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Review

Human Physiological Parameters Related to Solar and Geomagnetic Disturbances: Data from Different Geographic Regions

Helen Mavromichalaki [1,*], Maria-Christina Papailiou [1], Maria Gerontidou [1], Svetla Dimitrova [2] and Karel Kudela [3]

[1] Athens Cosmic Ray Group, Faculty of Physics, National and Kapodistrian University of Athens, 15784 Athens, Greece; mpapahl@phys.uoa.gr (M.-C.P.); mgeront@phys.uoa.gr (M.G.)
[2] Space and Solar-Terrestrial Research Institute (SSRI), Bulgarian Academy of Sciences, 1000 Sofia, Bulgaria; svetla_stil@abv.bg
[3] Institute of Experimental Physics, Slovak Academy of Sciences, 04001 Kosice, Slovakia; kkudela@saske.sk
* Correspondence: emavromi@phys.uoa.gr

Abstract: It is well known that the various manifestations of space weather can influence a wide range of human activities, from technological systems to human health. Various earlier, as well as more recent multi-disciplinary heliobiological and biometeorological studies have revealed that the human organism is sensitive to environmental physical activity changes and reacts to them through variations of the physiological parameters of the human body. This paper constitutes an overview of the National and Kapodistrian University of Athens investigations in regard to the possible effect of solar, geomagnetic, and cosmic ray activity on human physiological parameters. The Athens Cosmic Ray and Solar Physics Groups collaborated with scientific teams from different countries, statistically processing and analyzing data related to human physiological parameters (such as mean heart rate, arterial systolic, and diastolic pressure), or the number of incidents of different types of cardiac arrhythmias and so forth, in relation to data concerning and describing geomagnetic activity (geomagnetic indices Ap and Dst) and variations in cosmic ray intensity (Forbush decreases and cosmic ray intensity enhancements). In total, four projects were carried out concerning data from different geographical regions (Baku, Azerbaijan; Kosice, Slovakia; Tbilisi, Georgia; Piraeus, Greece), covering different time periods and time scales (daily data or yearly data), and referring to different groups of individuals (selected healthy persons or random persons). The studies concluded with interesting results concerning the possible influence of geomagnetic and cosmic ray activity on the human physiological state.

Keywords: space weather; arterial blood pressure; arrhythmias; heart rate

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1. Introduction

In order to study the possible effect of geomagnetic activity (GMA) and changes in cosmic ray intensity (CRI) on the physiological state of the human body, direct and indirect indicators have been used [1]. Direct indicators are physiological parameters that can be objectively verified and are obtained by direct measurements from the patient (e.g., heart rate, blood pressure, reaction time, etc.), by diagnostic methods in the laboratory, or by tissue analysis. It should be noted, however, that the main problem with direct indicators is that most of them vary considerably with factors other than GMA. On the other hand, indirect indicators refer to epidemiological data that reflect the temporal and spatial distribution of certain events or disturbances (e.g., time distribution of hospitalization, frequency of traffic or industrial accidents, etc.). They are usually analyzed in retrospective studies and involve a large number of individuals over a period of several years. However, when interpreting these indicators, other possible parameters must be taken into account, such as season, weather, demographic factors, working environment, diet, and so forth, which are likely to affect the measurements [1].

According to the above distinction, research related to the effect of space weather phenomena on the human body and, consequently, on human health can be classified into three categories depending on the medical sample under analysis and their results, as follows:

(a) Studies on variations in human physiological parameters, such as heart rate and arterial systolic and diastolic blood pressure [2–9], as well as heart rate variability [10–13], etc. This category could also include research on the effects of space weather parameters on the central and autonomous nervous system through changes in the functional state of the human brain and psycho-emotional state [14–16];
(b) Studies regarding the frequency of myocardial infarction, stroke, and sudden cardiac death [17–21];
(c) Studies related to traffic accidents [22–25].

Regarding the first category, there are several interesting results. Specifically, in the city of Sofia, Bulgaria, a study was conducted on a group of 86 volunteers in the periods of 1 October 2001 to 9 November 2001 and 8 April 2002 to 28 May 2002, that is, periods of high solar and geomagnetic activity [5,6,8,9,26–30]. As mentioned, daily values of heart rate, mean arterial systolic and diastolic pressure, and psycho-physiological complaints were studied in relation to variations in GMA (geomagnetic indices Ap and Dst) and the CRI. According to this study, mean arterial systolic and diastolic pressure increased statistically significantly during increased GMA and decreases in CRI [5,6,8,26,30]. It was further found that the effect of disturbances in the geomagnetic field on the human condition appears to be influenced by gender, with women being more sensitive [5,20], as well as by medication related to hypertension [5,28,29]. In addition, the same research shows that while the dynamics of blood pressure show a compensatory response of the body to adaptation, the heart rate for healthy people (mainly in middle latitudes) can be considered as a stable cardiovascular parameter, which is not so sensitive to changes. That is, it does not show a statistically significant response to geomagnetic disturbances or to variations in CRI [8,9,16]. The effect of GMA on the function of the human brain, human health, and the psycho-emotional state was studied in the Baku region of Azerbaijan [15,16]. This experiment covered the time periods of the pre-maximum, maximum, and declining phases of the 23rd solar cycle, and the medical data obtained from 27 healthy volunteers (women only) were analyzed in relation to variations in the geomagnetic indices Ap and Dst. It has been confirmed that for mid-latitudes, human physiology and psychology are affected by geomagnetic disturbances. The same research concluded that stress and the ability to concentrate and work can be affected by GMA, and so the need to understand the connection between space weather and human physiology is imperative in order to prevent or treat any disease.

Regarding the second category, there are a number of studies that refer to the possible dependence of the frequency of cardiovascular and other diseases, and even deaths from solar and geomagnetic activity as well as from CRI variations. In fact, [23] and [18] argue that cardiovascular disease is affected by space weather both in the long-term (solar activity) and short-term (Forbush decreases—FDs). FDs of cosmic rays can be considered sensitive indicators of the relationship between geomagnetic disturbances and health parameters, such as ischemic attacks and myocardial infractions [22,31–33]. The most important and statistically significant results for myocardial infractions and strokes are observed on days of geomagnetic disturbances accompanied by FDs [24,31,34] and especially during the main phase of the decrease [24]. Furthermore, periodicities in cardiovascular events [35] and the number of sudden cardiac deaths [14] have been determined and their relationship to the periodicities of the geomagnetic effects of the solar cycle has been examined. In fact, the international program BIOCOS (BIOsphere and COSmos), aims to monitor, record, and analyze changes in human physiological parameters in different geographical locations and in relation to geomagnetic phenomena and solar activity [12].

Additionally, in an investigation conducted in the Baku region, the possible relationship between the number of sudden cardiac deaths and solar and geomagnetic activity was examined [36]. More specifically, 788 cases of sudden cardiac death in an emergency and all first aid stations in Baku were analyzed in relation to the changes of various geomagnetic indicators and different types of geomagnetic storms. The results showed that disturbances in the geomagnetic field can affect the number of cases of sudden cardiac death, which are increased during periods of low GMA and during days of high-intensity geomagnetic storms, as well as the day after them.

Recent studies [21,37] on heliobiological data (acute myocardial infarction from 21 first aid stations) from Baku from the period of 2003–2005 show that the number of sudden cardiac deaths and deaths from acute myocardial infarction before admission to hospitals increased on days with the highest and lowest daily levels of GMA as well as on days with high activity in cosmic rays as recorded by ground-based neutron monitors. The effect of solar and geomagnetic activity on the number of cases of acute myocardial infarction has also been studied in two parallel studies in the cities of Sofia and Baku [38]. The daily distribution of the number of patients diagnosed with acute myocardial infarction (1192 cases) in Sofia for the period of 1 December 1995 to 31 December 2004, and the corresponding one for Baku (4479 cases) for the period of 1 January 2003 to 31 December 2005, showed that there is a positive correlation between the number of acute myocardial infarctions and geomagnetic indices. Furthermore, the frequency of acute myocardial infarction increased from one day before to one day after the occurrence of geomagnetic storms of different intensities.

The effects of solar and geomagnetic activity as well as CRI variations on the monthly number of acute myocardial infarctions in men and women, separately, were also studied by [20]. This study was based on 16,683 patients in the Kaunas region (Lithuania) for the period of 1983–1999. There was a significant correlation between solar activity and geomagnetic indices and a correlation with cosmic ray activity levels. The correlation was stronger for women than for men.

Another study investigated the distribution of monthly deaths in Lithuania in relation to solar, geomagnetic, and cosmic ray activity. This study was completed in four stages. Initially, the database covered the period of 1990–1999 and included 424,925 cases of deaths due to ischemic heart disease, stroke, accidents (traffic or otherwise), suicides, and deaths related to causes other than cardiovascular [39]. Then, the data increased and extended to the period of 1990–2001, for a total of 504,243 deaths [40]. Moreover, the number of deaths under analysis (630,205 in total) covered the period of 1990–2004 [41], and finally, the total sample refers to the period of 1990–2005 with 674,004 deaths [42]. According to this research, the total monthly number of deaths (total, stroke, suicide, and deaths due to non-cardiovascular causes) is significantly correlated with solar and geomagnetic activity and is significantly correlated with cosmic rays.

In [43], a large epidemiological study (among all ages and gender) in 263 U.S. cities was conducted in order to assess the effects of geomagnetic disturbances on daily deaths (total, cardiovascular diseases, myocardial infarction, and stroke). In total, 2,008,990 days with 44,220,261 deaths in approximately 30 years were analyzed. In a two-step meta-analysis approach, city-specific, and season-stratified mortality risk associated with a geomagnetic disturbance parameter (Kp index) was estimated. The results suggested that geomagnetic disturbances are associated with total cardiovascular diseases and myocardial infarction deaths in 263 U.S. cities.

More recently, in [44], the relationship between the morbidity from acute myocardial infarction and mortality from ischemic heart diseases and geomagnetic storms and other space weather events, such as solar proton events, solar flares, high-speed solar wind, interplanetary coronal mass ejections, and stream interaction regions was studied. The data were from the time period of 2000–2015 and concerned the city of Kaunas (Lithuania). The results showed that the most expressed space weather variations often coincided with a higher risk of acute myocardial infarction morbidity and mortality from ischemic heart diseases, depending on age and sex.

The possible association between daily numbers of ischemic and hemorrhagic strokes and space weather events was also studied by [45]. Daily numbers of ischemic strokes, subarachnoid hemorrhages, and intracerebral hemorrhages, which were obtained from the Kaunas Stroke Register, were from the time period of 1986–2010. They were analyzed using time- and season-stratified multivariate Poisson regression. Generally, it was concluded that an increased risk of different subtypes of stroke may be related to geomagnetic storms, very low GMA, and stronger solar flares and solar proton events.

In another study by [46], the effects of solar activity changes on the mortality from cardiovascular causes of death were examined during the time period from 1994 to 2011 (which coincides with solar cycle 23) in the Czech Republic. Solar activity indices (e.g., the relative sunspot number, solar radio flux intensity), geomagnetic indices, and physical parameters describing the ionospheric effects were related to the daily time series of numbers of deaths by cause. The results revealed that the variability in the number of deaths from acute myocardial infarction or brain stroke during the maxima of the solar cycle had no direct correlation with the geomagnetic solar index, Kp, whereas the ionospheric parameters explained a greater part of this variability.

Furthermore, in [47], the influence of solar cycles and geomagnetic effects on systematic lupus erythematosus disease activity was examined. Data from 327 observations of 27-day Physician Global Assessment averages (covering the time period from January 1996 to February 2020) were investigated in relation to the AP index, the sunspot number index R, the F10.7 index, the AU index, and the high energy (>60 Mev) proton flux events. The results revealed that systematic lupus erythematosus disease activity may be influenced by geomagnetic disturbances, including the level of geomagnetic activity, sunspot numbers, and high proton flux events. Moreover, increases in geomagnetic activity Ap index and high energy proton fluxes were associated with decreases in systematic lupus erythematosus disease activity, while increases in the sunspot number index R anticipated decreases in the systematic lupus erythematosus disease activity.

The monthly stroke mortality events between 1985 and 1989 (in total 792 strokes), as they were registered in the archives of the Piraeus Civil Registry, were analyzed in relation to sunspot numbers in [48]. It should be mentioned that over 54% were women and over 61% occurred at ages over 69 years. It was concluded that the sunspot numbers and stroke mortality were inversely correlated. Moreover, a violent fluctuation of sunspot numbers over 35% shifted monthly mortality with a phase delay of two months. Finally, a common, novel, non-anthropogenic chronome of 6.8 days in solar activity (sunspot numbers) and stroke mortality was revealed.

Finally, the third category includes studies on how geomagnetic field disturbances, such as geomagnetic storms, can affect the nervous system and, therefore, be related to work and/or traffic-related car accidents due to stress or nervous or delayed reactions [23,33,49]. Studies on this subject already began many years ago, when [50] and [51] correlated work and traffic accidents with the reaction time, which, in turn, was associated with geomagnetic field disturbances. A high correlation between car accidents and geomagnetic disturbances also emerged from [52]'s study of traffic accident data in various large cities. There are, however, more recent studies in this field. The study of [53] presents the statistical analysis of the effect of solar and geomagnetic activity and FDs of CRI on car accidents in Poland for the period of 1990–1999. In fact, as reported in [24], after statistically processing several million medical cases in Moscow and St. Petersburg (Russia) the most statistically significant results referred to traffic accidents that occurred on days of geomagnetic disturbances accompanied by FDs, since, as they mentioned, their average number increased during the main phase of the decrease by (17.4 $\pm$ 3.1) % [23,24]. The authors of [23] analyzed the daily and monthly data related to malfunctions/breakdowns and accidents on the Siberian Railway in the period of 1 January 1986 to 30 November 1993, in relation to space weather parameters. The data were divided into two groups depending on whether the train accidents were due to technical problems or human error. It turned out that space weather disturbances were not associated with accidents due to mechanical failures. On the other hand, their relationship with those accidents due to human error was statistically significant [21]. Another study concerned the effect of the level of GMA on car accidents in the Irkutsk region (Russia) for the period of 2000–2003 [54]. In the study by [40] and [41,42], the monthly number of car accidents is correlated with solar and geomagnetic activity and is anti-correlated with cosmic rays. The possible effect of physical activity (solar and geomagnetic activity and CRI variations) on the number of car accidents for the period of 2000–2005 in the Baku region was studied by [25]. Data analysis of 7160 serious car accidents related to 7558 deaths and 1647 cases of serious injuries showed interesting results. Specifically, it was concluded that the monthly number of car accidents and victims was related to levels of physical activity. There was a significant correlation with cosmic rays and an anti-correlation with solar activity.

Another aspect of space weather phenomena influence on human health is the evaluation of the radiation dose deposited by atmospheric neutrons in human tissues. This is a subject of great importance since overexposure to this radiation can be harmful to human health. In [55,56], DYASTIMA-R, which is a Geant4-based software application implemented by the Athens Cosmic Ray Group, is presented as a reliable dosimetry calculation (ambient dose equivalent rate) tool at different atmospheric altitudes, geographic coordinates, and magnetic cut-off rigidity of the exposure of aviators and passengers to ionizing cosmic radiation during air flights.

The radiation dose that atmospheric neutrons (from 1 to 1000 MeV of energy) deposit in tissues of the human body (blood, adipose, bone, and brain) as a function of both altitude and latitude was investigated in [57]. It was concluded that the radiation dose deposited by atmospheric neutrons increases with an increase in altitude and latitude. Moreover, the radiation dose deposited in the bone tissue sample was considerably lower than that deposited in the blood, adipose, and brain tissue samples, with energies from 1 to 100 MeV, whereas the opposite result was found for energies between 200 and 1000 MeV.

This article is an overview of a number of investigations conducted by the Cosmic Ray and Solar Physics Groups of the National and Kapodistrian University of Athens (NKUA) concerning the possible influence of space weather phenomena on the human physiological state. In the frame of this work, the aforementioned groups from Athens (Greece) have collaborated with foreign and domestic scientific and medical teams while conducting the following:

1. The Baku (Azerbaijan) study, in which the potential effects of environmental, physical activity changes (geomagnetic field disturbances and CRI variations through FDs) on the cardio-health state of functionally healthy humans [58] were examined;
2. The Kosice (Slovakia) study on the potential influence GMA and CRI variations may have on the human physiological state through the variations of physiological parameters, such as arterial systolic and diastolic pressure of a group of aviators [59,60];
3. The Tbilisi (Georgia) project with results that concern mainly the influence that solar, geomagnetic, and CRI variations might have on the occurrence of cardiac arrhythmias. Importantly, the polarity reversal of the solar magnetic field seems to affect the correlation between the frequency of arrhythmias and the aforementioned variations [61];
4. The Piraeus (Greece) project, which examined the possible relation of the number of sunspots Rz, solar flares, and coronal mass ejections, as well as the CRI on the number of patients with cardiac arrhythmia, especially on those with atrial fibrillation [62].

2. Data and Method

2.1. Cosmic Ray Data

For the Baku study, pressure-corrected daily data of the hadronic component of the CRI were obtained from the Neutron Monitor Station (Super 6NM-64, cut-off rigidity of 8.53 GV) of the NKUA (http://cosray.phys.uoa.gr, accessed on 15 November 2021). This station is located at an altitude of 260 m above sea level. CRI data were normalized to the mean value of CRI for the time period of 15 July 2006 to 31 March 2008. CRI variations during the examined period ranged from −4 to +1% (i.e., maximal decreases in cosmic ray activity of up to −4% and increases of up to +1%). CRI was divided into six levels by steps of 1%, including −4%, −3%, −2%, −1%, 0%, and 1%, [58].

It is important to note that the latitude of Baku (where the experiment was conducted) is quite close to the latitudinal location of the Athens Station.

For the Kosice study, daily data of pressure-corrected CRI obtained from the Lomnicky Stit Neutron Monitor (SNM-15, cut-off rigidity of 3.84 GV) of the Department of Space Physics, Institute of Experimental Physics, Kosice, Slovakia (http://neutronmonitor.ta3.sk/realtime.php3, accessed on 15 November 2021) were used. This station is located at 2634 m above sea level. Cosmic ray activity was divided into six levels (−3, −2, −1, 0, +1, and +2) according to CRI [60].

For the Tbilisi project, pressure-corrected daily data of the CRI obtained from the Moscow Neutron Monitor Station (24NM64, effective vertical cut-off rigidity of 2.43 GV) of the Cosmic Ray Department of the Solar–Terrestrial Division of IZMIRAN were used [61]. This station is located 200 m above sea level (https://www.nmdb.eu/station/mosc/, accessed on 15 November 2021).

For the Piraeus project, daily values of the CRI, corrected for pressure and efficiency, were obtained from the Oulu Neutron Monitor Station (9-NM-64, effective vertical cut-off rigidity of ~0.8 GV) of the University of Oulu [62]. This station is located 15 m above sea level (https://www.nmdb.eu/station/oulu/, accessed on 15 November 2021).

2.2. Geomagnetic Activity Data

For the Baku and Kosice study, the World Data Centre for Geomagnetism, Kyoto (http://swdcwww.kugi.kyoto-u.ac.jp/, accessed on 15 November 2021) and the Space Weather Prediction Centre at NOAA, Boulder (http://www.swpc.noaa.gov/ftpmenu/indices/old_indices.html, accessed on 15 November 2021) provided the index data on the geomagnetic indices Dst and Ap. GMA was divided into five levels (0, I, II, III, and IV) according to the Dst index and Ap index [58,59].

For the Tbilisi project, the geomagnetic indices Dst and Ap were obtained from the Space Physics Interactive Data online database (http://spidr.ngdc.noaa.gov, accessed on 15 November 2021) [61].

2.3. Solar Data

For the Tbilisi project, the National Geophysical Data Center (NGDC) (ftp://ftp.ngdc.noaa.gov, accessed on 15 November 2021) provided the total number of solar flares. The Proton Events Database of the Athens Neutron Monitor Station (http://cosray.phys.uoa.gr, accessed on 15 November 2021) provided the total daily number of solar proton events for each day. Daily values for the Bz component of the interplanetary magnetic field obtained from the Space Physics Interactive Data online database (http://spidr.ngdc.noaa.gov, accessed on 15 November 2021) were also used [61].

For the Piraeus project, the National Geophysical Data Center (NOAA, http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber.html, accessed on 15 November 2021) provided daily values of sunspots and flare numbers. The daily number of CMEs, based on the SOHO/LASCO CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/, accessed on 15 November 2021), was provided by [63]. Solar proton events obtained from the Solar Proton Events Database of the Athens Cosmic Ray Station (http://cosray.phys.uoa.gr/index.php/data/solarproton-events-database, accessed on 15 November 2021) and from the NOAA Space Environment Services Center (http://umbra.nascom.nasa.gov/SEP/, accessed on 15 November 2021) were also used [62].

2.4. Statistical Methods

For the Baku and Kosice studies, the analysis of variance (ANOVA) statistical method was applied using the statistical package STATISTICA ver. 6 (StatSoft Inc., Tulsa, OK, USA, 2001) to establish statistical significance levels (*p*) of the effect of GMA levels and CRI variations on the human physiological parameters (heart rate, RR intervals, arterial systolic and diastolic blood pressure). The effects of GMA levels and CRI variations up to three days before and after the respective events (geomagnetic storm development and CRI decreases and increases) on the examined parameters were also investigated with the help of ANOVA and the method of superimposed epochs. Significance levels (p-values) were calculated for the days before (−), during (0), and after (+) geomagnetic storms and CRI variations. The chosen level for statistical significance in the used data analysis software system STATISTICA was set to $p < 0.05$, and the same value was used for interpreting the results [58–60]. Different significant levels have different advantages and disadvantages; a smaller p-value gives greater confidence in the determination of significance, but causes greater risks of failing to reject a false null hypothesis.

More specifically, in order to analyze and process the experimental data, the ANOVA method was applied. As independent variables, that is, 'factors', the Ap level, the Dst level, and the percentage decrease in the CRI (CRI, %) were considered. The physiological parameters HR, RR, SP, and DP were considered as dependent variables. The ANOVA method tested the effect of each of the factors on each of the dependent variables under study. Each time, it was assumed that the mean values of a parameter, for example, HR, were equal for all populations, that is, the mean values were equal for each level of the independent variables, for example, the Ap level.

With the help of the STATISTICA program, tables with the calculated mean values were obtained for each examined physiological parameter and for each factor level. These tables also showed the normal error in calculating the average value with a 95% confidence interval, the maximum and minimum parameter values for this confidence interval, and the number of measurements at each factor level. The value of the F function was also calculated, depending on the degrees of freedom of each case and the p-level significance level for each case. These results were also presented graphically.

As already mentioned, for the acceptance of the null hypothesis, the p-level value had to be greater than 0.05. Otherwise, for $p < 0.05$, the null hypothesis was rejected. This means that the alternative hypothesis is valid; for example, in this case, the variations of the factor (e.g., Dst level) had an effect on the parameter under study (e.g., HR). The study of the effect of each factor (e.g., Dst level) in each parameter (e.g., HR) was on the day of the measurement as well as three days before (−) and three days after (+) any geomagnetic disturbance or CRI variation. In this way, the effects before, during, and after a geomagnetic disturbance or CRI variation were studied. The *p*-level values from the ANOVA analysis were collected in tables, where the values of $p < 0.05$, for which the alternative hypothesis applies, were indicated.

In addition, the variations of the mean values of the physiological parameters, which were calculated during the ANOVA as a function of days (from three days before to three days after the CRI and GMA variations) were plotted. This was done for all three factors (Ap level, Dst level, and CRI, %). Thus, from the plots and tables with the p-levels, it was easier to define whether CRI and GMA variations had a statistically significant effect on the physiological parameters.

For the Tbilisi and Piraeus projects, the adjacent averaging method of smoothing was used and the Pearson r-coefficients were calculated in order to examine the possible relation of the different solar and geomagnetic activity parameters as well as the CRI variations on the occurrence rate of the patients with different types of cardiac arrhythmias. The statistical method of adjacent averaging smoothing was applied on a 365-day basis (1 year) using the program Origin Pro 8.5 (Origin Lab Corporation, Northampton, MA, USA, 1991–2010). The statistical package STATISTICA was used for the calculation of all correlation coefficients and *p*-values [61,62].

3. Results

3.1. The Baku Study

A permanent group of functionally healthy men and women (with an average age of 31.6 years) was used in order to conduct the relevant heliobiological (medical) measurements. This study took palace in Baku, Azerbaijan (geographic coordinates: latitude: 40° 23′ North; longitude: 49° 51′ East) from 15 July 2006 to 31 March 2008. Digitized electrocardiograms were recorded on the same day on working days and Saturdays in the mornings at the Laboratory of Heliobiology located at the Medical Centre INAM (Baku). In total, 1673 digital recordings were obtained and subjected to analysis. These data included cardiologic parameters such as heart rate (HR) values and RR intervals (time series of beat-to-beat HR intervals or HR period in ms), including minimal (RRmin), maximal (RRmax), and average (RRavg).

In the Baku study, geomagnetic disturbances and CRI variations were analyzed in relation to daily values of HR and RR intervals for the whole group of healthy volunteers, collectively, as well as separately for each individual [58]. The most important results are summarized below.

(a) Geomagnetic activity

- High levels of GMA for day 0 were related to an increase and decrease in the HR and RR interval physiological parameters, respectively. In fact, their maximum and minimum values were observed at levels III ($30 \leq Ap < 50$) and IV ($Ap \geq 50$) of the geomagnetic Ap index and at level III ($Dst \leq -50$) of the geomagnetic Dst index, respectively.
- The physiological parameters of HR and RR intervals varied significantly on the days before (−), during (0), and after (+) intense geomagnetic storms. In fact, these variations are more pronounced for levels III and IV of the GMA.
- For level IV of the geomagnetic Ap index, the minimum values of the HR were recorded on days 0 and +1, while for the RR parameters on the same days, their maximum values were recorded.
- For level IV of the geomagnetic Dst index, abrupt fluctuations were observed for both the HR and RR intervals, and on day 0, the minimum value for the HR and the maximum for the RR parameters were recorded.
- As shown by the p-values regarding the effect of the GMA variations on the HR and RR parameters, the statistically significant results were mainly related to the days before the geomagnetic event.

(b) Cosmic ray intensity variations

- Strong decreases in CRI for day 0 were connected to an increase and decrease in the HR and RR interval physiological parameters, respectively. Their maximum and minimum values, respectively, were observed for decreases from −3% to −2%.
- The HR and RR interval physiological parameters varied significantly on the days before (−), during (0), and after (+) CRI decreases. Furthermore, these variations were more intense with decreases of −3% and −4% in the CRI.
- For strong CRI variations (decreases from −4% to −2%), the HR showed sharp fluctuations in the days before, during, and after these decreases. The RR parameters for the whole group showed similar behavior.
- Specifically, for the strongest decreases in the CRI (−4%), on the day of the decrease, a minimum value was recorded for the HR and a maximum value for the RR parameters.
- As can be seen from the p-values, the effect of the CRI variations on HR seems to be more significant in relation to the RR parameters.

The behavior of the HR and RR intervals in relation to the geomagnetic field and CRI variations verifies the expected relation between them; the higher the HR (more pulses per second), the smaller the RR intervals. There may have also been differences between the results for each volunteer, which is an indication that environmental changes are likely to have a different effect on each individual's physiology.

3.2. The Kosice Study

In this study, we analyzed the arterial diastolic pressure (DP) and systolic pressure (SP) measurements of a group of 4018 Slovak aviators, which were obtained during their periodical medical checks at ground level. The group consisted only of men (from 18 to 60 years old) all in a good health state, according to the aviator personnel requirements. The daily mean values of DP and SP (mmHg) for the group were registered. More specifically, the measured parameters were as follows:

- DP and SP in rest without load (DPR and SPR);
- DP and SP in the first degree of load (DPFDL and SPFDL—sitting on a stationary bike and pedaling at a power of 50–100 Watts);
- DP and SP in the second degree of load (DPSDL and SPSDL—sitting on a stationary bike and pedaling at a power of 100–150 Watts);
- Maximum DP and SP achieved by load (DPMAX and SPMAX—sitting on a stationary bike and pedaling at maximum power).

Each physiological parameter value represents the mean daily value of all the aviators examined that day. In total, the number of the days of measurements is equal to 1341 (on some days, weekends, holidays, etc., no medical data were available) and includes the time period of 1 January 1994 to 31 December 2002. The most important results of this study [59,60] are summarized below.

- Geomagnetic activity
  - High levels of GMA for day 0 are related to decreases in the physiological parameters of arterial SP and DP. Their minimum values were observed at levels III ($-100 < \text{Dst} \leq -50$ and $30 \leq \text{Ap} < 50$) and IV ($\text{Dst} \leq -100$ and $\text{Ap} \geq 50$) of the geomagnetic indices Ap and Dst.
  - The physiological parameters of arterial SP and DP varied significantly on the days before (−), during (0), and after (+) intense geomagnetic storms. These changes were more pronounced for levels III and IV of the GMA.
  - For level IV of the GMA, there was a decrease in the values of the physiological parameters on the days before the intense events and then an increase on the days after the events. This behavior was present in the majority of the physiological parameters, except for cases where there were sharp fluctuations for different days, mainly for the DP parameter.
  - For level IV of the geomagnetic Ap index, the SP parameters (apart from SPMAX) show a minimum value one day before the geomagnetic storm (day −1), while the DP parameters (apart from DPR and DSDL) show a minimum value on day −3.
  - For level IV of the geomagnetic Dst index, the SP parameters show a minimum value either on day 0 (SPMAX and SPFDL) or on day −1 (SPR and SPSDL). The DPR, DPMAX, and DPSDL diastolic pressure parameters show minimums on days −1 and 0, respectively, while the DPFDL shows abrupt fluctuations.
  - As shown by the p-values, the Ap index levels seemed to have a greater effect on the SP (only in the SPMAX parameter on days 0 and +1). There are no statistically significant results for any of the DP parameters.
  - As can be seen from the p-values, the Dst levels statistically significantly affected the SP parameters (SPR, SPMAX, SPFDL, and SPSDL) and DP parameters (DPR, DPMAX, DPFDL, and DPSDL) on day +3 after the geomagnetic disturbance.
- Cosmic ray intensity variations
  - Strong decreases in the CRI (decreases from −16% to −6%) were connected to SP parameter decreases. The behavior of the DP parameters differed since their values increased from level −2 (decreases from −11% to −6%) to level −3 (decreases from −16% to −11%), where the maximum value was recorded.

- The physiological parameters of arterial SP and DP varied significantly on the days before (−), during (0), and after (+) CRI decreases. Moreover, these variations were more pronounced for level −3 of the CRI variations.
- For level −3 of the CRI variations, decreases in the physiological parameters on the days before the strong decreases in the CRI were observed, followed by an increase on the days after. This behavior was present in the majority of the physiological parameters, except for cases where there were sharp fluctuations on different days, mainly for the DP parameters.
- For level −3, the SP parameter minimum values were observed on day 0 (except for SPMAX). The DP parameters recorded a minimum value two days before the decrease (day −2), except for DPR (day −1).
- As can be seen from the p-values, CRI variations appear to have had a significant effect on the SP and DP parameters.

3.3. The Tbilisi Project

This study examined the possible association between solar, geomagnetic, and CRI variations and the number of incidents of different types of cardiac arrhythmias (supraventricular extrasystoles (S), supraventricular paroxysmal tachycardia (Ps), ventricular single extrasystoles (V1), and ventricular multiple extrasystoles (Vm)). The medical data, which were statistically collected with daily Holter monitoring and electrocardiogram recordings from different hospitals of Georgia, refer to a group of 1902 patients (from 30 to 75 years old) with ischemic heart disease. This particular study refers to the time period of 1983–1992, covering almost one complete solar cycle (solar cycle 22). It should be mentioned that in the years 1989–1990, the polarity reversal of the solar magnetic field occurred. Therefore, the time interval under examination was separated into two different time periods (1983–1988 and 1989–1992). As a result, all the examined parameters, as well as the different types of arrhythmias, showed different behaviors during the two time intervals.

The correlation coefficients between the examined parameters and the number of arrhythmias (total and for each type separately on a yearly basis) were calculated and the most interesting results [61] are summarized as follows:

- Significant correlations were observed between ventricular extrasystolic arrhythmias (V1 and Vm) and the SPE and Dst index.
- V1 type of arrhythmias are also significantly correlated with the sunspot number, the number of solar flares, (with importance greater than M) and the CRI.
- Supraventricular arrhythmias (S and Ps) displayed significant correlation coefficients for different parameters. The highest correlation coefficients concerning S types of arrhythmias were observed for the number of solar flares with significance greater than with the M, SPE, and Dst index. The results for Ps types of arrhythmias are different. The highest correlation coefficients were observed for the number of C-type solar flares, CRI, and Ap index.
- The total number of arrhythmias shows a high correlation with the majority of the parameters, with the exception of the Bz component of the interplanetary magnetic field and the Ap index.
- This study also focused on the possible relation between the various types of arrhythmias and the polarity reversal of the solar magnetic field. As a result, the following occurred:
- The primary and secondary maxima observed in the solar parameters during solar cycle 22 also appeared in the V1, Vm, Ps, and all types of arrhythmias, with a time lag of about 5 months, which is consistent with the time lag of cosmic rays against the solar activity;
- Changes in the polarity sign of the solar magnetic field were found to affect the sign and value of the correlation between the frequency of arrhythmias and solar and geomagnetic variations, as well as CRI.

- Ventricular arrhythmias (V1 and Vm) appeared to be more sensitive to changes in the polarity sign of the solar magnetic field compared to supraventricular arrhythmias (S, Ps).

3.4. The Piraeus Project

In this investigation, the possible relation between the solar activity and the CRI variations and cardiac arrhythmias was examined. A database of 4741 patients (from 15 to 98 years old) with cardiac arrhythmias (ARRY), 2548 of whom were diagnosed with atrial fibrillation (AF), was created in cooperation with the Second Cardiological Clinic of the General Hospital of Nicaea, 'St. Panteleimon', Piraeus, in Greece. These data refer to the time period of 1997–2009, covering solar cycle 23.

It should be mentioned that for the year 1998, the clinic did not work properly, while during the years 2001 and 2011, an increase in the number of cases was noted, even though the population of Piraeus and the neighboring islands of Saronic Gulf, regions that are covered by this hospital, did not change significantly (Hellenic Statistical Authority EL.STAT., Piraeus, Greece; http://www.statistics.gr/portal/page/portal/ESYE, accessed on 15 November 2021). In this work, medical data of ARRY and AF were analyzed in comparison with the solar magnetic field polarity reversal and the occurrence of solar eruptive events (solar flares and coronal mass ejections), which were correlated with the sunspot number, as well as with the CRI. It is noticeable that the correlation between the daily smoothing values of ARRY and AF with the corresponding values of sunspots, solar flares, coronal mass ejections, solar proton events, and CRI changes sign during the time period of this reversal.

The most interesting results [62] are as follows:

- The medical cases and the sunspot number both increased during the rise phase of solar cycle 23 (1997–2001).
- There was an expected decrease in the sunspot number, while the number of medical cases continued to increase during the decay phase (2002–2009) and after the polarity reversal of the solar magnetic field (September 2000 until the end of 2002).
- The medical cases increased during the CRI decrease in the period of 1997–2001 and during the CRI increase (2002–2009).
- A good relation or anti-relation of the examined arrhythmia cases (and especially the AF cases) with the occurrence number of eruptive solar phenomena (solar flares and coronal mass ejections) was presented during the rise and the decay phases of solar cycle 23. This means that the polarity reversal of the solar magnetic field (during the maximum phase in each solar cycle) affected the correlation or anti-correlation.
- A good correlation or anti-correlation of the AF cases with solar activity, as expressed by the number of sunspots, solar flares, and coronal mass ejections, during the rise and decay phases of the solar cycle, was respectively revealed. Moreover, a good anti-correlation or correlation with the CRI during the rise or the decay phase of the solar cycle was respectively noticed.
- A possible relation between the increased arrhythmia cases and the arrival of energetic solar protons in the Earth's environment, as well the increase in CRI, is indicated by the high correlation coefficient between the ARRY cases and the occurrence of solar proton events or the CRI during the rise phase.

4. Discussion and Conclusions

From the above analysis and description of the four projects, the following important conclusions were obtained.

First, the most interesting and common result from the Baku and Kosice studies is that geomagnetic and CRI variations seemed to have an influence on the physiological state of the human organism. The human physiological parameters (HR, RR interval, SP, and DP) variations appeared to be connected to geomagnetic disturbances and CRI variations. The effects were more pronounced for high levels of GMA (when geomagnetic storms occur) and strong CRI decreases. As it is shown HR and RR intervals, SP, and DP had the maximum or minimum values for high levels of GMA, that is, levels III and IV of the geomagnetic indices Ap and Dst. On the days of geomagnetic storms, the physiological parameters SP, DP, and RR intervals had their minimum values for the Ap and Dst indices, levels III and IV, while the HR had its maximum value. Moreover, similar results were obtained during CRI variations. CRI decreases (FDs) were associated with arterial blood pressure and HR variations. Levels −3 and −2 of the CRI variations were connected to the maximum values of the physiological parameters HR and DP, and the minimum values of the parameters RR intervals and SP.

Analysis of the human physiological parameters variations before (−), during (0), and after (+) geomagnetic disturbances with different intensities and CRI variations revealed similar behaviors in the two studies. Human physiological parameters presented peak values (increases and decreases) for high GMA as well as for the largest CRI decreases, which were registered during the examination period.

Secondly, results from the Tbilisi and Piraeus projects show that the number of incidents of different types of cardiac arrhythmias was correlated or anti-correlated to solar, geomagnetic, and CRI variations. Different types of cardiac arrhythmias were related to various solar and GMA parameters (solar flares, CMEs, sunspot number, Dst index, etc.) and CRI for both solar cycle 22 (the Tbilisi project) and solar cycle 23 (the Piraeus project).

It should be highlighted that in both projects, the polarity reversal of the solar magnetic field, which occurs during the maximum phase in each solar cycle, coincided with the period when the correlation between the frequency of cardiac arrhythmias and atrial fibrillation cases and the frequency of the solar eruptive events and the CRI changed sign for both solar cycles 22 and 23. It was concluded that the solar magnetic field polarity reversal was connected with the sign and the value of the relation of the patients' number with the types of arrhythmias and the solar, cosmic ray, and geomagnetic parameters. Moreover, it was revealed that the number of patients with types V1 and Vm of cardiac arrhythmias seemed to be more sensitive to the changes of the solar magnetic field polarity sign, compared to the arrhythmia types S and Ps.

In sum, it can be said that the results from these four projects, which were conducted in different geographic regions, confirm the notion that has been developed over the last decades and has been thoroughly examined by a significant number of scientists worldwide, supporting that space weather phenomena can influence the human physiological state and can be related to variations of physiological parameters or the number of incidents of different diseases.

Publications related to the research of the possible effect of solar and geomagnetic activity and variations of CRI on the human physiological state have increased in the last decades. A number of scientific papers show that cardiovascular, nervous, and other functional systems respond to changes in geophysical factors. After all, according to Chijevskii, 'even a not so important stimulus can cause a gradual or momentary increase in instability and the body can be led to death. This stimulus may come from a change in meteorological or geophysical factors' [64]. These new data in the literature confirm the fact that further research on these basic issues for human activities is necessary. The modern scientific fields of physics and space weather specifically study the effects of energetic solar particles on the proper functioning and reliability of terrestrial and satellite technology systems, as well as human health (European Space Agency—Space Weather, Brussels, Belgium). The study contributes substantially in this direction.

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