Report

Noninvasive investigation of the body functional state during night sleep in microgravity

Irina I. Funtova[1], Elena S. Luchitskaya[1], Irina N. Slepchenkova[1], Anna G. Chernikova[1*], Roman M. Baevsky[1]

[1] Institute of Biomedical Problems of the Russian Academy of Sciences, 123007, Russia, Moscow, 76A Khoroshevskoye Ch.

[*] Corresponding author phone: +7 (499) 193-62-44, e-mail: anna.imbp@mail.ru

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Abstract

The Sonocard experiment purpose was a noninvasive physiological signal recording from sleeping humans. In 2007-2012 the experiment was made by 22 Russian members of 17 missions to the International space station. Of the overall 302 experimental sessions 47 were performed pre, 215 in and 40 after flight.

The seismographic technique was used to pick up cosmonaut's body microoscillations induced by cardiac beats, respiration and motor activity. The flight Sonocard model is a midget device fitting into the T-shirt pocket. Heart rate variability analysis (HRV) was the major method of securing conclusive evidence on stress level and blood circulation autonomic regulation. We were first to trace reorganization of the autonomic regulation at the night time on different phases of long-duration space mission and pioneered a systematic investigation of the human body functional state during sleep. It was shown that in the absence of work loads and emotional stresses the central mechanisms of circulation regulation tend to increase their activities. The characteristic subsidence of breathing waves (HF) and growth of the vascular center (LF) portion within the HRV total spectrum by the end of flight were observed.

Sleep quality in the course of long-duration missions was assessed. We succeeded in the first ever sleep assessment following operations in open space.

The noninvasive physiological signal recording was recommended for use in spacecrew medical monitoring and ground-based experiments.

Keywords

Noninvasive physiological signal recording • Recovery of the functional reserve • Body microoscillations • Sleep • Seismocardiography • Autonomic regulation • Heart rate variability • Sleep quality • Straining degree

Imprint

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Introduction

Studies of the human sleep-wakefulness cycle in the unusual environment of long stay aboard space vehicles are of high practical significance. The reason is that the particular biological role of sleep among vital activities of the organism is the recovery phase. Though sleep in space flight has been the objective of a large number of investigations [1], assessment of recovery completeness in these conditions is a fundamentally new task. It is well known that organism recovery during sleep occurs with the autonomic balance shifting toward prevalence of the parasympathetic regulation. The process can be controlled by the instrumentality of the methods of heart rate variability analysis [2,3].

Till recently autonomic balance in orbiting cosmonauts has been investigated only during workday hours. Simultaneously with the influence of the specific factor of microgravity cosmonaut's organism is also affected by "factors of production" such as mental and emotional straining and physical loads of daily exercises. Effects of microgravity per se can be studied in sleep only. This being so, the theoretical aspect of the investigation implies filling the gap in the knowledge of microgravity effects on autonomic regulation of human physiological functions in the course of long-duration mission. The practical aspect consists in exploring the possibility to assess sleep quality in microgravity and, therefore, effectiveness of the recovery process as staples of the human ability to work and functionality in general. In this context, it was crucial to develop a simple and comfortable procedure sleep studies other than present-day cumbersome polysomnography, which, because of placement of numerous sensors and electrodes and complex data analysis is unsuitable for the space flight environment.

Materials and methods

Procedure

Noninvasive signal recording, a simple, comfortable and physiologically seamless method of investigation imparted uniqueness to space experiment Sonocard. The patented space-oriented device with the same name is an original development of Russian engineers [4]. It was delivered onto the International space station in September of 2007. The first record was made on October 19, 2007 by a Russian member of ISS crew-16.

Inside the midget device (210x140x18 mm) there are an accelerometer-type sensor, amplifier-transformer, memory box, and controllers for communication with external PC and power supply.

Before going to bed, cosmonaut put Sonocard in the T-shirt pocket and got into the sleeping bag (fig. 1). After waking-up, cosmonaut was to copy the night records into the board PC memory. The records were downlinked via the Internet at the first opportunity; on the eve of landing, the records were copied to PCMCIA for more careful analysis in laboratory.

The active sensor detects microoscillations of the chest wall caused by mechanic work of the heart. In parallel, it captures all other oscillations associated with breathing, motor activity or external factors (fig. 2). Since amplitudes of irrelevant oscillations may be many times over the magnitude of heartbeat signals, total records are subject to special processing in order to isolate useful information

Specialized software Corr serves to recognize and measure continuous dynamic series of cardiac interval durations over the entire period of investigation (night sleep). The choice fell on the method of standards, i.e. construction of the cross-correlation function between a current signal and a selected typical seismic or ballistic cardiocomplex. Software executes digital filtration of signals to facilitate recognition of individual complexes and measurement of time intervals between them.

In addition to the priority objective of constructing cardio intervals along the night record, Corr also permits prompt isolation and measuring time of interferences, mostly due to motor activity (MA). MA parameters are calculated automatically on the analysis of signal power. Besides, software is capable to isolate and measure breathing movements by way of low-frequency filtration of a seismic or ballistic cardiogram. The snap analysis function provides immediate data on subject's heart rate, breathing rate and motor activity while he or she was asleep.

In 2007-2012, space experiment Sonocard was performed by 22 cosmonauts in 17 ISS missions. The overall number of experimental investigations is 302 including 47 pre launch, 215 in and 40 after mission. Every cosmonaut was investigated 2 or 3 times before launch; during ISS missions 17 - 28 the investigations were scheduled twice a month; starting from ISS mission-28 they were made once a month and twice after return.

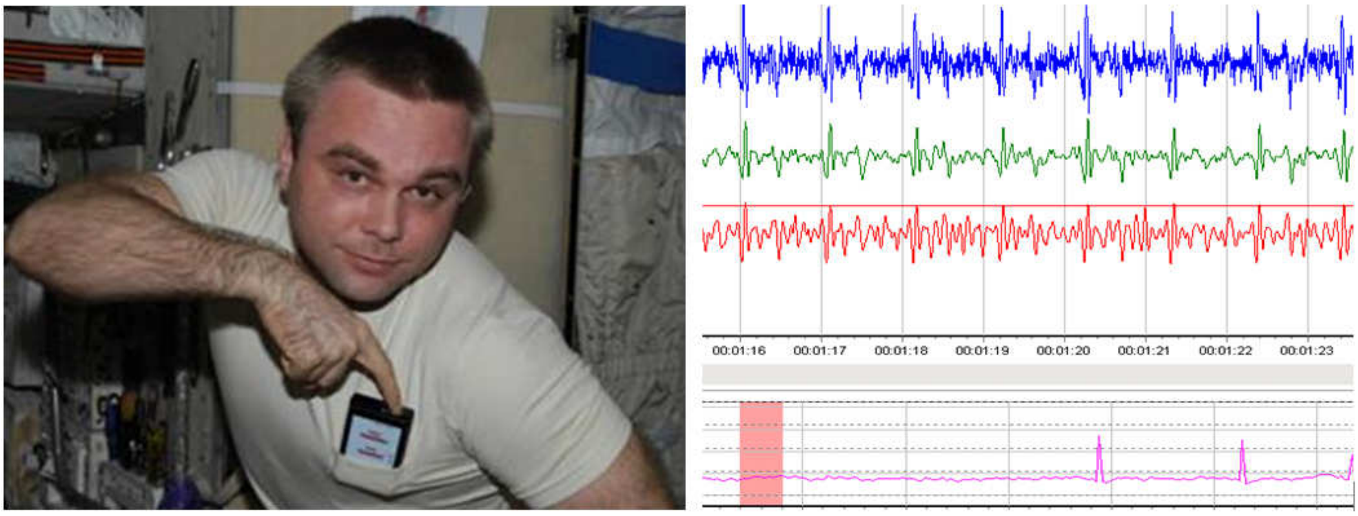
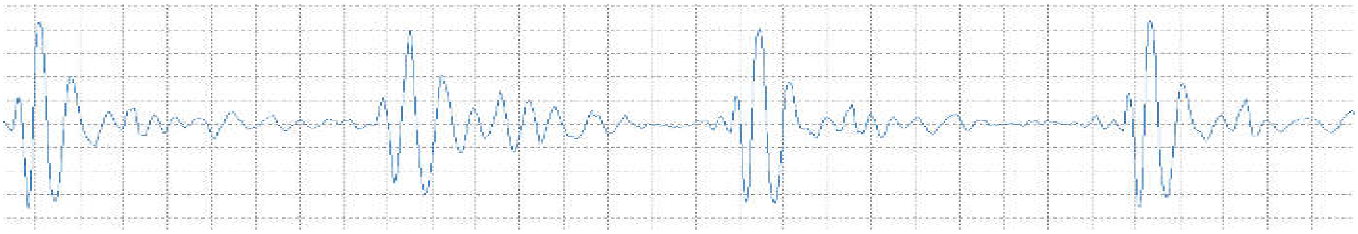
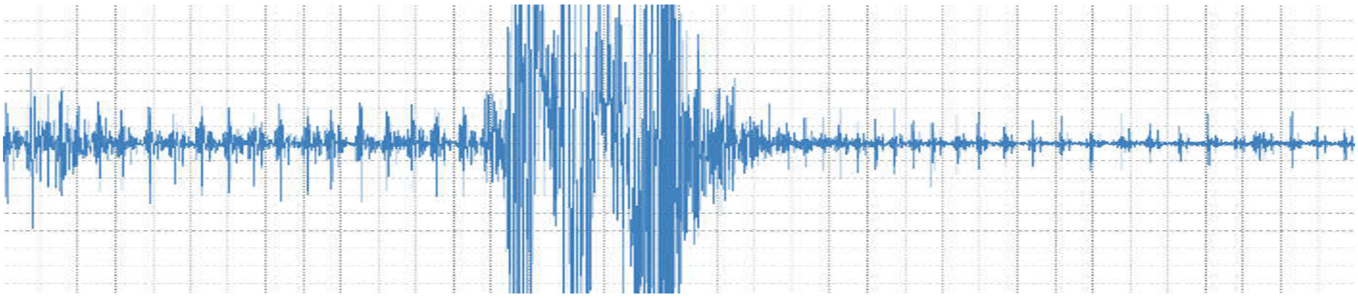


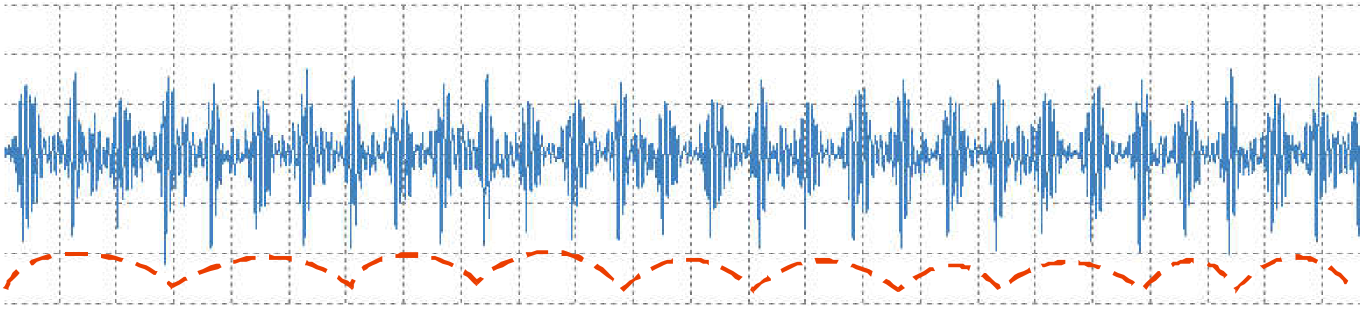
Figure 1. Implementation of experiment Sonocard onboard the ISS (left) and signal analysis program (right).



A) a fragment of signal with heartbeat-related complexes



B) a fragment of signal recorded at the moment of in-sleep movement



C) a fragment of signal with breathing-induced envelope

Figure 2. Fragments of signals reflecting different physiological processes.

Data processing

Heart rate variability (HRV) constitutes the core of the noninvasive physiological records analysis. Corr identifies 5-minute fragments clean of motor activity and artifacts for ensuing calculation of the HRV standard time and frequency parameters. Analysis and physiological interpretation of HRV parameters were performed with consideration of the recommendations given by a group of Russian experts [5] and standards of the European Society of cardiologists and North American Society of electrostimulation and electrophysiology [6]. Heart rate variability analysis is modern methodology and technology of investigating and evaluating the functional state of organism and specific components of the autonomic nervous system. Space medicine was one of the disciplines and practical areas where HRV analysis was used as a source of new information and a tool of medical monitoring humans exposed to extreme environments [7, 8, 9, 10, 11]. Since systematic investigations of organism functions during sleep in long-term microgravity have not been attempted in the past, attention was focused on person-unique features of autonomic regulation.

Results and Discussion

1. Dynamics of mean values of the set of physiological parameters during sleep on different flight phases

Table 1 presents mean values of the main HRV parameters in experiment Sonocard. From these data it follows that mission average changes in heart rate were significantly lower in orbit and reliably higher in the post-landing period. Analysis points to statistically significant shifts in the autonomic balance during flight. Parasympathetic regulation declines (HF), the subcortex sympathetic vascular center (LF) builds up its activity while power of the energy metabolism regulation (VLF) goes down.

Table 1. Mean values of the main HRV parameters in experiment Sonocard

Flight phase	HR	SI	pNN50	HF %	LF %	VLF%
Before flight	58.18	90.90	18.66	27.15	42.65	29.8
In flight	55.81*	91.5	18.2	23.9*	48.55*	27.5*
After flight	68.55**	150.14**	9.73**	18.36**	50.31**	31.26**

* $p<0.05$ ** $p<0.01$

These changes sum over the data from all 22 ISS cosmonauts and evidence common trends. Post-landing changes reveal distinct and of greater reliability growth in heart rate and shifting of autonomic balance toward sympathetic tone regulation (rise in SI, LF % and VLF%, reduction in pNN50 and HF %).

Table 2. Nighttime average HRV parameters in space experiment Sonocard.

		HR	SDNN	pNN50	SI	TP	HF, %	LF,%	VLF,%	BR	MA min	MA %
Before flight -1	M	56,44	59,17	25,64	78,85	2848,56	27,93	42,77	29,26	13,79	9,21	2,26
	σ	7,39	18,49	16,27	55,38	1529,60	10,18	8,06	8,23	1,77	4,16	0,92
	m	1,79	4,48	3,95	13,43	370,98	2,47	1,96	2,00	0,43	1,20	0,22
Before flight -2	M	58,31	56,28	20,18	93,40	2963,26	26,98	41,95	29,69	13,84	9,59	2,20
	σ	6,95	18,78	14,23	61,98	1938,85	8,61	6,86	7,70	2,35	4,38	1,08
	m	1,52	4,10	3,11	13,53	423,09	1,88	1,50	1,68	0,51	1,09	0,24
1-st months of flight	M	54,95*	54,85	21,99	83,44	2683,17	25,16	43,56	29,60	11,37*	9,45	2,21
	σ	7,83	19,23	13,82	60,34	1551,43	11,07	11,06	9,23	2,67	5,18	1,61
	m	1,34	3,30	2,37	10,35	266,07	1,90	1,90	1,58	0,49	1,13	0,28
2-nd months of flight	M	56,46	56,65	21,69	80,57	2752,74	23,45	46,41	28,59	12,17	7,67*	2,01
	σ	7,78	18,81	14,44	48,25	1367,29	8,56	9,72	7,77	1,77	3,81	0,91
	m	1,33	3,23	2,48	8,27	234,49	1,47	1,67*	1,33	0,32	0,78	0,16
3-rd months of flight	M	56,04	53,11	21,86	85,19	2413,19	24,76	45,18*	27,22	12,02	7,46*	1,95
	σ	7,08	18,41	13,62	46,20	1266,62	9,14	10,18	7,46	1,82	3,62	1,07
	m	1,25	3,25	2,41	8,17	223,91	1,62	1,80	1,32	0,33	0,83	0,19
4-th months of flight	M	56,14	54,23	19,92	81,81	2574,84	23,49	46,38*	27,72	11,66*	8,02	1,86
	σ	7,31	17,59	12,20	43,36	1270,73	10,60	9,87	7,31	2,27	3,35	0,87
	m	1,20	2,89	2,01	7,13	208,91	1,74	1,62	1,20	0,38	0,68	0,15
5-th months of flight	M	55,54	55,78	20,41	80,38	2942,53	21,51*	47,53*	28,65	11,30*	8,68	2,12
	σ	7,08	17,69	12,61	49,72	1533,27	6,53	8,96	6,06	2,97	3,99	1,12
	m	1,21	3,03	2,16	8,53	262,95	1,12	1,54	1,04	0,52	0,89	0,19
6-st months of flight	M	56,24	58,19	23,13	77,52	2860,02	22,93*	45,03*	29,87	11,42*	6,11*	1,52*
	σ	7,13	19,70	13,47	49,67	1734,79	7,91	7,28	8,18	2,23	1,87	0,87
	m	1,46	4,02	2,75	10,14	354,11	1,62	1,49	1,67	0,46	0,66	0,18
After Flight-1	M	68,70*	46,43*	11,16*	157,65*	2013,33*	17,00*	51,00*	33,69	14,58	10,57	2,26
	σ	11,25	20,74	13,71	105,99	1441,85	6,58	10,27	9,79	2,60	5,28	1,00
	m	2,65	5,03	3,33	25,71	349,70	1,60	2,49	2,37	0,63	1,52	0,24
After Flight-2	M	64,03*	46,64:*	10,49:	131,28*	2175,42*	21,52*	48,72*	29,77	14,13	9,80	2,42
	σ	8,33	14,96	9,34	79,33	1302,20	5,17	5,84	6,83	1,86	3,39	0,87
	m	2,15	4,00	2,50	21,20	348,03	1,38	1,56	1,83	0,50	0,94	0,23

Table 2 presents night average values of all main parameters on specific flight phases (prior to launch, in every mission month, after landing).

Before launch, measurements were fulfilled twice (at L-2 months and L-2-3 weeks). According to the table, differences between the first and second measurements of all parameters were statistically insignificant. Results of the second, close to launch measurements, were used for comparison with in- and post-flight data.

In orbit, night average values of many parameters did not change to the degree of statistical significance. In the first month of life in microgravity night-time heart rate reduces fiducially and breathing rate increases (breathing cycle grows short). The only reliable change on the second month is only reduction in motor activity during sleep. From month 3 till mission end there is a significant growth in relative power of the HRV low-frequency spectrum controlled by the sympathetic vascular center [5]. Breathing rate gets markedly rapid after 4 months on mission.

Considerable weakening of relative high-frequency power on months 5 and 6 points to a more active sympathetic involvement. Motor activity of sleeping cosmonaut becomes reliably less on mission month 5.

After return to Earth, virtually all parameters exhibit considerable changes. Heart rate increases already on days 1 to 4 of landing. Shifting of autonomic regulation toward sympathetic regulation declares itself by decreased pNN50 values and rise of stress index paralleled by significant reduction in HRV total spectral power (TP). Obvious changes in high- (HF) and low-frequency (LF) relative power are an additional indication of the domination of sympathetic regulation.

In summary, the nighttime average data obtained in long-duration space missions evidence that microgravity produces a statistically reliable activation of the sympathetic autonomic regulation and a slight increase in breathing rate. Motor activity of sleeping cosmonauts gradually decreases testifying indirectly relaxation of the neuromuscular tension. However, individual adaptive reactions of cosmonauts on mission are characterized by a large diversity depending on type of autonomic regulation.

2. Individual patterns of autonomic balance

Table 3 contains mean HRV parameters before, in and after space flights in five groups of cosmonauts differing in the type of autonomic regulation.

Table 3. Mean HRV parameters in cosmonauts differing in type of autonomic regulation in the course of space flight

Type of autonomic regulation		HR	SI	pNN50	HF %	LF %	VLF%	n
V (vagotonic)	Before flight	52,6	80,6	22,83	26	45	29	6
	In Flight	47,6*	64,8*	21	21*	49,4*	29,8	
	After Flight	63,4*	104,8*	12,8*	17,4*	47,2	35,2*	
NV (normal-vagotonic)	Before flight	57,5	73,8	20,2	28,2	40,4	31,2	8
	In Flight	54*	65,3	22,5	26,5	48	25,4*	
	After Flight	63,3*	94,8*	15*	19,5*	50,8	29,5	
N (normotonic)	Before flight	63	134,1	11,1	26,6	43,3	28,6	6
	In Flight	61	124,3	12	25,3	48	26,3	
	After Flight	75,4*	240*	8,2*	19*	51,6	29,4	
NS (normal - sympathotonic)	Before flight	58	48	28	36	41	23	1
	In Flight	69	121	8	22	51	27	
	After Flight	97	363	0	10	56	34	
S (sympathotonic)	Before flight	68	72	18	19	44	37	1
	In Flight	75	234	0.5	13	49	38	
	After Flight	73	202	3	20	50	30	

As viewed in table 4, the majority of 22 ISS cosmonauts (n=8) belonged to the group with normal vagotonic (NV) regulation. Groups with vagotonic (V) and normal tonic (NT) regulation consisted of six participants in the experiment each; one cosmonaut had normal sympathotonic (NS) and also one - sympathotonic (S) regulation. Table 5 contains mean HRV parameters in different mission periods for each type of autonomic regulation.

As is evident from these data, reaction to prolonged microgravity varied in cosmonauts with different types of regulation. Those who have regulation of the vagotonic type displayed substantial reductions of heart rate, index of tension and relative high-frequency power (HF %). The low-frequency power (LF %), on the contrary, showed a significant growth. Cosmonauts with NV regulation were found to slow down heart rate and to reduce relative HRV power in the very low-frequency spectrum (VLF%) considerably. Cosmonauts with NT regulation did not change the HRV parameters significantly during space flight. To sum up, the trend in adaptive reactions in all groups was identical; however, it was the strongest in cosmonauts with vagotonic regulation.

Preliminary assignment to the groups was made with consideration of individual heart rate values averaged for the entire period of life in microgravity (table 4).

Table 4. Determination of the type of autonomic regulation by the criterion of heart rate averaged over the entire period of life in microgravity

Type of autonomic regulation	Mean heart rate in microgravity (beats/min)
V (vagotonic)	50 or less
NV (normal- vagotonic)	51-60
N (normotonic)	61-65
NS (normal -sympathotonic)	66-70
S (sympathotonic)	Above 70

Cosmonauts with normal sympathotonic and sympathotonic regulation exhibited same trend of reaction as the other groups but the reaction per so was sharper with the values SI, pNN50, HF % and LF % suggesting high activation of the sympathetic nervous system.

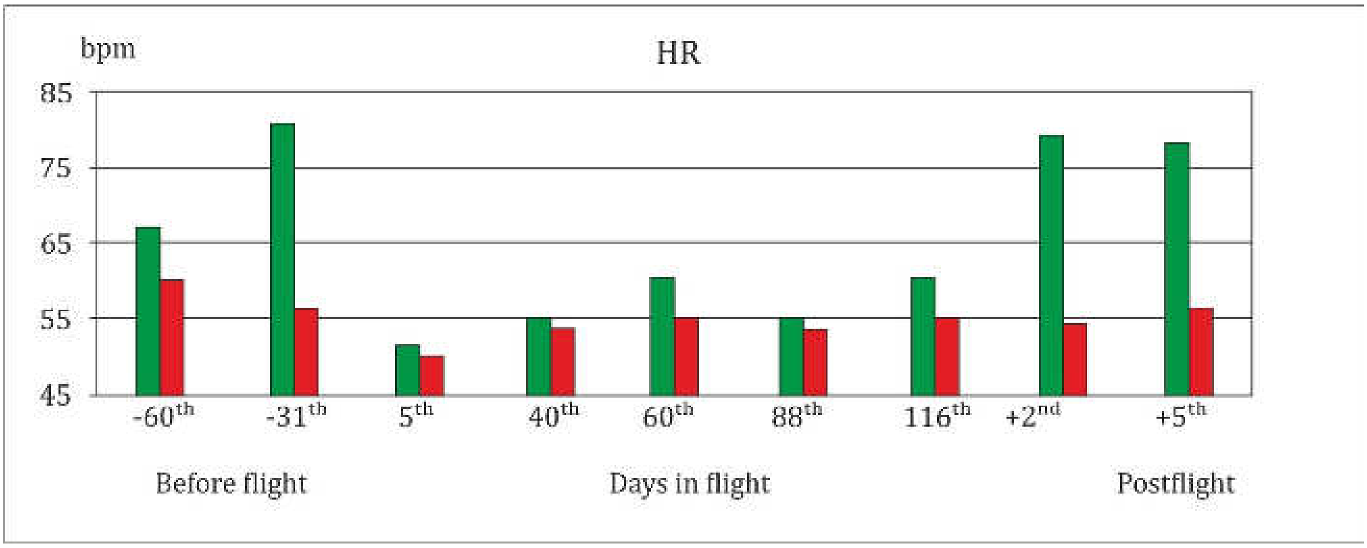
In the post-landing period, all cosmonauts displayed identical reactions though of different strength. The reaction was the strongest in cosmonauts with normotonic regulation.

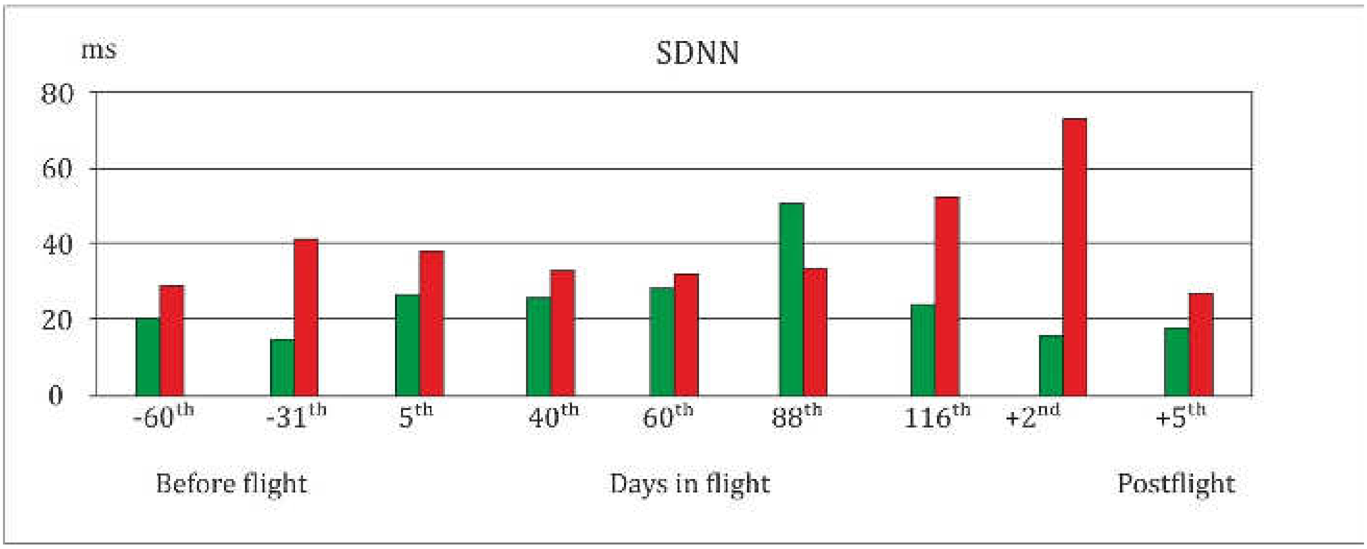
3. Functional reserve recovery during sleep in microgravity

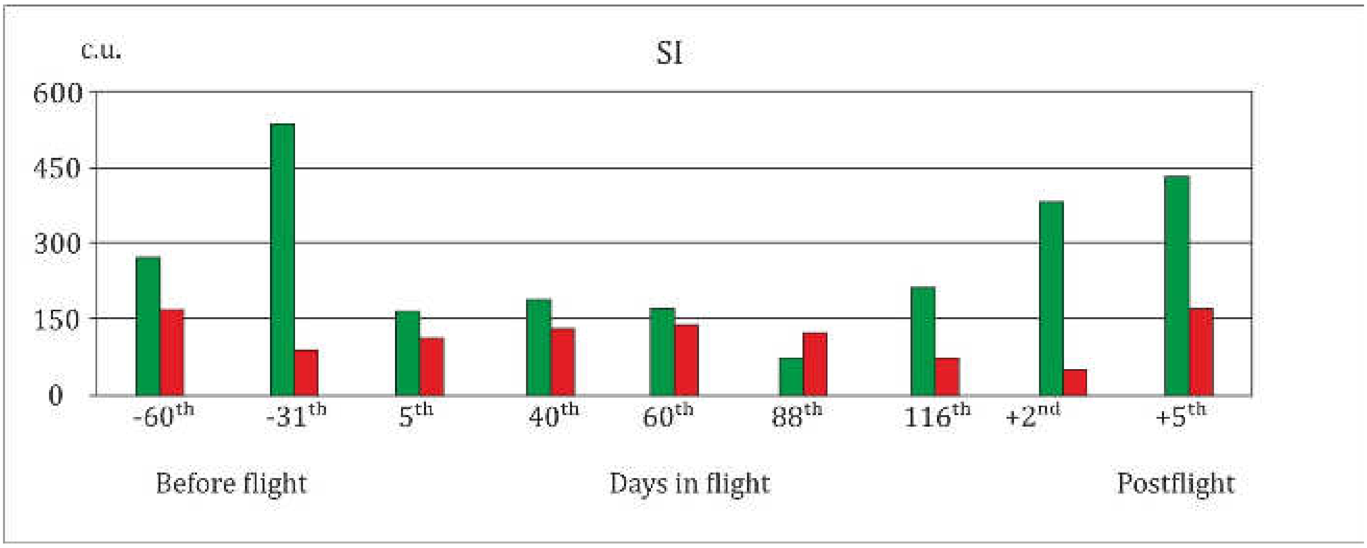
Quality of sleep and completeness of the functional reserve recovery can be assessed by comparison of data recorded at the first and last sleep hours. Even HR changes are enough to see that difference values of the parameters furnish important information about sleep quality (fig. 3). Heart rate variability parameters are particularly informative. It is well known that sleep is the kingdom of vagus. In sleep, parasympathetic structures take over dominance, owing to which the functional reserve of the organism restores and is spent minimally. The defensive-recovery function of the parasympathetic system is vital for those whose occupation is associated with exposure to stressful environments. That is why it is so interesting to find out how autonomic regulation changes in sleeping cosmonauts in different period of space flight.

To be certain that sleep quality can be indeed assessed by difference values of the HRV parameters, special comparative studies with the use of polysomnography were performed [12].

We studies cross-correlation between polysomnographic data and results of HRV analysis. The following polysomnography parameters were considered: sleep index, falling asleep time, wakefulness, time, sleep effectiveness, duration of rapid eye movement sleep and number of sleep cycles. HRV analysis results were used to calculate HR SDNN, pNN50 and SI difference values. The highest correlation was established between polysomnography data and sympathetic (SI) and parasympathetic (pNN50) regulation activities.







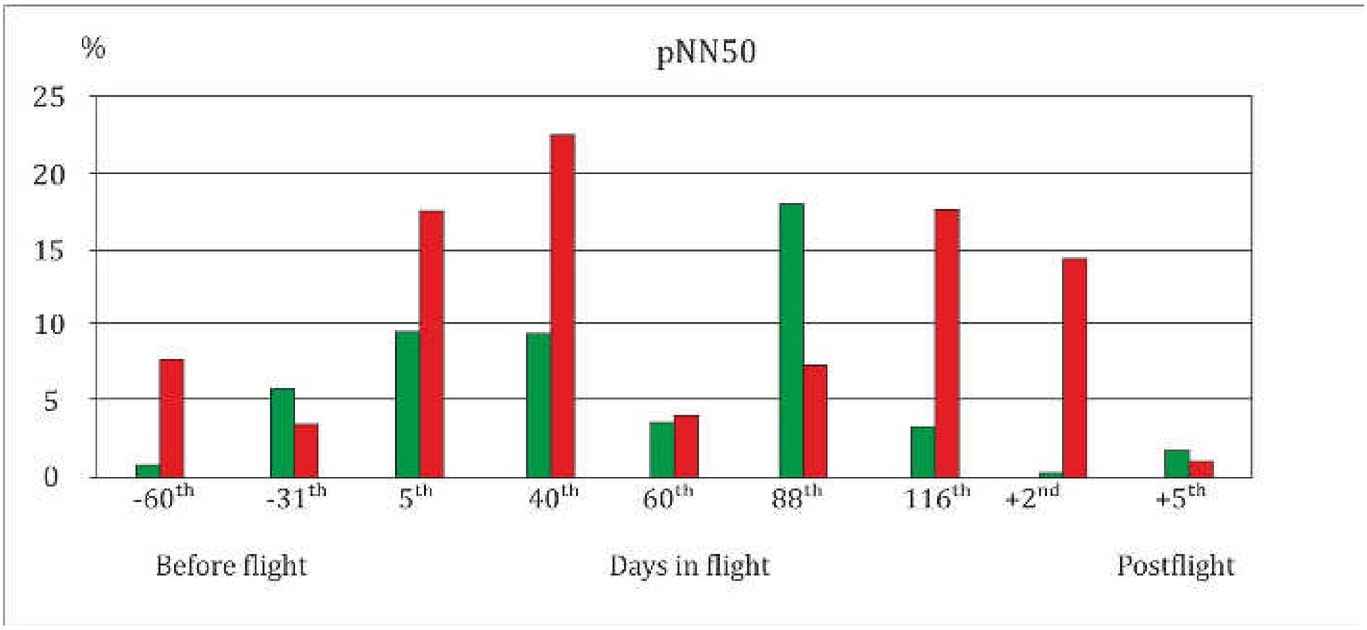


Figure 3. Evening and morning HR, SDNN, SI and pNN50 values measured in crew member (K1) in different periods of space flight.

This seems to be the linked with the fact that their parasympathetic segment of the autonomic nervous system (pNN50) is very active and reacts to inhibitory processes in the brain cortex controllers of the falling asleep quicker than other segments.

To sum up, analysis of sleep quality in ISS cosmonauts by HRV difference values allows quantify to what degree sleep in microgravity recovers functional reserve of the organism. It should be mentioned that subjective sleep assessment by cosmonauts coincides with objective data in no more than 70-80 %. However, as a rule, when a cosmonaut said that he had not slept well his words were supported by objective data.

4. "SONOCARD" as an instrument of assessing recovery from open space operations

It is well known that sleep is crucial for restoration of the functional reserve of organism. This explains the importance of assessing the quality of cosmonauts' sleep after heavy flight duties. One of the most demanding spaceflight operations is egress into open space and extravehicular activities (EVA) on outer surface of the International space station. These operations challenge cosmonauts physically and psycho-emotionally. That is why it is essential to know the reserve potential of organism before cosmonaut goes out and when he returns into the station. The latter needs to be known as for assessment of cosmonaut's fatigue and energy cost of planned operations, so prediction of fitness for next EVAs. Practical aspects of this approach were validated on the ISS by the instrumentality of device "SONOCARD" [13, 14, 15].

One investigation was scheduled 3 to 10 days prior to preplanned EVA and the other, on the night following open space operations. Three Russian crewmembers (К1, К2 и К3) were investigated. The very first investigation was performed on November 15, 2010 with two cosmonauts (К1 and К3). К3 made three egresses in a mission. К2 went out in open space twice.

Tables 5 and 6 present night average values of the main HRV parameters following EVA performed by К2 and К3. Six days before the EVA (mission day 33) К2 developed moderate bradycardia (night average heart rate = 47.1 /min) and had slightly increased LF (52.4 %). On the night following the first EVA his heart rate rose to 54.2 /min and LF made up 63.5%. Functional straining was testified also by reductions in pNN50, TP and HF, and growth in the stress index (SI).

By his second EVA (mission day 62) all means of the HRV parameters were back within the ranges identified on the eve of the first egress. After the second EVA, the pattern of HRV changes was analogous to what had been observed previously; pNN50, TP and SI underwent more significant changes. It should be noted that degree of regulation straining after the working in open space was more obvious following the second EVA as compared with the first one.

So, already the first investigation showed that work in open space involves high straining of the regulatory systems and costs gross expenses of the functional reserve. Subsequent investigations reinforced this conclusion and demonstrated that repeated participation in EVA causes fatigue accumulation and every next egress becomes more demanding for the regulatory systems.

Table 5. Changes in mean HVR parameters in К2 on the night following EVA

Period	Mission day	HR	pNN50	SI	TP	HF	LF	VLF
Before EVA-1	33	47.1	38.6	31.9	5090	22.5	52.4	25.1
After EVA-1	39	54.2*	16.4*	64.7*	2932.6*	13.9*	63.5*	22.5
Before EVA-2	62	46.8	28.9	34.5	4973.8	18.4	49.6	32
After EVA-2	64	52.8	12.9*	94.3*	1891*	19.3	53.4	27.3

*- statistically significant change ($p < 0.05$)

Table 6 contains similar data from К3 who made three egresses onto the ISS outer surface over his 6-month mission. HRV analysis following the first EVA found no other changes except a considerable LF increase and VLF reduction in comparison with baseline values collected 9 days prior to EVA. The second EVA produced a somewhat moderate LF increase and VLF reduction. Obvious signs of the functional straining, i.e. SI growth and TP reduction, appeared only following the third EVA.

Table 6. Changes in the night average HVR parameters in К3 on the night following EVA

Period	Mission day	HR	pNN50	SI	TP	HF	LF	VLF
Before EVA-1	32	47,1	13,3	102,4	1370	27,8	36,7	35,6
After EVA-1	40	46	15,8	95,8	1650,2	20,9	50,4*	28,7*
Before EVA-2	102	46,1	12,9	97,6	1405,7	32,4	38,8	28,8
After EVA-2	106	47,5	11,5	112	1460,4	27,6	41,2	31,2
Before EVA-3	129	47,9	10,7	95	2220,8	19,3	46,8	33,9
After EVA-3	132	46,9	8,41	132,8*	942,8*	23,7	44,8	31,5

*- statistically significant change ($p < 0,05$)

Table 7. Results of К1 pre and post EVA data analysis (investigations with the use of “Sonocard”)

HRV parameter	12 d. prior to EVA	Second night post EVA
HR, beats/min	57.7	69.2*
pNN50,%	15.6	7.8*
SI, stand.unit	71.7	121.4*
TP, ms2	2356.3	1342.6*

*- statistically significant change ($p < 0.05$)

Table 7 presents the results of K1 investigations. He made one egress on mission day 153; implementation of this EVA at the end of his six-month mission could have affected the results. On the second night following EVA the pronounced increase of the degree of functional straining was manifested by significant rises in HR and SI and reductions in pNN50 and TP. Functional straining due to depletion of the functional reserve of organism was developed in all cosmonauts though to a variable extent. Apparently, much depends on individual functional potential which is subject to gradual depletion as mission continues. It may be that functional straining is a function of the length of stay in microgravity

Conclusions

Implementation of experiment "Sonocard" aboard the ISS furnished important scientific and practical results. First of all, the unique technique of noninvasive physiological signal recording for sleep investigations in long-duration piloted missions was developed. The simple and comfortable technique provides high quality data recording all night through. Five years of the research experiments on the ISS demonstrated steady reliability of device "Sonocard". Software products for in-sleep seismocardiogram analysis ensure acquisition of valuable data about quality of cosmonauts' night sleep during space flight [16]. We should also point out the possibility to assess sleep quality which is essential for judging about completeness of the functional reserve recovery and adjustment of cosmonaut's work/rest cycle, if necessary. The series of investigations scheduled on the eve and soon after operations in open space showed the utility of this approach for estimating degree of organism straining and ability to recover, and energy cost of these operations [17]. The unprecedented systematic physiological signal recording during sleep in space is the best argument for advocating this technique as an enabling instrument for the system of spacecrew medical monitoring.

Results of experiment Sonocard rationalized the development of concrete recommendations for continuation of the investigations and research data application. Specifically, the new technique should be integrated into the system of medical monitoring of crew members in orbital and future remote space missions. Other fields of application of the in-sleep signal recording are clinical and rehabilitation medicine and applied physiology.

The experimental use of the Sonocard technique in the Mars-500 project (simulation of a mission to Mars) testified its validity in ground-based investigations with simulation of the effects of space factors on human organism.

Statement on ethical issues

Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest

None declared.

Author contributions

I.I.F., E.S.L., I.N.S. defined the aim of research and supervised the implementation. I.N.S., A.G.C., R.M.B. prepared the manuscript and analyzed the data, R.M.B. drafted the manuscript. All authors read and met the ICMJE criteria for authorship. All authors read and approved the final manuscript.

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