above 10.00 Hz;
- Smoothing with a median five-point moving average filter;
- Z-normalization of each quadrature component of the BRL signal.

Typical forms of the BRL signals after preprocessing are shown in Fig. 16.

BRL signals with typical forms for the sleep disordered breathing (SDB) episodes were analyzed. They are visually similar to the correspondent signals registered by abdominal belt sensors within the framework of the complete PSG research. These signals differ significantly from periods of quiet sleep without SDB.

While estimating the quality of BRL monitoring in non-contact screening of OSA sensitivity value of 69 % was obtained with the prognostic value of positive decision 72 % of the SDB 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 OSA severity compared to the standard PSG method, which satisfies standard medical recommendations.

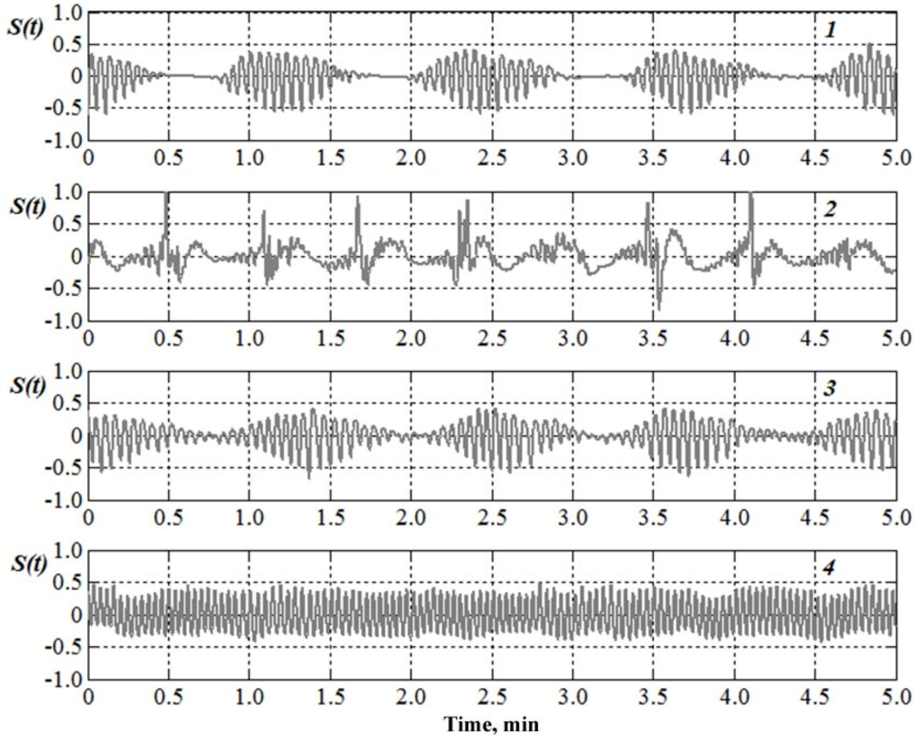


Fig. 16. Typical forms of the BRL signals at registration of different respiration patterns: 1) central apnea, 2) obstructive apnea, 3) hypopnea, 4) normal breathing pattern

3.5 Estimation of Animal's Movement Activity by Means of the Radar

Although previously the BRL method was for non-contact monitoring of human vital signs, the same approach can be also applied for tracking movement of small laboratory animals (mice and rats) activity [15]. In this case BRL may be used in pharmacology and zoo-psychology, e.g. for testing new drugs. The main problem is that the rat is just a little bit bigger than the space resolution of the designed bioradar in case of using the probing signal of 3.6-4.0 GHz. That is why a new bioradar which operates at frequency range of 13.8 – 14.2 GHz was designed to monitor rats' locomotor activity.

The photo of the experimental set up for estimation of animal's movement activity by means of bioradar is given in Fig. 17. During the experiment the animal was placed into a box with dielectric walls. Transmitting and receiving antennas of the bioradar were pointed towards the box.

The signal reflected from the animal was recorded for further processing. The distance between antennas unit and the box was approximately 1 m. Such short distance was caused by relatively small scattering cross section of an animal. Video signal was recorded simultaneously by means of a simple web-camera placed over the box. Information about behavior and movement activity of the animal during the experiment recorded by the camera was used for identification of different types of a rat locomotor activity in bioradar signals. It is known that the power flux density value close to radar receiving antennas is inversely as the 4th order of a range between antennas and an object. That is why the power of the signal, reflected from an animal and received by bioradar, depends greatly on distance between antennas block and animal. Because of this fact correct estimation of rat's movement activity becomes a very challenging task. Corner reflector was used to make power of signal indifferent to location of an animal inside the box. It was formed by two walls and floor of the box covered with metallic foil.

Fig. 17. The experimental set up for estimation of animal's movement activity

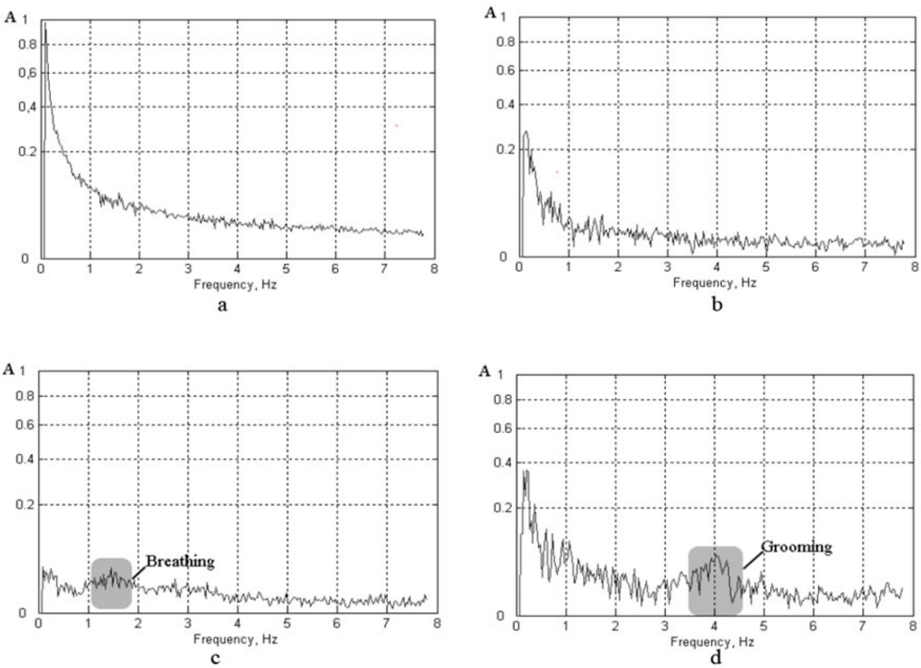


Fig. 18. The results of the experiments: a) active movements, b) steady state, c) sleeping, d) grooming

Several short term experiments were carried out, during which several types of animal's behavior were present. Amplitude frequency spectrums for different animal locomotor activity types were obtained. They are given in Fig. 18. For easier comparison of spectrums for different states of the animal, amplitude of the frequency spectrum is represented by using of nonlinear scale for vertical axis that is proportional to square root of amplitude.

The spectrums differ greatly in magnitude and form. That is why it is possible to distinguish grooming from steady state, sleep or active movement of the animal by applying spectral analysis methods for bioradar signal processing.

4 Conclusion

In the paper the highlights of BRL method and possible areas of its application are discussed. The technical characteristics of the bioradar BioRASCAN designed at Remote Sensing Laboratory, BMSTU (Moscow, Russia) were given and results of bioradar experiments conducted with the help of designed apparatus were presented. As it was experimentally proven, it is possible to use bioradar for estimation of a human psycho-emotional state and adaptive capabilities of the organism (including tolerance to oxygen starvation) during professional selection. By the experiments, in which bioradar was applied simultaneously with standard contact methods for respiratory and heart rate parameters monitoring, it was shown that bioradiolocation should be considered as reliable and correct approach for non-contact remote monitoring of external respiration activity parameters and heart rate. The results of the experiments, in which the designed bioradar was used for monitoring stress influence on the sleep pattern during prolonged isolation while imitating manned flight to Mars, are presented. Moreover BRL was used for evaluation of sleep apnea syndrome severity and revealed good agreement with full night PSG.

At present on the base of Almazov Federal Heart, Blood and Endocrinology Centre (St. Petersburg, Russia) bioradar assisted experiments are under way. The main goal of these experiments is the investigation of the possibility to distinguish different sleep phases only by processing of breathing patterns recorded by bioradar without applying any additional contact sensors.

Acknowledgments. The study was supported by grants of The Ministry of Education and Science of the Russian Federation and Russian Foundation for Basic Research.

References

1. Greneker, E.F.: Radar Sensing of Heartbeat and Respiration at a Distance with Applications of the Technology. In: IEE RADAR 1997, pp. 150–153 (1997)
2. Greneker, E.F.: Non-Contact Heartbeat Signature Measurement for Possible Personnel Biometric Identification. In: 13th Annual ADPA Symposium and Exhibition on Security Technology, Virginia Beach, VA (1997)

3. Holzrichter, J.F., Burnett, G.C., Ng, L.C., Lea, W.A.: Speech Articulator Measurements Using Low Power EM-Wave Sensors. J. Acoust. Soc. Am. 103(1), 622–625 (1998)
4. Chen, K.M., Huang, Y., Shang, J., Norman, A.: Microwave Life Detection Systems for Searching Human Subjects Under Earthquake Rubble or Behind Barrier. IEEE Trans. Biomed. Eng. 27(1), 105–114 (2000)
5. Barnes, M.A., Nag, S., Payment, T.: Covert Situational Awareness with Handheld Ultra-Wideband Short Pulse Radar. In: Radar Sensor Technology VI. Proc. SPIE, vol. 4374 (2001)
6. Staderini, E.M.: UWB Radars in Medicine. IEEE AESS Systems Magazine 17, 13–18 (2002)
7. Immoreev, I.Y., Samkov, S., Tao, T.-H.: Short-Distance Ultrawideband Radars. IEEE Aerosp. Electron. Syst. Mag. 20(6), 9–14 (2005)
8. Droitcour, A., Lubecke, V., Lin, J., Boric-Lubecke, O.: A Microwave Radio for Doppler Radar Sensing of Vital Signs. In: IEEE MTT-S Int. Microw. Symp. Dig., pp. 175–178 (2001)
9. Bugaev, A.S., Chapursky, V.V., Ivashov, S.I.: Through Wall Sensing of Human Breathing and Heart Beating by Monochromatic Radar. In: 10th Int. Conf. on Ground Penetrating Radar (GPR 2004), June 21-24 (2004)
10. Bugaev, A.S., Chapursky, V.V., Ivashov, S.I.: Mathematical Simulation of Remote detection of Human Breathing and Heartbeat by Multifrequency Radar on the Background of Local Objects Reflections. In: IEEE Int. Radar Conf., May 9-12, pp. 359–364 (2005)
11. Vertiy, A., Voinovskyy, I., Ozbek, S.: Experimental Tomography Setup for Imaging of Electrodynamic Structure on Millimeter Waves. In: 25th International Conference on Infrared and Millimeter Waves Workshop on Microwaves, pp. 477–478 (2005)
12. Immoreev, I.Y.: Practical Applications of UWB Technology. IEEE Aerospace and Electronic Systems Magazine 25(2), 36–42 (2010)
13. Li, C., Lin, J., Xiao, Y.: Robust Overnight Monitoring of Human Vital Signs by a Non-Contact Respiration and Heartbeat Detector. In: Conference Proceedings IEEE Engineering in Medicine and Biology Society, vol. 1, pp. 2235–2238 (2006)
14. Kelly, J.M., Strecker, R.E., Bianchi, M.T.: Recent Developments in Home Sleep-Monitoring Devices. ISRN Neurology, 2012, Article ID 768794, 10 p. (2012)
15. Anishchenko, L.N., Bugaev, A.S., Ivashov, S.I., Vasiliev, I.A.: Application of Bioradiolocation for Estimation of the Laboratory Animals' Movement Activity. PIERS Online 5(6), 551–554 (2009)
16. Nezirovic, A., Tesfay, S., Valavan, A.S.E., Yarovoy, A.: Experimental Study on Human Breathing Cross Section Using UWB Impulse Radar. In: 5th Eur. Radar Conf., pp. 1–4 (2008)
17. Scott Jr., W.R., Schroeder, C., Martin, J.S.: An Acousto-Electromagnetic Sensor for Locating Land Mines. In: SPIE, AeroSense, Detection and Remediation Technologies for Mines and Minelike Targets III, FL, pp. 176–186 (1998)
18. Ivashov, S.I., Razevig, V.V., Sheyko, A.P., Vasilyev, I.A.: Detection of Human Breathing and Heartbeat by Remote Radar. In: Progress in Electromagnetics Research Symposium (PIERS 2004), pp. 663–666 (2004)
19. Korchagina, D., Alekhin, M., Anishchenko, L.: Bio-radiolocation Method at Chest Wall Motion Analysis during Tidal Breathing. In: EURad, Paris, France, pp. 475–478 (2010)
20. Alekhin, M., Anishchenko, L., Tataraidze, A., Ivashov, S., Parashin, V., Dyachenko, A.: Comparison of BRL and Respiratory Plethysmography Signals in Time and Frequency Domains on the Base of Cross-Correlation and Spectral Analysis. International Journal of Antennas and Propagation 2013, Article ID 410692, 6 p. (2013)

21. Anishchenko, L., Bugaev, A., Ivashov, S., Zhuravlev, A.: Bioradar for Monitoring of Human Adaptive Capabilities. In: General Assembly and Scientific Symposium of International Union of Radio Science (XXXth URSI), 4 p. (2011)
22. Rechtschaffen, A., Kales, A.: A Manual of Standardized Terminology: Techniques and Scoring System for Sleep Stages of Human Subjects. UCLA Brain Information Service/Brain Research Institute, Los Angeles (1968)
23. "Mars-500" Project Simulation of a Manned Flight to Mars, http://mars500.imbp.ru/en/index_e.html
24. Alekhin, M.D., Anishchenko, L.N., Zhuravlev, A.V., Ivashov, S.I., Korostovtseva, L.A., Sviryaev, Y.V.: Evaluation of Sleep Disordered Breathing Using Non-contact Remote Bioradiolocation Method. In: World Congress on Sleep Medicine (2013)