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Effects of the geomagnetic field time–varying components compensation as evidenced by heart rate variability of healthy males.

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ABSTRACT

Evolutionarily, a human organism is adapted to the natural geomagnetic environment and its slight alterations. However, during geomagnetic storms (GMSs), the strength of the geomagnetic field (GMF) sharply increased hundreds of times and can pose a serious threat to people. We examine the effects of controlled compensation in the time-varying components of the GMF, using a specially created experimental setup with electrically shielding solutions, providing an electromagnetically quiet environment. The measurement of heart rate variability (HRV) on 25 healthy young male volunteers was carried out in the laboratory using the experimental setup at different levels of outdoor geomagnetic activity (GMA). The geomagnetic K-index was used to characterize the magnitude of GMSs; volunteers were tested during quiet magnetic days ($K = 1$–3), days with $K = 4$, and days with GMSs ($K \geq 5$) in the period of solar cycle maximum. During quiet magnetic days, the comparison between HRV baseline values with values measured under GMF time-varying components compensation mode (CM) did not reveal any changes. On days with $K = 4$ some HRV indices shifted from their initial values, but it was statistically not significant. However, on days with GMSs statistically significant changes in SDNN* ($p = 0.033$) and LF* ($p = 0.011$) indices of HRV were observed in the GMS CM compared to their baseline values. The experiments showed that GMSs cause a sensitive reaction of the heart rate regulatory mechanism, the effect of which can be canceled in the GMS CM. The efficiency of the used technology is supported by the results of this study. * SDNN (Standard Deviation Normal to Normal R-R of cardiointervals), LF (Low frequency spectral band of cardiointervals).

1. Introduction

Geomagnetic storms (GMSs) are considered a possible risk factor for cardiovascular diseases. Geomagnetic activity (GMA) is dependent on the solar cycle phase. The Sun undergoes a cyclical (covering two ~ 11-year pole phases) pattern of magnetic reversals observable in the frequency of sunspot activity, that is maximal in the peaks of each ~ 11-year phase. Solar phenomena such as solar flares, solar energetic particle events, and coronal mass ejections (CMEs) are the origin of solar wind and the followed space weather events. Geomagnetic storms mainly are caused by Earth-bound CME, while solar radiation storms and radio blackouts are caused by solar flares. CMEs are vast clouds of seething gas, charged plasma of low to medium energy particles with an embedded magnetic field, that blast into interplanetary space from the Sun. When a CME strikes Earth, this causes a worldwide temporary disturbance of Earth's magnetic field. The battle between charged particles and magnetic fields shake the Earth's magnetic field over a period of several hours or days (Scherer et al., 2006; Marusek, 2007).

There are also the storms driven via co-rotating interaction regions (CIRs) of the solar wind. CMEs are strongly phase-dependent on the position within the solar cycle and occur basically during solar cycle maxima. CIR-driven storms are not strongly phased dependent within the solar cycle, and also occur during solar cycle minima (Borovsky and Denton, 2006). The geomagnetic activity (GMA) on the maximum or descending phases near maximum, is maximal, in the minimum of the solar cycle it becomes minimal. Geomagnetic field (GMF) is characterized by the strength of a few nT. During GMSs, the intensity of GMF sharply exceeds from 30 to 70 nT to 100–1200 nT. The strength of GMF varies depending on the latitude and corresponds to several categories of geomagnetic fluctuations. At high latitudes, the geomagnetic perturbations are permanent and most intensive, although, effects are observed at lower latitudes at times of strong GMA. GMSs consist of three phases: The initial, main, and recovery phases (The Earth's Magnetic Field: An Overview. 2021; Space Studies Board, 2008).

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The central and autonomic nervous systems, and heart rate are mainly affected by GMSs. GMSs break the regular, synchronous rhythm of vital processes, leading to an abrupt drop in cardiac activity. During GMSs days existing diseases aggravate. On storm days' arrhythmias and large-wave fibrillation were determined (Stoupel, 1993). During GMSs the risk of in-hospital death, myocardial infarction, and stroke increase by over 1.5 times (Cornelissen et al., 2002), (Vencloviene et al., 2014). In healthy people effects can be manifested in time elongation of simple locomotor reaction to the velocity of the visual information processing, worsening of the attention characteristics, short and long-term memory (Khorseva, 2013), this argues that during GMS human organism is under the influence of the irritating (stress) effect. As reported by some authors in a test population, the ratio between magneto sensitive and magneto insensitive healthy individuals is around 60% to 40% respectively, in hypertensive patients 84% to 16% compared to the insensitive patients (Zenchenko and Breus, 2008).

Several projects have been known to use shielded rooms for biomagnetic research with compensation for the external magnetic field. The principles to construct an isolated, radiofrequency-shielded room wrapped with several sets of orthogonal square coils for high central field uniformity have been designed by Merritt et al. in 1983 (Merritt et al., 1998) and in future improved by Kirschvink (Kirschvink, 1992). This technology is used in magnetoreception studies (Prato et al., 2011, 2013), (Wang et al., 2019).

At present, a number of researches have shown the effects of hypomagnetic field (near zero and zero) using squared coils, that shielded the working volume from static and low-frequency electromagnetic fields. However, some authors reported that by exposure to the hypomagnetic field resulted from an increased incidence of somatic defects in animals and deterioration of cognitive processes in humans (Tombarkiewicz et al., 2004), (Sarimov et al., 2008), (Guanghao et al., 2012).

Other authors have been reported that during 60 min of zero magnetic field exposure significantly reduce the heart rate and decrease the diastolic blood pressure to the end of exposure in healthy subjects without cardiovascular pathologies and in patients with ischemic heart diseases. Authors suggested that such technology can be used for the protection of people from the negative influence of GMSs (Gurfinkel and Ljubimov, 2004), (Gurfinkel et al., 2016). However, in such rooms owing to full electromagnetic isolation the induced hypo magnetic environment allowed the absence as static as well as time-varying components of the GMF, which significantly differs from natural GMF conditions and makes it impossible to achieve a various degree of compensation of GMF.

Based on the above-mentioned earlier technologies Georgian engineers including engineers of the current study have been developed technology for active compensation of time-varying components of the GMF for the protection of magneto-sensitive individuals during GMSs (Khomeriki et al., 2004), (Khomeriki et al., 2008).

Russian scientists were designed an experimental setup like the setup used in the presented experiments (see below) allowing the generation–compensation of the three-component magnetic field and consisting of two systems of mutually orthogonal Helmholtz coils. The direction of each pair of Helmholtz coils was the same as the direction of the compensated GMF component. One system of Helmholtz coils was used to create GMS. However, this setup is designed for small working volume and used for experiments under laboratory plants (pea plants) and animals (Daphnia Magna) (Krylov et al., 2014).

There are also active magnetocompensation systems available for protecting sensitive EM instruments, such as MRI systems, electron microscopes, etc. from AC/DC environmental magnetic fields, but these systems provide real time compensation of environmental magnetic field fluctuations caused by moving vehicles, trains, elevators, electrical distribution equipment and other sources (Bilz catalog 2000; Ets-Lindgren 2000; Active magnetic field compensation system-MACOM II 2000).

Building on these results the objective of our current study was determining the effects of GMF time-varying components compensation on heart rate variability (HRV) of healthy males.

2. Material and methods

2.1. Engineering and geomagnetic part

The current study was performed at a middle geomagnetic latitude (41°41′38″ N), in Tbilisi, Georgia, in the 2016 year that corresponds to the descending phase near the maximum of the "24th solar cycle", in the months around the winter solstice, in January and February. For the analysis and classification of the GMA days, the geomagnetic K-index (Menvielle et al., 2011) was used to characterize the magnitude of the GMS, where days with a value of $K \leq 2$ are ascribed to magnetically quiet periods and those with $K \geq 5$ as those with GMSs occurring. The data on K-index of GMA were obtained via the Internet using the datasets of Izmiran, Troitsk, Russia, 55.4774°, http://www.izmiran.ru. For the control procedure, we compared this data to the dataset from Potsdam, Berlin, Germany, 52.391842, (www-app3.gfz-potsdam.de/k-p_index/quietdst/qd201019.html).

All stages of experiments were done in the experimental room at the central scientific research laboratory (CSRL) of David Tvildiani Medical University (DTMU). In this study, we used an experimental setup so-called GMSs magneto active compensation and simulation device designed by Invia et al., (2015). Using a highly sophisticated electronic technology the device provides reliable shielding solutions from environmental low-frequency magnetic fields (MF). The current system (including circuits in a rectangular shape in 3 axes system, 3 component fluxgate magnetometer, computer, and electronic block) is able (i) to compensate automatically in real-time the disturbed GMF and (ii) to recreate the required characteristics of the GMF with a uniform MF. The inhomogeneity of the field created by all subsystems does not exceed 2%, which determines the quality of GMF disturbance compensation, with respect to the center of the room. This region is shown in Fig. 1.

Fig. 2 shows the overall dimensions of the room in which is allocated

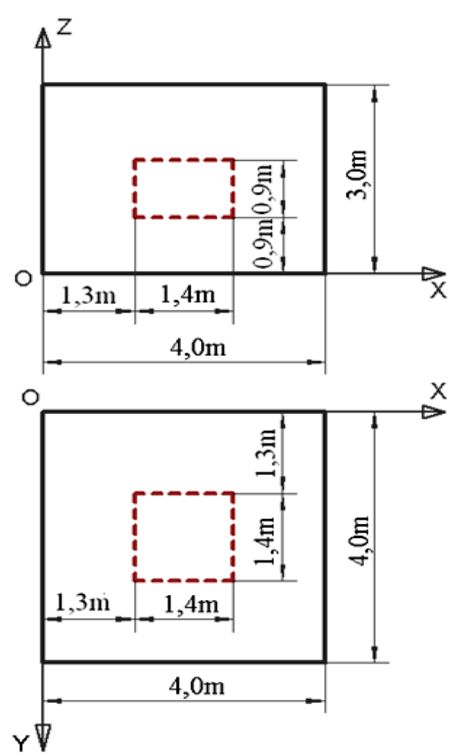

Fig. 1. The region of space with the magnetic field inhomogeneity of less than 2%.

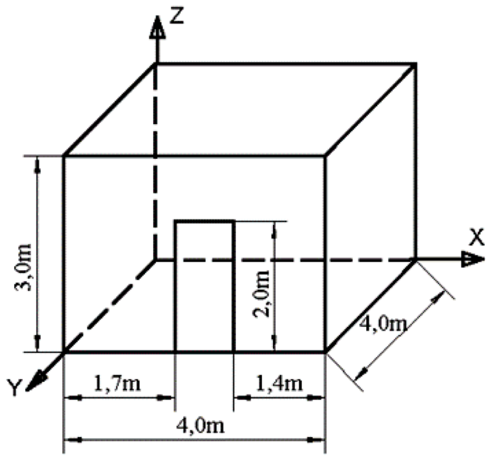

Fig. 2. Overall dimensions of the room for the experimental setup.

the experimental setup.

Fig. 3 shows the calculations of the magnetic system configuration, X- and Y- subsystems are made of two pairs of rectangular circuits, Z-subsystem is formed of the two circuits.

In the compensation mode, the magnetic system compensates for (removes) perturbed variations of the time-varying components of the naturally occurring GMF but saves the normal GMF variations (in the range of < 40 nT) providing an electromagnetically quiet environment.

In the simulation mode, the magnetic system also compensates for (removes) naturally occurring GMF variations and saves only the static component of the GMF whereafter it simulates the required characteristics of the GMF (Tvildiani et al., 2018), by using the reprocessed magnetometer data (this magnetometer was allocated in the village region with a minimum level of man-made electromagnetic interferences). In our experiments, the constant part of GMF was obtained by taking averages over long time-series of the GMF, and in the frame of reference used by us the amount of its components to BX0 = 20 200 nT, BY0 = - 3800 nT, BZ0 = 38 100 nT. The GMS compensation mode (K = 0) corresponds to a magnetic field strength within the range of (B = 0–5 nT) and simulation mode (K = 7) to a natural magnetic field strength within the range of magnetic induction (B = 200 nT).

In the room the coils have been covered within acoustically attenuated, plastic and wooden brackets without using any ferromagnetic materials, forming the walls, floor, and top.

Photograph 1 shows the inside magnetometer mounted on a wooden rack, by which the control measurements of the magnetic induction were performed.

Photograph 2 shows the current view of a low-frequency, light, and sound isolated experimental room, with a wooden platform and plastic deck chair in the center of the room.

2.2. Medical part

In this study, the following ethical standards were complied with: The laws of Georgia, the Helsinki Declaration as well as data protection stipulations. All participants gave their written consent to participate in the study. The study was approved by the Ethics Committee of David Tvildiani Medical University (REC 05/2014) and was conducted according to the guidelines of the clinical trials service of the U.S. National Institutes of Health (https://clinicaltrials.gov/ct2/about-studies/learn). The measurement procedures and methods applied were non-invasive and approved according to the relevant guidelines.

The experiments performed in this work compared changes in the heart rate variability (HRV) indices taken during quiet geomagnetic days and days of GMSs with those obtained when groups were exposed in the conditions of compensation of perturbed time-varying components of GMS. HRV measures the autonomic nervous system (ANS) response, which indicates the adaptive reactions of the whole organism. HRV is considered as a measure of neurocardiac function that reflects heart-brain interactions and ANS dynamics. ANS consists of sympathetic and parasympathetic parts (SP, PP). The PP and SP competitively regulate HR (accentuated antagonism), where increased sympathetic activity is paired with decreased parasympathetic activity and both

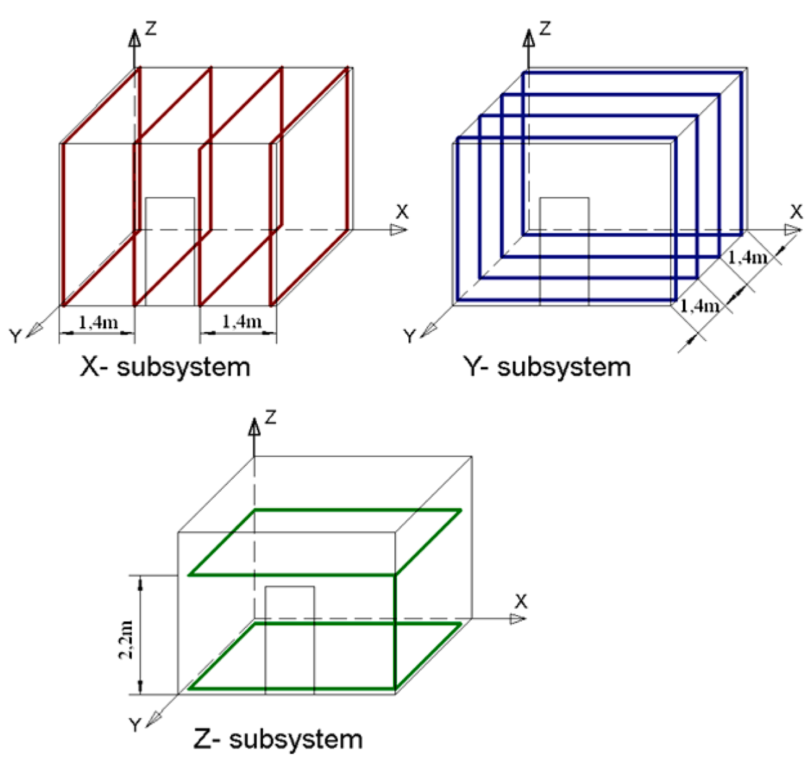

Fig. 3. The configuration of the magnetic system in 3 axes system.

branches of the ANS are simultaneously active (Bernston et al., 1997). The PP and SP show different responses to stress. The parasympathetic influence prevails at relaxation, and the sympathetic factor is dominant under stress. The dynamic interplay between the antagonistic subsystems of the ANS enables efficient cardiovascular responses to external and internal influences (Friedman, 2007). The sympathetic and parasympathetic activity is integrated into the activity occurring in the heart's intrinsic nervous system, all of which contribute to beat-to-beat changes (European Society of Cardiology and the North American Society of Pacing and Electrophisiology, 1996), (Shaffer et al., 2014). The vagal tone (parasympathetic activity) helps maintain the dynamic autonomic regulation important for cardiovascular health, while, reduced parasympathetic activity has been found in a number of cardiac pathologies and in patients under stress or suffering from panic, anxiety, or worry (Thayer et al., 2010). In HRV for the characteristic of a dynamic number of cardio intervals, there are used some indices, that include as time-domain indices: HR- Heart Rate, SDNN - Standard Deviation Normal to Normal R-R interval, RMSSD - the square root of the sum of squares of different values, etc. as well as frequency domain indices, that obtain quantitative data on oscillatory and wave processes in the cardiointervals, including 4 primary frequency bands: high-frequency (HF - 0.15–0.4 Hz), low-frequency (LF - 0.04–0.15 Hz), very low-frequency (VLF - 0.0033–0.04 Hz), and ultra-low-frequency fluctuations (ULF - below 0.0033 Hz).

The research was carried out as a single-blinded study using a block and between-subjects design (Nielsen Norman Group, 2018). The current study took part in $n = 25$, 19–24 years old healthy male volunteers. Before the inclusion in the group under supervision the subject was informed of the experiment essence, however, to avoid psychological stress and ensure the reliability of the results, the investigated was not informed of an approaching GMS or the device is turned on or off during specific experiments. Subjects were recorded on the days with different outdoor GMA. The total recording time for all experiments lasted 2 months.

Measurements were done after breakfast (at least by 1–2 h.), with a constant temperature of 22–23°C in the room, in a supine position on the plastic deck chair with quiet breathing. A period of 10 min for adaptation of volunteers to local environmental conditions preceded measurements. Within 3 days before recordings a prerequisite precondition for the test volunteers was avoiding any negative influences, resulting from emotional and physical excitation, heavy nutrition, alcohol, etc. The total measurements lasted 60 min. The values of HRV with three 20 min consecutive sub-spans in pre (when the device was turned off), during compensation (when the device was turned on) and on the restoration (when the device was turned off) stages, have been detected using the ArguSys++ Holter monitoring system (www.innomed.hu), which communicates with the recording computer via an optical fiber cable to a control room ~ 3 m away.

For statistical analysis of the data obtained we used "Primer of Biostatistics" software by Stanton A. Glantz,(seventh edition) that provides corresponded 95% CI.

All mentioned HRV indices and heart rate were processed and evaluated, indices changed during the experiments and processed statistically, are presented in the section "Results".

3. Results

3.1. Experiments in GMS compensation regime

Measuring was carried out at different outdoor levels of GMA: $n = 8$ volunteers were tested during quiet magnetic days ($K = 1$–3); $n = 11$ volunteers during days with $K = 4$; $n = 6$ volunteers tested during days with GMS ($K \geq 5$). Table 1. Shows the comparison of means of measured HRV indices to the K index of GMF in three 20 min consecutive sub-spans of experiments.

During quiet magnetic days, the comparison between HRV initial values with the values measured under GMS CM did not reveal any changes in the ANS. However, in the case of pronounced natural magnetic activity ($K = 4$–5), as observed under natural conditions, a similar comparison clearly showed changes in the ANS within the investigated subgroups. During $K = 4$ in outdoor environment conditions, HR values apparently show a shift from their initial values (the levels reduced under GMS CM and RS), however, these have not been proven by the corresponding statistical significance levels. VLF significantly increased under GMS CM from their initial values. Regarding the experimental studies, VLF rhythm is intrinsically generated by the heart and are modulated by efferent sympathetic activity, when there is a significant stressor (Bernardi et al., 1996), although, the consideration of VLF

Table 1
Means and standard deviations of HRV of healthy males in three 20 min consecutive sub-spans of experiments during different levels of outdoor GMA.

n	Stages	K	HR (b/m)	SDNN (ms)	RMSSD (ms)	VLF (%)	LF (%)	HF (%)
8	In. values	1–3	68.88 ± 2.96	79.38 ± 8.5	29.88 ± 8	30.73 ± 5.1	37.05 ± 2.99	32.42 ± 3.56
	CM	0	68.1 ± 3.1	70.25 ± 13	40.1 ± 7.4	30.41 ± 3.26	37.66 ± 3.75	31.93 ± 4.97
	RS	1–3	67.75 ± 2.9	77.5 ± 12.3	33.5 ± 7.3	32.15 ± 4.99	37.6 ± 3.33	30.22 ± 3.87
11	In. values	4	72.6 ± 2.97	60.5 ± 6.9	23.9 ± 5.4	29.99 ± 6.25	37.4 ± 3.08	32.63 ± 7.31
	CM	0	70.55 ± 2.3	72.5 ± 8.4	32.8 ± 5.7	32.24 ± 6.25*	35.57 ± 4.53	32.15 ± 7.28
	p					0.047		
	RS	4	69.2 ± 2.1	78.7 ± 9.3	30.4 ± 5.7	32.65 ± 6.22	35.85 ± 3.21	31.45 ± 6.7
6	In. values	≥5	83.3 ± 3.57	50.17 ± 6.6	31.7 ± 7.2	32.28 ± 10.4	33.88 ± 4.97	33.85 ± 9.5
	CM	0	78 ± 2.6	67.3 ± 7*	49.3 ± 12	30.43 ± 8.37	38.3 ± 4.98*	31.28 ± 9.21
	p		0.033			0.011		
	RS	≥5	79.5 ± 2.67	65.17 ± 5.9	22.5 ± 3.2	34.15 ± 4.42	39.98 ± 3.04	22.2 ± 10.64

Remarks:
In. values – initial values;
CM - GMS compensation mode;
RS - Restoration stage;
N - number of participants;
HR - heart rate, heart beats in min.;
SDNN - Standard deviation of all Normal to Normal RR cardiointervals;
RMSSD - The square root of the arithmetical mean of the sum of the squares of differences between adjacent NN intervals;.
VLF- very low-frequency band;
LF - low-frequency band;
HF - high-frequency band,
p-p value.
* indicates statistically significant differences;

rhythm is not recommended from short RR recordings due to their ambiguous physiological meaning (European Society of Cardiology and the North American Society of Pacing and Electrophisiology, 1996).

For $K = 5$ during GMSs in outdoor environment conditions statistically significant increases in SDNN and LF indices are clearly seen in the GMS CM. In short-term recordings, the primary source of the variation of SDNN is parasympathetically mediated respiratory sinus arrhythmia (Shaffer et al., 2014). the LF band mainly reflects baroreflex and vagal activity and not cardiac sympathetic innervation (De Lartique, 2014). Changes occurred also in HR and RMSSD values, in the case of HR, the shifts gradually reduce, in the case of RMSSD there are increased shifts that show an intensification of the PP of the ANS compared to initial values. All changes in HRV indicate a prevalence of the PP of ANS. The experiments showed that GMSs cause a sensitive reaction of the heart rate regulatory mechanisms in healthy young males, the effect of which can be canceled in the GMS CM, this is argued by the control results obtained for the naturally quiet GMF where the results were similar (differences were insignificant) to the ones under GMF compensation mode. As evidenced by the results of these experiments, the compensation mode of experimental GMSs magneto active compensation and simulation device facilitate the restoration of the autonomic regulation balance of the heart rate.

In Fig. 4 (a, b) statistically significant changes in the means of SDNN and LF are shown, in the consecutive subspans of the experiments.

4. Discussion

4.1. General considerations

Results of the experiments extend studies that report the effects with changes in GMA are observed also at lower latitudes at times of strong GMA (Palmer et al., 2006) and confirm the existence of GMA as the specific risk factor (Babayev et al., 2012), (Stoupel, 2019).

There are only a few studies involving healthy popuation. Results of presented experiments partly coincide with the results of study in which, the statistical significance of the influence of geomagnetic activity levels and cosmic ray intensity variations on heart rate and RR intervals of a large healthy population was estimated. Results revealed that heart rate increase and RR intervals variations were more pronounced for high levels of geomagnetic activity and large cosmic ray intensity decreases (Mavromichalaki et al., 2012).

Results partly confirm results of a study performed in a young and

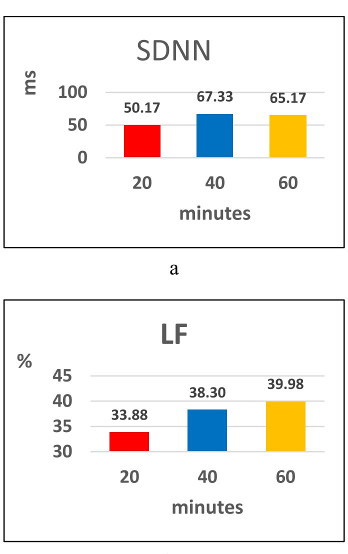

Fig. 4. (a, b) the shifts of the means of SDNN and LF indicating a prevalence of the PP of ANS under GMS CM during outdoor GMS conditions.

Photograph 1. The wooden rack with the mounted magnetometer.

healthy population, by the changes in heart rate and blood pressure depending on the geomagnetic activity and earth weather, to use some geophysical and meteorological parameters and to reveal the dependence of physiological parameters from these parameters. The study shows, HR clearly increases with an increased Kp index at low temperatures and low atmospheric pressure (Ozheredov et al., 2017).

Results coincide with the previous study which revealed non-specific stress reaction by enhanced tonus of the sympathetic nervous system (increased heart rate, reduced spectrum power of respiratory waves) during geomagnetic storms in astronauts (Breus et al., 2012)

Results extend and confirm also some previous studies that report hypomagnetic conditions (zero magnetic field) exposure reduces the heart rate to the end of 60 min exposure (Gurfinkel and Ljubimov, 2004), (Gurfinkel et al., 2016). However, the effects of the GMF time-varying components compensation differs from the effects of zero and near-zero magnetic fields; absence as static as well as time-varying components of GMF (see Section 1. Introduction) makes it impossible to compensate for the perturbed time-varying component of GMF and achieving natural quiet geomagnetic conditions saving normal variations and a static component of GMF to which a human organism is adapted evolutionarily.

Results of the experiments confirm the hypothesis of Berntson et al. (Berntson et al., 2008), that the PP and SP competitively regulate HR (accentuated antagonism), where increased sympathetic activity is paired with decreased parasympathetic activity or vice versa. The decrease of activity in one part of the ANS and increase in another is observed by achieving an optimal adaptive reaction.

These results coincide with the theory Thayer et al. (Thayer et al., 2010) and to the findings of some authors (Groves and Brown, 2005), regarding the vagal tone that helps maintains the dynamic autonomic regulation important for cardiovascular health and to the concept that vagally HRV has been linked to optimal psychophysiological well-being in normal people.

4.2. Limitations

The current study has some limitations due to the number of investigated subjects in the groups being small and the results obtained in our study demonstrate the effect only to brief exposure of compensated perturbed GMF on HRV.

Currently, K-index internet datasets for middle latitudes are unavailable. The datasets from Izmiran (Troitsk, Russia, 55.4774°, http://www.izmiran.ru), and Potsdam (Berlin, Germany, 52.391842°, www-app3.gfz-potsdam.de/kp_index/quietdst/qd201019.html) are intended for rather high latitudes of the Earth, where GMSs are most

Photograph 2. The current view of the experimental room.

intensive and can diverge from real events occurring at local middle latitudes by several hours, however, the trend of people's reactions remains the same.

5. Conclusions

The performed experiments consistently showed that high GMA produces health effects. Measurements carried out under artificially compensated GMS conditions significantly change SDNN ($p = 0.033$) and LF ($p = 0.011$) indices. Interpretations of the results from our study are summarized here:

1 Strong geomagnetic storms in solar cycle maximum, have an effect on healthy males at middle latitudes but have not been caused significant stress reactions.
2 Seems the magneto active compensation technology can be used for the safety and protection of people during GMSs via compensating the negative influence of GMSs and balancing the regulatory mechanism of the heart rate.

Based on the above we suggest considering this technology for its future use to protect magneto-sensitive people from the possible negative influence of the near-Earth space environment. In addition, such technology with specially created room do not cause psychological and physical discomfort and can provide an increased level of safety during GMSs.

In order to arrive at more definite conclusions, we propose to continue such studies by collecting and analyzing more data, using the setup described in this paper.

Availability of data and materials

The datasets used and analyzed during the current study and part of reports with some information about created magneto compensation technology are available in the supplementary materials.

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Authorship contributions

K.J. Conceptualization, Formal analysis, Funding acquisition, Investigation, Visualization, Writing - original draft, Writing - review & editing, L.T. and T.T. Data curation, Methodology, Project administration, Resources, Supervision, , N.I. Methodology, Resources, Software, Validation, . All authors read and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.lssr.2021.10.003.

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