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SPACE WEATHER EFFECTS ON HUMANS IN SPACE AND ON EARTH

ИНСТИТУТ КОСМИЧЕСКИХ ИССЛЕДОВАНИЙ
SPACE RESEARCH INSTITUTE

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IMPACT OF COSMIC RAY INTENSITY AND GEOMAGNETIC ACTIVITY ON HUMAN HEART RATE

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Accumulating evidence suggests a link between solar and geomagnetic disturbances and human physiological parameters. Several published studies have addressed the alterations in human physiological responses at different levels of geomagnetic activity. We sought to examine the potential association between heart rate variations and specific cosmophysical activities. In the present study, a total of 190 individuals treated at the Cardiology clinics of the Nikaia General Hospital in Piraeus and the Heraklion University Hospital in Crete, Greece, were assessed from July 2011 to June 2012. The heart rate of the subjects was recorded hourly by a Holter monitor, while the hourly variations of the cosmic ray intensity and the geomagnetic index Dst were measured by the Neutron Monitor Station of the Athens University and the Kyoto Observatory, respectively. Statistical methods included the ANalysis Of VAriance (ANOVA) and the Multiple Linear Regression analysis. A statistically significant effect of both cosmic ray and geomagnetic activity on heart rate was observed (negative and positive correlation, respectively). Our findings indicate that changes in space weather parameters could be possibly related to heart rate variations.

INTRODUCTION

Cosmic rays are energetic subatomic particles with a large energetic range ($10^6 \dots 10^{21}$ eV) and their precise origin is still unknown. Cosmic rays are divided into two categories, the primary cosmic rays and the secondary particles. When the primary cosmic rays enter the Earth's atmosphere they collide with molecules, mainly oxygen and nitrogen and a cascade of billions of lighter particles are produced (secondary particles). Cosmic rays are everywhere, and several dozen slam into our body every moment. Our body receives an average dose of about 2.4 mSv of radiation due to the cosmic rays every year. The intensity of the primary and secondary cosmic ray particles is known as the cosmic ray intensity (CRI). High energetic cosmic particles are primary detected from ground detectors. Grossly, CRI depends on the altitude and latitude, as the Earth's magnetic field deflects some of the cosmic radiation away from the Earth and the shielding ability of the magnetic field is more effective over the equator than over the poles. Moreover the Sun's magnetic field can deflect cosmic ray particles away from the Earth, depending on the phase of solar cycle. When solar activity is low (solar minimum), the magnetic field is less effective to deflect particles. On the other hand, Sun ejects energetic particles (solar flares and coronal mass ejections) that contribute to the cosmic ray intensity. This intensity is also affected by atmospheric conditions, such as atmospheric temperature and pressure [Olbert, 1953].

Geomagnetic activity (GMA) is caused by solar wind, which hits the Earth with hot, magnetized, supersonic plasma that carries a large amount of energy (kinetic and electric). This energy is drained to the Earth's magnetosphere causing geomagnetic storms, substorms and auroras, which constitute the geomagnetic activity. The level of this activity is measured by using different geomagnetic indices, such as Kp, Ap and Disturbances Storm Time index (Dst), which is used in the present study. A negative Dst index value means that Earth's magnetic field is weakened. This is particularly the case during solar storms. A geomagnetic storm is caused by a solar wind shock wave and cloud of magnetic field which interacts with the Earth's magnetic field. The frequency of geomagnetic storms depends on the sunspot cycle.

According to the United States National Space Weather Program, space weather "refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health" (http://www.nswp.gov/). Interestingly, space weather may affect many aspects of human life and health [Stoupel, 2006]. In 1989, a geomagnetic storm energized ground (Ground Level Enhancement- GLE) induced currents which disrupted electric power distribution throughout most of the province of Quebec [Bolduc, 2002]. Space weather effects on human health depend on the latitude and altitude; in this regard, people living at higher altitude can obtain several times more cosmic radiation than at sea level, and long-distance airline crews can significantly increase their yearly ionizing radiation exposure due to this source [Beck et al., 2007]. The potential health outcomes such as the occurrence of cataract and the increased incidence of cancer in aircraft crews have been discussed in many studies [Kagami et al., 2009; Reynolds et al., 2002). Furthermore, since the intensity of cosmic rays is much higher outside the Earth's atmosphere and its magnetic field, it is expected to have a major impact on astronaut health, and therefore should be taken under consideration in the design of spacecraft that can safely transport humans in interplanetary space. Last, a study conducted by the University of Alabama at Birmingham concluded that cosmic radiation is related to the occurrence of atherosclerosis [Yu et al., 2011].

The potential relationship between space weather and human physiological parameters has been studied extensively. Specifically, many studies have examined the impact of geomagnetic factors and cosmic ray intensity on physiological human parameters. These cosmophysical factors may affect the function of human brain and nervous system, and have been associated with cerebrovascular accidents, disturbances on circadian rhythm, as well as motor vehicle accidents. Specifically, cosmogeophysical parameters appear to be related to the occurrence of cerebrovascular infarctions [Mikulecký, Strestík, 2007]. In addition, it has been observed that geomagnetic activity influences the melatonin secretion and is therefore related to changes in normal sleep patterns [Conesa, 1997; Weydahl et al., 2001]. Geomagnetic variations have been related to motor vehicle accidents, which in turn were associated with increased driver anxiety and nervousness [Ascikaliev et al., 1995; Dorman et al., 2001]. Space weather also seems to affect human emotional state. Geomagnetic storms may play a significant role in the seasonal increase of incidents with depression in susceptible individuals [Babayev, Allahverdiyeva, 2007]. Similarly, a raise in hospital admissions with depression and manic-depressive illness during the week which follows a geomagnetic storm has been observed [Kay, 1994]. Last, the number of monthly newborns (of both genders) has been related to the level of monthly cosmic ray intensity and solar activity indices 9 months before the month of delivery [Stoupel et al., 2006a].

Heart rate is a physiological parameter that may reflect the response of the human body in external or internal stimuli. Heart rate is regulated by the combination of the neural and chemical components in the body and it is generally genetically determined. It varies among individuals, and can also be affected by many variables such as the age, the sex, substances and drugs, the lifestyle, the variations in temperature, pressure, humidity and other meteorological parameters and disease states [Corsetti et al., 2012; Hopstock et al., 2012; McNarry et al., 2012; Pal et al., 2012). Also, situations as lack of sleep, irritability, rapid changes in blood chemistry can diversify the heart rate [Sørensen et al., 2012; Suzuki et al., 2012]. Moreover, emotions play a significant role, especially the condition of stress [Stapelberg et al., 2012]. In addition to these factors, disturbances in cosmophysical parameters may also play a role in the observed variations in human heart rate.

During the last decades many researchers have dealt with the potential relationship between space weather and cardiovascular homeostasis. Many studies have demonstrated that geomagnetic activity (GMA) and cosmic ray intensity (CRI), are associated with variations in human physiological parameters such as heart rate (HR) and arterial blood pressure [Dimitrova, 2008; Mavromichalaki et al., 2008; Papailiou et al., 2011; 2012]. Also, there is a link between the above indicators (GMA, CRI) with cardiovascular disease, including arrhythmias, ischemic heart disease, and myocardial infarction [Baevsky et al., 1997; Cornelissen et al., 2002; Dorman et al., 2001; Stoupel et al., 2002; 2007]. It has been indicated that the daily and monthly temporal distribution of sudden cardiac death and therefore the sudden cardiac death mortality is higher on the highest and lowest daily levels of GMA, while the monthly number of sudden cardiac mortality is inversely related to solar and geomagnetic activity [Stoupel et al., 2006b]. Furthermore, decrease in parameters of heart rate variability has been determined in periods which characterized by high geomagnetic activity [Baevsky et al., 1997; Dimitrova et al., 2009]. In addition, a temporal relationship has been suggested between the periodicities of geomagnetic phenomena of the solar cycle and cardiovascular incidents [Cornelissen et al., 2005]. Furthermore, myocardial infarctions and heart arrhythmias have been connected with the periodicity of the solar activity (11 year cycle) and geomagnetic storms, while others have observed a relation between polarity reversal of solar magnetic field and various types of arrhythmias [Giannaropoulou et al., 2012].

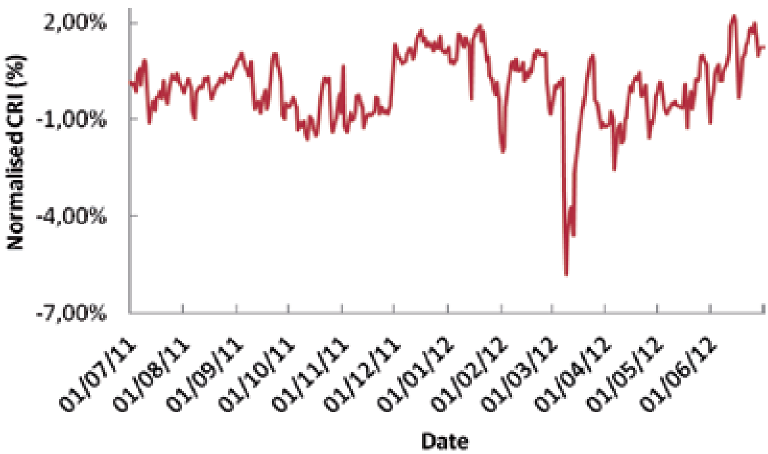
Despite the accumulating evidence regarding the impact of space weather on human health, no definitive studies have been published yet. Taking into account that heart disease is the leading cause of mortality [Murphy et al., 2012; Thom, 1989; http://www.cdc.gov/nchs/data/nvsr/nvsr60/nvsr60_04.pdf), the study of factors that may adversely affect cardiac functionality is of great importance. In this context, we sought to examine the possible association of the cosmic ray intensity and the geomagnetic activity with human heart rate. A sample of 190 individuals monitored with a Holter monitor at the Cardiology clinics of the Nikaia General Hospital in Piraeus and the Heraklion University Hospital in Crete, Greece, were assessed from July 2011 to June 2012. The hourly variations of the cosmic ray intensity and the geomagnetic index Dst measured by the Athens Neutron Monitor Station and the Kyoto Observatory, respectively, were also used. The statistical methods of Analysis Of VAriance (ANOVA) and Multiple Linear Regression analysis were applied to evaluate the effect of both geomagnetic activity and cosmic ray intensity variations on the heart rate variations.

1. DATA AND METHOD OF ANALYSIS

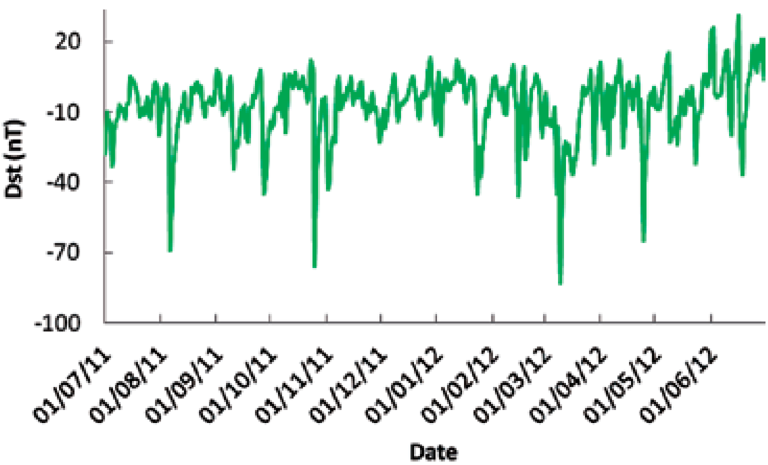
For the purposes of this work medical data as well as cosmic ray intensity and geomagnetic activity data were used.

1.1. Medical Data

In this study, a total of 190 people were assessed in the time period from July 2011 to June 2012. Data on the hourly heart rate were collected during their treatment in the Cardiology clinics of the Nikaia General Hospital in Piraeus and the Heraklion University Hospital in Crete, Greece. The patients' heart rate was monitored using a Holter (ambulatory electrocardiography) device. This device records the heart rate on a 24-hour base, while the patient carries out everyday life activities. Each one of the Holter devices was placed in each patient for 24 hours.



a



b

Figure 1. Distribution of normalized daily CRI (%) during the examined period (*a*); Daily average Dst index variations during the examined period (*b*)

1.2. Cosmic Ray Intensity Data

The hourly corrected for pressure values of the hadronic component of the cosmic ray intensity, were adapted from the Athens Neutron MOnitor DAta Processing centre (ANMODAP) of the National and Kapodistrian University of Athens.

The Athens Neutron Monitor Station is a modern one providing high resolution real-time cosmic ray data to the Internet (http://cosray.phys.uoa.gr), while those are transfered every 1-min to the European High resolution Neutron Monitor Database (http://www.nmdb.eu). This station is located at the University Campus at 260 m above the sea level and detects particles with a cut-off rigidity of 8.53 GV. The cosmic ray intensity data were normalized according to the relation

$$\frac{CRI_{obs} - CRI_{aver}}{CRI_{aver}}.$$

Where CRI_{obs} is the observed value and CRI_{aver} is the average CRI pertaining to the examined period. The normalized cosmic ray intensity values (%) during the time period under examination are presented in Figure 1a. The total values were divided into five levels (0, 1, 2, 3, 4) corresponding to the CRI intervals given in table. A similar technique has been used in previous studies, such as by [Papailiou et al., 2011].

The CRI and the Dst levels and the respective mean HR in the ANOVA analysis

CRI				
Levels	**Normalised CRI intervals, %**	**Number of measurements**	**Mean HR, bpm**	**95 % CI**
0	CRI ⩽ –3 %	220	76.33	74.11...78.55
1	–3 % < CRI ⩽ –1 %	602	76.00	74.67...77.35
2	–1 % < CRI ⩽ 1 %	2227	70.61	70.00...71.21
3	1 % < CRI < 3 %	1150	68.51	67.75...69.27
4	CRI ⩾ 3 %	17	67.12	60.34...73.89
Dst index				
Levels	**Dst intervals, nT**	**Number of measurements**	**Mean HR, bpm**	**95 % CI**
0	Dst ⩾ 0	1444	71.24	70.50...71.98
1	–20 < Dst < 0	1850	70.63	69.92...71.35
2	–50 < Dst ⩽ –20	824	71.97	71.03...72.91
3	–100 < Dst ⩽ –50	106	71.00	68.08...73.92
4	Dst ⩽ –100	9	61.11	54.99...67.23

1.3. Geomagnetic Activity Data

The geomagnetic activity during the time period that the above mentioned medical data were recorded, was analyzed. For this reason, hourly values of the geomagnetic index Dst was used. These data were obtained from the World Data Centre for Geomagnetism, Kyoto, which provides online real-time data (http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/index.html). Dst index variations during the examined period are shown in Figure 1b. The GMA data were divided into five levels (0, 1, 2, 3, 4), as in the CRI data, according to Dst index values given in table. This stratification technique has been used in the past [Papailiou et al., 2011].

1.4. Statistical Methods

The statistical methods of Analysis Of VAriance (ANOVA) and Multiple Linear Regression analysis were applied to evaluate the effect of both geomagnetic activity and cosmic ray intensity variations on the heart rate variations. The respective levels of significance (*p*-values) were calculated and discussed. In the applied regression models, the HR was taken as dependent variable, while the independent variables included the CRI, the Dst index, the time of data recording, and a unique patient identifier (to control for inter-patient variability). The statistical package SPSS version 17.0 software (SPSS Inc., Chicago, IL, USA) and STATISTICA (ver. 6, StatSoft Inc., 2001), were used for the statistical analyses.

2. RESULTS AND DISCUSSION

As it was mentioned above, a sample of a total of 190 individuals was examined, among which 106 (56 %) were men, 74 (39 %) were women and 10 (5 %) unknown, while their average age was 64 years. In total, 4560 measurements of heart rate, Dst index and cosmic ray intensity were recorded and analyzed (Figure 2).

At first, the heart rate variations of the individuals were analyzed with regard to CRI and Dst index variations using the method of ANOVA analysis. This analysis indicated a statistically significant negative correlation between HR and CRI ($p < 0.01$). The mean heart rate values in the different cosmic ray intensity levels are presented in Figure 3. It is noticed that the highest heart rate was documented at the lowest CRI level, and as the mean cosmic ray intensity increased, the heart rate decreased. In contrast, no significant association between heart rate and Dst index variations was observed ($p = 0.064$; see table), as depicted in Figure 4, where the mean heart rate values in the different Dst index levels are presented. In the lowest levels of Dst index that correspond to low geomagnetic activity, the variations of the heart rate were small.

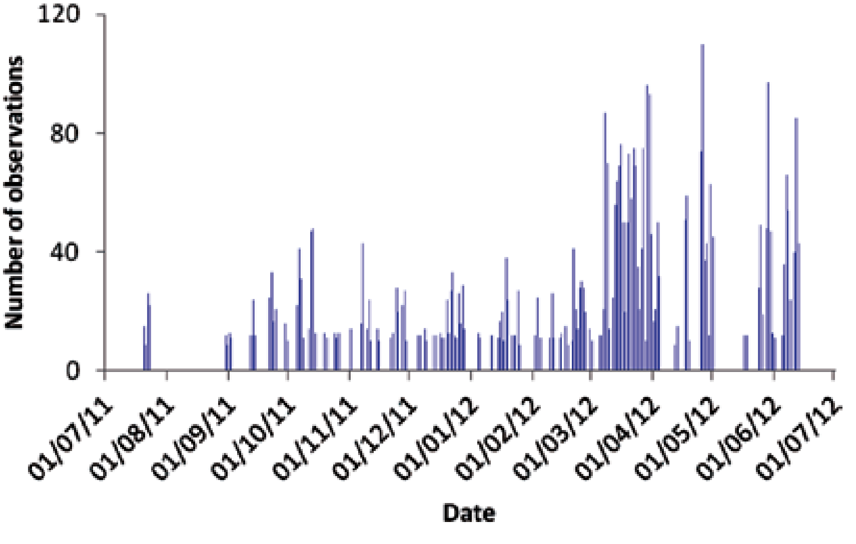


Figure 2. Number of Holter measurements during the period under examination

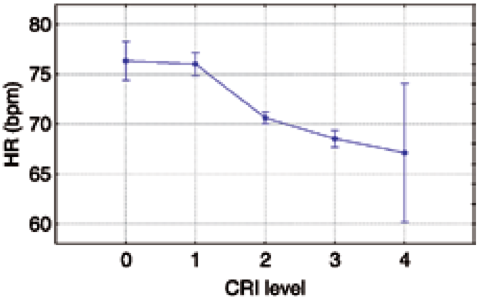


Figure 3. Distribution of the mean HR values for the different CRI levels

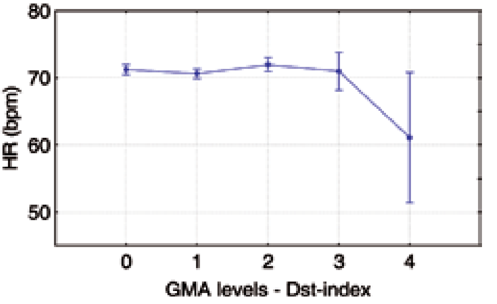


Figure 4. Distribution of the mean HR values for the different Dst index levels

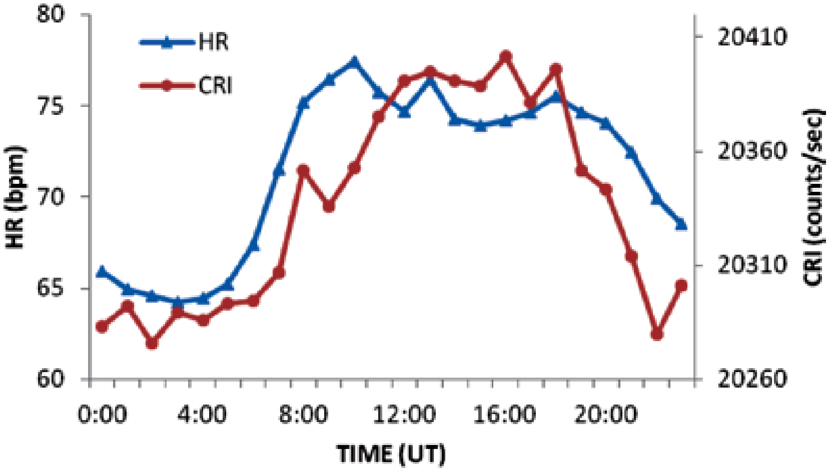


Figure 5. Daily distribution of the mean hourly HR and CRI values during the time period from July 2011 to June 2012

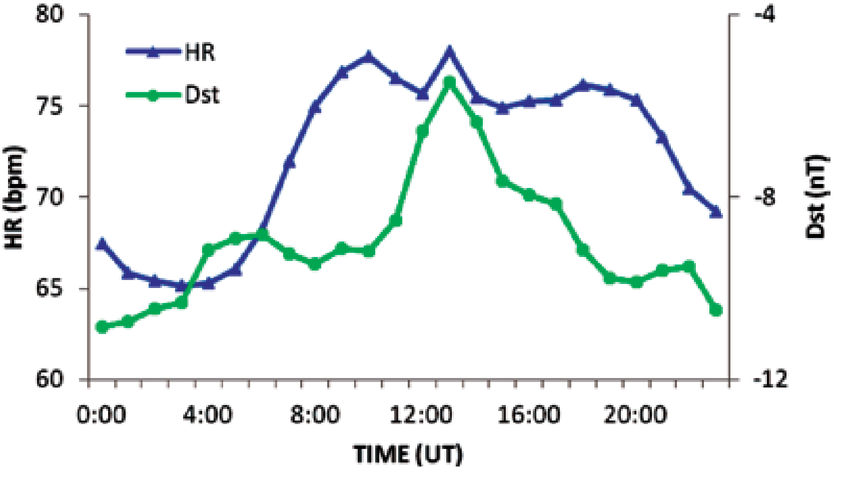


Figure 6. Daily distribution of the mean hourly HR and Dst index values during the time period from July 2011 to June 2012

According to the multiple linear regression model, after adjusting for day time and individual patient, both CRI and Dst index were found to be independently associated with HR. The cosmic ray activity was negatively correlated to the heart rate with a regression coefficient: –0.203 (95 % CI: –0.011, –0.008) and p-value <0.01, while Dst index values were positively correlated with a regression coefficient: 0.064 (95 % CI: 0.028, 0.081) and p-value <0.01.

Moreover, the average HR, CRI, and Dst values, stratified by day time, based on our data, were calculated. A graphic presentation of the mean hourly HR and CRI values, as well as of the mean hourly HR and Dst ones, is given in Figures 5 and 6, respectively.

Our results suggest a statistically significant association between space weather and human heart rate, as assessed by ambulatory Holter monitoring in individuals treated in two cardiology clinics in Greece, from July 2011 through June 2012. This time period is very close to the maximum period of the solar cycle 24 starting in January 2009 and is predicted to peak in 2013; it is considered to be an active period in the last active cycle in the past 100 years, according to NASA's predictions [Hathaway, 2012; Paouris et al., 2012]. In this regard, there were limited observations corresponding to days with strong geomagnetic disturbances (low GMA) in our study, and the extrapolation of our findings regarding the relationship between HR and Dst to such a setting may be limited.

Our findings are in concordance with previous studies. Two recent studies examined the potential influence of cosmic ray activity and geomagnetic disturbances on human cardio-health state [Mavromichalaki et al., 2008, 2012]. Both studies refer to the time period from July 2006 to March 2008 and included a total of 1673 measurements of HR from seven healthy volunteers. The HR was studied in relation to daily variations in cosmic ray intensity (CRI) and the respective daily variations of Dst and Ap geomagnetic indices, with a focus on days of geomagnetic storms. The investigators observed that the effects on HR were stronger in the low levels of Dst (when geomagnetic storms exist) and in high CRI decreases (Forbush dicrease). It was as well determined that HR increased on the days before, during and after geomagnetic storms and on the days preceding, and following CRI decreases. Both studies concluded that HR variations might be connected to geomagnetic disturbances and CRI variations. In another study, the variations of heart rate, geomagnetic activity and cosmic ray intensity were examined in a group of 4018 aviators (healthy volunteers) [Papailiou et al., 2011]. The investigators concluded that the cardiovascular function of the subjects was affected by both geomagnetic activity and cosmic ray intensity variations.

However, not all studies have detected a statistically significant relationship between GMA and HR. A study examining the effect of geomagnetic activity on some cardiovascular parameters found that low GMA was associated with disturbances in heart functionality such as higher levels of growth hormone and 11-ketosteroids in the peripheral blood, more sudden deaths and higher rate of ventricular tachycardia. In contrast, other studied parameters, including hemoglobin level, electrolyte level, heart beat and pulse rate, were found not to be related to the GMA [Stoupel, 2002]. Similarly, another study conducted for about 5 consecutive years found no such association, although the investigators acknowledged several limitations in the study design [Ghione et al., 1998]. An additional study examined the potential influence of GMA on heart rate variability during exercise recovery. And found out that there is no linear effect of GMA on heart rate variability after the exercises [Weydahl, 2002].

It should be noted that, in order to reach definitive conclusions about the association (or not) of GMA with HR, larger studies with long follow up, which might include more data about GMA events, are warranted. Multicausality and multicomplexity should be taken under consideration in the design of such studies, since approaches focusing only on individual parameters (not adjusting for possible cofounders) may mislead research needed to clarify the impact of space weather parameters on health. Therefore, even though CRI and GMA variations, in some cases, seem not to be the main contributors in causing specific illnesses, further research is warranted to examine their precise role in the development of disease.

CONCLUSION

This study examined the potential association between Space Weather variations, indicating by the cosmic ray intensity and the geomagnetic activity parameters, with the human heart rate. It is interesting that a statistically significant inverse relationship between cosmic ray intensity and heart rate on a daily basis was found. While the Dst index values were positively associated with the heart rate, indicating a significant effect of geomagnetic parameters on human heart rate. In this regard, the thorough comprehension of the profound mechanisms underlying this association may be helpful in identifying the pathophysiology, prevention, and treatment of cardiovascular disease, which is complex and multifactorial. Further studies with a greater sample of measurements are warranted to precisely determine the role of geomagnetic factors on human health.

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ВЛИЯНИЕ ИНТЕНСИВНОСТИ КОСМИЧЕСКИХ ЛУЧЕЙ И ГЕОМАГНИТНОЙ АКТИВНОСТИ НА ЧАСТОТУ СЕРДЕЧНЫХ СОКРАЩЕНИЙ ЧЕЛОВЕКА

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Накопленные данные свидетельствуют о связи между солнечной и геомагнитной активностью и физиологическими параметрами человека. Ряд опубликованных исследований относился к изменениям в физиологических реакциях человека при различных уровнях геомагнитной активности. Мы стремились изучить потенциальную связь между изменениями частоты сердечных сокращений и конкретной космофизической активностью. В настоящем исследовании, в общей сложности 190 лиц, находившихся на лечении в кардиологической клинике Никеи, больницы в Пирее и Ираклион — университетской больнице на острове Крит, Греция, были исследованы за период с июля 2011 г. по июнь 2012 г. Частота сердечных сокращений пациентов записывалась ежечасно с помощью холтеровского монитора, в то время как почасовые вариации интенсивности космических лучей и геомагнитных индексов Dst были измерены на станции Афинского университета с помощью нейтронных мониторов и на обсерватории Киото, соответственно. Статистические методы включали дисперсионный анализ (ANOVA) и множественную линейную регрессию. Наблюдается статистически значимое воздействие как космических лучей, так и геомагнитной активности на частоту сердечных сокращений (отрицательная и положительная корреляции, соответственно). Наши результаты показывают, что изменения частоты сердечных сокращений у людей могут быть связаны с изменением параметров космической погоды.