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Statistical Associations between Geomagnetic Activity, Solar Wind, Cosmic Ray Intensity, and Heart Rate Variability in Patients after Open-Heart Surgery

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Abstract: The aim of this study was to identify associations of the parameters of heart rate variability (HRV) with the variations in geomagnetic activity (GMA), solar wind, and cosmic ray intensity (CRI) in patients after coronary artery bypass grafting or valve surgery in Kaunas, Lithuania, during 2008–2012. The data from 5-minute electrocardiograms (ECGs) in 220 patients were used. ECGs were carried out at 1.5 months, 1 year, and 2 years after the surgery (N = 495). A lower (higher) very-low-frequency-band (VLF) and a higher (lower) high-frequency band (HF) in normalised units (n.u.) were associated with a low maximal daily 3-hourly *ap* (the DST index > 1). A lower mean standard deviation of beat-to-beat intervals (SDNN) and VLF, LF, and HF powers were lower in patients when Ap < 8 occurred two days after the surgery, and a low solar wind speed (SWS) occurred two days before the ECG. The effect of CRI was non-significant if the linear trend was included in the model. Low GMA and a low SWS may effect some HRV variables in patients after open-heart surgery. The GMA during the surgery may affect the SDNN in short-term ECG during the longer period.

Keywords: heart rate variability; geomagnetic activity; solar wind; cosmic ray intensity; patients after open-heart surgery

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1. Introduction

Heart rate variability (HRV), which is determined by using the length of successive beat-to-beat intervals in an electrocardiogram, is an emergent property of interdependent regulatory systems which helps us adapt to environmental and psychological changes. HRV reflects the regulation of the autonomic nervous system, blood pressure, heart, and vascular tone [1]. In daily clinical routine practice, the mean and standard deviation (SD) of the RR intervals (SDNN) is mostly used for HRV analysis [2]. The most commonly used frequency domain components of HRV are the very-low-frequency band (VLF: $\leq$0.04 Hz) reflecting the influence of the endocrine system on heart rate and linked to thermoregulation [3], the low-frequency band (LF: 0.04–0.15 Hz) reflecting baroreflex activity in resting conditions, and the high-frequency band (HF: 0.15–0.4 Hz) reflecting parasympathetic activity, and called the respiratory band because it corresponds to the heart rate (HR) variations related to the respiratory cycle [1]. Non-linear HRV indices such as Poincare plots, fractality, entropy, and symbolic dynamics have also been used [4].

The results of experimental and ecological studies showed changes in HRV and its component due to exposure to air temperature [5–7], diurnal temperature range [8], thermal comfort [9,10], and air pollution [11,12]; in addition, the impacts of air pollutants on HRV variables were stronger in participants with some cardiovascular diseases [13]. Other environmental factors such as geomagnetic activity (GMA) or other space weather variables are also linked to changes in HRV and other parameters of the electrocardiogram [14,15].

Reduced HRV was observed during geomagnetic storms [16–18]. Otsuka et al. (2001), in their study with repeated measurements of eight participants, found decreases in VLF and LF power during geomagnetically disturbed days [19]. During active-stormy days, in participants with baseline HR >80 beats/min, a higher LF/HF was observed as compared with that seen on days with a lower GMA [20]. A statistically significant correlation was found between GMA indices and normalised HRV variables [14,21,22], and a positive correlation of cosmic ray intensity (CRI) with VLF, LF, and HF was observed [15].

The results of the analysis of HRV variables in simulated GMA showed that increased GMA levels were associated with a higher LF and LF/HF [23] and with a higher HR and LF/HF and a lower SDNN in participants with a higher baseline HR [20]. During the modelled zero magnetic field, an increase in the mean beat-to-beat interval was observed [24], as well as a decrease in normalised VLF as compared with those seen during active-stormy GMA [25].

Studies have found a stronger HRV response to changes in environmental conditions in participants with poorer cardiovascular health [13,16,20]. During magnetic storms, patients with impaired cardiovascular functions demonstrate deterioration in capillary blood flow [26–28]. In the elderly, elevated GMA had a stronger negative effect on survival after the acute coronary syndrome [29] and on the risk of emergency calls due to the exacerbation of arterial hypertension [30]. It is probable that the GMA and CRI variations influence patients with cardiovascular problems; this has been linked to a decreased HRV.

In cardiac surgery, preoperative, intraoperative, and postoperative management modifies the autonomic nervous system, and it is known that many drugs might induce alterations in HRV [31,32]. HRV becomes decreased after coronary artery bypass graft (CABG) surgery [33] and after valve surgery [2]. Changes in GMA and other space weather conditions may affect HRV parameters in patients after open-heart surgery.

Some space weather patterns affect atmospheric circulation and tropospheric vorticity [34–37] and may affect the atmospheric electricity, thus increasing electromagnetic noise in the ultra-low frequency (ULF) range (1–3 Hz) [38] which overlaps with the frequency range of human heart rhythms [39]. A decrease in the average area of high vorticity (cyclonic activity) in winter storms was observed on a few days near the times of changes in the interplanetary magnetic field (IMF) direction [40] and after Forbush decreases [41]. Solar wind modulates the current density in the global electric circuit (GEC) [42]. It is probable that variations in solar wind affect the HRV parameters in more sensitive populations due to increases in electromagnetic noise.

The aim of the study was to detect an association of HRV parameters with GMA, changes in the IMF direction, and solar wind speed (SWS) and CRI variation detected during heart operations and during HRV measurements based on a 5-minute resting ECG in patients who underwent CABG or valve surgery (VS) during 2008–2012, the period of the solar cycle minimum-ascending phase. Our results could help to identify the complex of space weather conditions related to autonomic nervous system disorders.

2. Materials and Methods

2.1. Patients

This study was performed during 2008–2012—the years of the solar cycle minimum-ascending phase—in Kaunas city (geomagnetic latitude 52.38 N), Lithuania. We used the data of 220 patients who underwent CABG, VS, or a combination of these surgeries. The information about patients and their health data is presented in our previous study [43]. We used the following time-domain parameters: the mean RR interval (NN, ms) and the SDNN (ms). Power spectral density was calculated to analyse the beat-to-beat interval series in the frequency domain. We used measurements of the VLF, LF, and HF power components in absolute values of power (ms^2) and in normalised variables VLF%, LF%, and HF% presented in percentages in relation to the total power. In addition, the LF/HF ratio was used.

The variables of HRV were measured at 1.5 months, 1 year, and 2 years after the surgery.

2.2. The Data of Space Weather Variables

As a measure of geomagnetic activity, we used the following geomagnetic indices: a local A index of Niemegk observatory (ftp://ftp.gfz-potsdam.de/pub/home/obs/monrep/ (accessed on 4 March 2021)), whose geomagnetic latitude (52.04 N) is close to that of Kaunas city, planetary 3-hourly ap indices, the daily Ap indices designed to measure solar particle radiation by its magnetic effects, and the daily DST index. The DST index provides information about the strength of the ring current around the Earth's magnetosphere caused by solar protons and electrons. The ap, daily SWS, Ap, and DST data were downloaded from the National Geophysical Data Center OMNIWeb database (http://omniweb.gsfc.nasa.gov/ (accessed on 4 March 2021)) and from the World Data Centre for Geomagnetism, Kyoto homepage (http://wdc.kugi.kyoto-u.ac.jp/kp/index.html#LIST (accessed on 4 March 2021)). The values of the daily CRI were obtained from the OULU Cosmic Ray station (http://cosmicrays.oulu.fi/ (accessed on 4 March 2021)). The data of the IMF polarity (the direction along the field lines to the Sun (negative polarity) or from it (positive polarity)) were obtained from https://svalgaard.leif.org/research/sblist.txt (accessed on 4 March 2021).

To eliminate the effect of meteorological conditions and air pollutants on HRV variables, we used the term "weather variables".

2.3. Statistical Analysis

The tests of normality of the HRV variables are presented in more detail in our previous study [43]. After the exclusion of extreme outliers, a Shapiro–Wilk test was performed for NN, VLF%, LF%, and logarithms of SDNN, LF/HF, VLF, LF, HF, and HF% showed that these data came from a normally distributed population.

To assess the relationships between space weather variables, a linear mixed model for measurements was constructed. Linear mixed models are an extension of simple linear models to allow for both fixed and random effects and are particularly used when there is non-independence in the data. We assessed the effects of space weather variables, adjusting for linear trends, the month, weather variables, and sociodemographic and health variables. In the models, the month, sex, and the type of the surgery were included as categorical predictors. The models also included the age, left ventricular ejection fraction, the presence of comorbidities, smoking, previous myocardial infarction (MI), the presence of depression, the concentration of fine particulate matter with an aerodynamic diameter of less than 2,5 μm (PM2.5), the linear trend, and weather variables with a significant effect on the dependent variables. Non-linear associations between GMA and adverse effects on health were observed [44]; therefore, the terms of GMA/CRI/SWS variables were used as categorised using quartiles and the classification and regression tree method [45]; the cut-offs were detected by the first split of nodes. In the analysis, we used these variables on the day of the ECG and on the two previous days. To assess the effect of GMA during the survey on health in later periods, we used data of GMA on the day of the survey and on the two previous/next days. The analysis was performed for all patients and separately for males and females, as well as for separate groups of the surgery. We analysed also the grade response of HRV variables to the GMA.

We presented the beta coefficients in the multivariate model with their standard errors (SE) and the p-value of beta.

3. Results

Most of the patients were men (74.4%). The CABG was performed on 143 (65.0%) patients, VS was performed on 43 (19.5%) patients, and CABG + VS was performed on 34

(15.5%) patients. The data of 220 patients (most of them were men) and the descriptive characteristics of 495 ECG measurements are presented in [43]. The descriptive characteristics of the geomagnetic activity indices are presented in Table 1.

Table 1. The descriptive characteristics of geomagnetic activity indices and SWS during the days of ECG (N = 495).

Variable	Median (Q1; Q3)	Min	Max
Local A, nT	5 (3; 8)	0	28
Ap, nT	4 (3; 7)	0	42
Ap during the surgery, nT	4 (3; 6.75)	0	38
Maximal 3-hourly ap, nT	7 (5; 15)	0	154
DST	−4 (−9; 1)	−80	20
SWS, km/s	375 (338; 430)	256	677

During 2009, a quiet GMA level was observed on 89.9% of days, and only 1.4% of days were named as active-stormy. The GMA had been increasing since 2010: active-stormy days in 2010, 2011, and 2012 represented 5.8%, 10.7%, and 15%, respectively (Figure 1a). A lower mean value of SWS was found in 2009, and higher means of SWS were observed in 2008 (Figure 1b). A negative IMF polarity was observed in 313 (63.2%) ECGs.

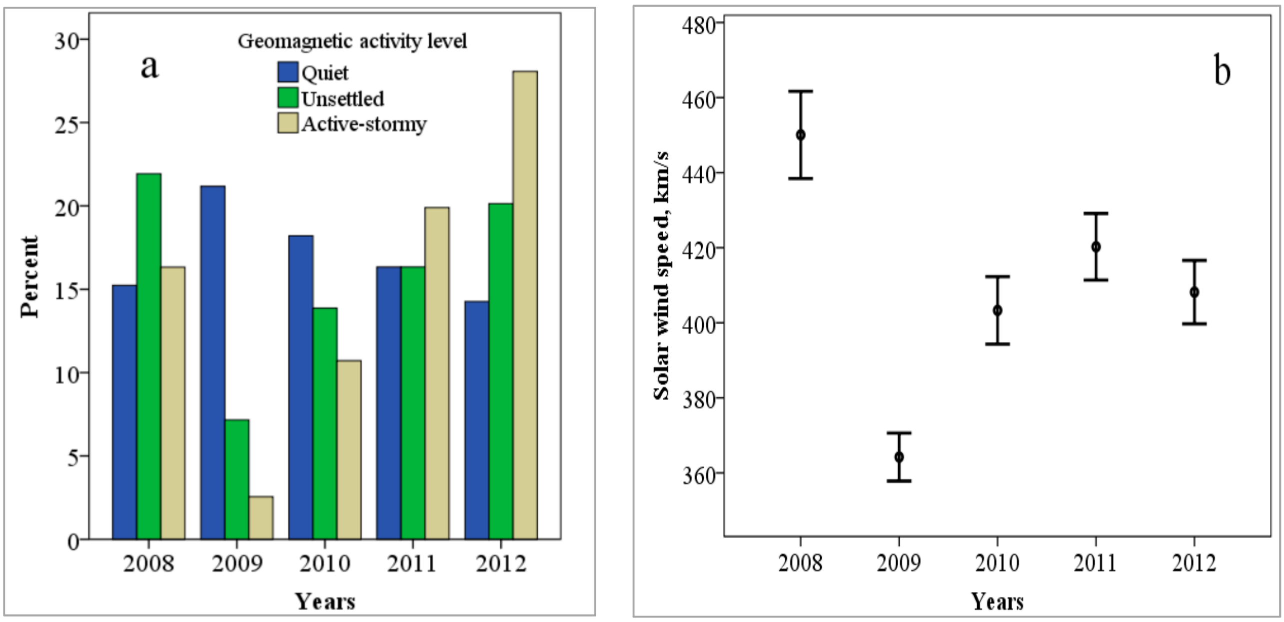

Figure 1. The distribution of GMA levels (**a**) and the mean values ± SE of solar wind speed (**b**).

The mean values of HF and HF% (LF/HF) were higher (lower) on the days of CRI > median, but the effect of CRI was non-significant if the linear trend was included in the model. The mean values of HRV variables in Ap, a maximal daily 3-hourly ap (apmax), DST, and SWS quartiles showed higher mean HF and HF% and a lower mean LF/HF if Ap and local A on the previous days were lower than the median. Lower HF% and LF% and a higher VLF% were observed one day after days with a DST over the 75th percentile. On the days of SWS < 25th percentile, lower mean values of logarithmic SDNN, VLF, LF, and LF/HF were observed, and on the days of SWS > 75th percentile, the mean HF% (LF/HF) was lower (higher). Most of these remained after adjusting for the linear trend and the month. The corresponding β coefficients are presented in Figure 2.

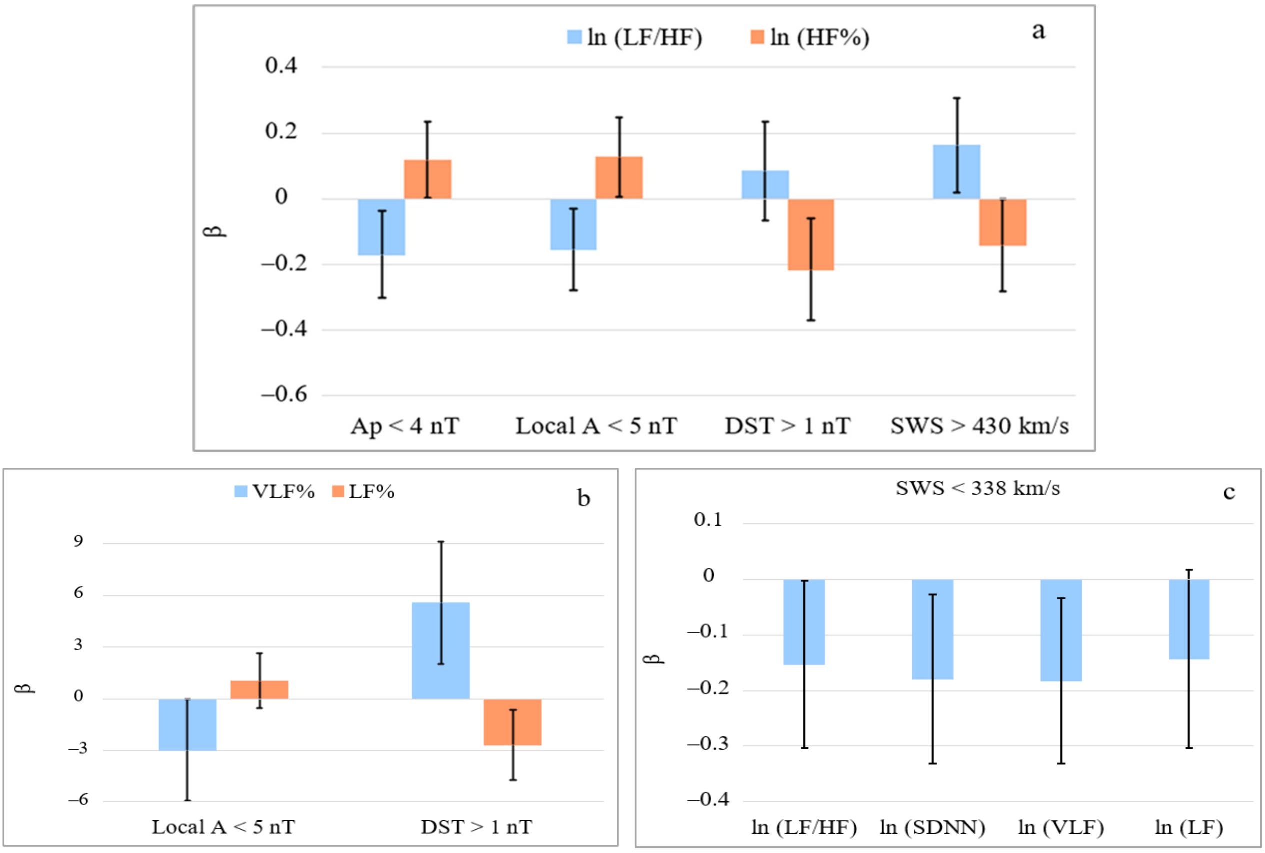

Figure 2. The effects of Ap, local *A*, and DST on the previous day (**a**,**b**), and SWS on the day of the ECG (**a**,**c**) quartiles on HRV variables (β coefficients with 95% confidence interval adjusting for the linear trend and month).

During days with a positive IMF polarity, a lower NN was observed, the effect being stronger in females (Table 2) and in patients who underwent VS (Table 3). When the GMA level was quiet (Ap < 8) two days after the surgery, patients had lower mean SDNN, VLF, LF, and HF; this effect was stronger in males and in patients who underwent VS (Table 3). The results of the classification tree show that SWS < 304 km/s, apmax < 4, DST > 4, and SWS > 425 km/s were statistically significant for some HRV variables; most of these variables were statistically significant in the multivariate models (Tables 2 and 3). The effect of a higher DST was found only in males, but the effect of apmax < 4 on VLF% and LF/HF was stronger in females. For patients who underwent VS, only the IMF direction and quiet GMA two days after the surgery had a statistically significant impact.

Table 2. Multivariate associations between space weather variables and HRV.

HRV Parameter	Variable	Lag	All		Male		Female	
			β (SE)	*p*	β (SE)	*p*	β (SE)	*p*
NN	IMF positive		−45.1 (12.5)	<0.001	−35.9 (15.4)	0.020	−91.4 (22.4)	<0.001
Ln (SDNN)	op: Ap < 8	2	−0.25 (0.08)	0.001	−0.25 (0.09)	0.005	−0.19 (0.16)	0.256
	SWS < 304	2	−0.34 (0.10)	0.001	−0.41 (0.12)	0.001	0.03 (0.26)	0.916
Ln (VLF)	op: Ap < 8	2	−0.23 (0.07)	0.002	−0.25 (0.09)	0.004	−0.09 (0.16)	0.586
	SWS < 304	2	−0.31 (0.10)	0.003	0.36 (0.12)	0.002	0.08 (0.26)	0.763
Ln (LF)	op: Ap < 8	2	−0.24 (0.08)	0.004	−0.22 (0.09)	0.018	−0.21 (0.18)	0.246
	SWS < 304	2	−0.36 (0.11)	0.002	−0.43 (0.13)	0.001	0.04 (0.29)	0.899

Table 2. *Cont.*

HRV Parameter	Variable	Lag	All		Male		Female	
			β (SE)	*p*	β (SE)	*p*	β (SE)	*p*
Ln (HF)	op: Ap < 8	2	−0.21 (0.09)	0.016	−0.19 (0.11)	0.067	−0.19 (0.18)	0.305
	SWS < 304	2	0.32 (0.12)	0.010	−0.35 (0.14)	0.014	−0.11 (0.29)	0.708
VLF%	DST > 1	1	4.90 (1.81)	0.007	5.85 (2.20)	0.008	3.37 (3.70)	0.365
	apmax < 4	0	−6.41 (2.42)	0.008	−4.70 (2.80)	0.094	−12.8 (5.60)	0.025
LF%	DST > 1	1	−2.39 (1.04)	0.022	−2.10 (1.22)	0.086	−2.41 (2.23)	0.282
Ln (HF%)	DST > 4	0	−0.27 (0.10)	0.010	−0.35 (0.13)	0.006	−0.13 (0.17)	0.440
	DST > 1	1	−0.18 (0.08)	0.025	−0.23 (0.10)	0.018	−0.04 (0.13)	0.775
	apmax < 4	0	0.29 (0.10)	0.004	0.25 (0.12)	0.041	0.39 (0.20)	0.054
	SWS > 425	0	−0.19 (0.08)	0.012	−0.22 (0.09)	0.013	−0.20 (0.15)	0.182
Ln (LF/HF)	DST > 4	0	0.38 (0.10)	<0.001	0.45 (0.12)	<0.001	0.23 (0.19)	0.237
	Ap < 4	1	−0.19 (0.07)	0.007	−0.16 (0.09)	0.069	−0.27 (0.13)	0.046
	apmax < 4	0	−0.28 (0.10)	0.006	−0.20 (0.12)	0.094	−0.50 (0.23)	0.037

β—coefficient slopes of the HRV variables adjusting for social and health variables, the linear trend, the monthly variation, $PM_{2.5}$ concentration, and weather variables. In the models for NN, VLF%, LF%, HF%, and LF/HF, RH, and AP were included, and in the models for other variables, T, the NAOI and WS were included.

Table 3. Multivariate associations between space weather variables and HRV for different types of surveys.

HRV Parameter	Variable	Lag	Only CABG		Only VS		CABG + VS	
			β (SE)	*p*	β (SE)	*p*	β (SE)	*p*
NN	IMF positive		−39.7 (14.4)	0.006	−112 (33.2)	0.001	−8.8 (38.8)	0.821
Ln (SDNN)	op: Ap < 8	2	−0.19 (0.09)	0.027	−0.73 (0.24)	0.004	−0.27 (0.28)	0.337
	SWS < 304	2	−0.34 (0.12)	0.007	−0.07 (0.33)	0.835	−0.58 (0.28)	0.048
Ln (VLF)	op: Ap < 8	2	−0.17 (0.08)	0.035	−0.63 (0.25)	0.015	−0.23 (0.27)	0.413
	SWS < 304	2	−0.26 (0.12)	0.027	0.05 (0.34)	0.880	−0.65 (0.27)	0.023
Ln (LF)	op: Ap < 8	2	−0.17 (0.09)	0.068	−0.74 (0.26)	0.005	−0.12 (0.29)	0.684
	SWS < 304	2	−0.33 (0.14)	0.018	−0.25 (0.35)	0.470	−0.51 (0.30)	0.101
Ln (HF)	op: Ap < 8	2	−0.12 (0.10)	0.265	−0.75 (0.25)	0.003	−0.02 (0.33)	0.949
	SWS < 304	2	−0.30 (0.15)	0.050	−0.23 (0.33)	0.482	−0.36 (0.33)	0.287
VLF%	DST > 1	1	5.23 (2.42)	0.032	−0.27 (4.16)	0.949	10.1 (5.15)	0.057
	apmax < 4	0	−5.95 (2.90)	0.041	0.09 (10.1)	0.930	−6.43 (6.11)	0.299
LF%	DST > 1	1	−3.28 (1.39)	0.019	2.63 (2.56)	0.248	−3.75 (2.52)	0.145
Ln (HF%)	DST > 4	0	−0.33 (0.13)	0.011	−0.30 (0.24)	0.214	−0.08 (0.30)	0.785
	DST > 1	1	−0.13 (0.10)	0.203	−0.10 (0.19)	0.598	−0.25 (0.23)	0.281
	apmax < 4	0	0.22 (0.13)	0.081	0.62 (0.43)	0.156	0.44 (0.25)	0.088
	SWS > 425	0	−0.28 (0.09)	0.002	−0.09 (0.21)	0.678	−0.01 (0.20)	0.989
Ln (LF/HF)	DST > 4	0	0.42 (0.13)	0.002	0.12 (0.23)	0.599	0.47 (0.28)	0.094
	Ap < 4	1	−0.21 (0.09)	0.023	−0.04 (0.17)	0.821	−0.15 (0.18)	0.405
	apmax < 4	0	−0.19 (0.12)	0.123	−0.41 (0.43)	0.343	−0.65 (0.26)	0.019

β—coefficient slopes of the HRV variables adjusting for social and health variables, the linear trend, the monthly variation, $PM_{2.5}$ concentration, and weather variables; CABG, coronary artery bypass grafting; VS, valve surgery. In the models for NN, VLF%, LF%, HF%, and LF/HF, RH, and AP were included, and in the models for other variables, T, the NAOI and WS were included.

We analysed the response of HRV variables in the categories of low GMA and SWS. In the range of apmax < 4, a dose–response association between apmax and VLF% and HF% was found (Table 4). Additionally, a dose–response association between SWS and HF% was observed. During a quiet GMA level, the lowest Ap after the surgery tended to have a stronger effect on SDNN and VLF, LF, and HF powers (Table 4), but we cannot state a statistically significant correlation between Ap and these HRV variables in the range of quiet GMA levels.

Table 4. Multivariate associations between space weather variables and HRV in graded GMA and SWS categories.

HRV Parameter	Variable	Lag	β (SE)	*p*
Ln (SDNN)	op: Ap $\geq$ 8	2	Reference category	
	op: 5 $\leq$ Ap $\leq$ 7		−0.29 (0.09)	0.001
	op: 3 $\leq$ Ap $\leq$ 4		−0.24 (0.09)	0.009
	op: Ap $\leq$ 2		−0.32 (0.10)	0.001
Ln (VLF)	op: Ap $\geq$ 8	2	Reference category	
	op: 5 $\leq$ Ap $\leq$ 7		−0.27 (0.09)	0.002
	op: 3 $\leq$ Ap $\leq$ 4		−0.21 (0.09)	0.016
	op: Ap $\leq$ 2		−0.29 (0.09)	0.002
Ln (LF)	op: Ap $\geq$ 8	2	Reference category	
	op: 5 $\leq$ Ap $\leq$ 7		−0.28 (0.10)	0.005
	op: 3 $\leq$ Ap $\leq$ 4		−0.22 (0.10)	0.026
	op: Ap $\leq$ 2		−0.31(0.10)	0.003
Ln (HF)	op: Ap $\geq$ 8	2	Reference category	
	op: 5 $\leq$ Ap $\leq$ 7		−0.27 (0.11)	0.010
	op: 3 $\leq$ Ap $\leq$ 4		−0.20 (0.11)	0.066
	op: Ap $\leq$ 2		−0.27 (0.11)	0.017
VLF%	apmax $\geq$ 4	0	Reference category	
	apmax = 3		−6.38 (2.9)	0.028
	apmax $\leq$ 2		−7.89 (4.2)	0.060
Ln (HF%)	apmax $\geq$ 4	0	Reference category	
	apmax = 3		0.29 (0.12)	0.018
	apmax $\leq$ 2		0.34 (0.18)	0.056
Ln (HF%)	SWS $\leq$ 425	0	Reference category	
	425 < SWS $\leq$ 600		−0.18 (0.08)	0.027
	SWS > 600		−0.32 (0.18)	0.076

β—coefficient slopes of the HRV variables adjusting for variables presented in Table 2.

4. Discussion

For the first time, we found a possible impact of GMA on HRV variables in patients after open-heart surgery. Changes in HRV parameters were mostly associated with low GMA levels during the performance of ECG and during the survey, and predominantly with a low SWS. For the first time, associations between the IMF polarity and mean values of NN were detected. The effect of space weather variables varied by type of surgery and sex (males and females).

In the analysis, as exposure to GMA during ECG, we used the local A index, the daily maximal 3-hourly ap, and the daily Ap and DST indices. In the multivariate models excluding the model for LF/HF, only a low apmax and the higher DST level were statistically significant. For the exposure to GMA during the surgery, the impact of local GMA was non-significant. The stronger impact of the planetary GMA on the HRV parameters may be explained by the reflection of Ap, ap, or DST of the global changes in atmospheric conditions.

The results of previous studies show that a daylong increase in solar wind ram pressure produces a positive DST [46]. Mostly, this situation occurs at the beginning of the magnetospheric disturbances due to high-speed solar wind streams which dominate the interplanetary medium activity during the solar minimum [47]. We hypothesised that changes in VLF%, LF%, and HF% during days of DST > 4 or on the next day after DST > 1 were due to atmospheric conditions occurring because of variations in the solar wind (SW).

SW parameters are affected by energetic electron precipitation [48], which affects the flow of the downward current density (J_z), which, in turn, affects the distribution of electric charge in the clouds [49], and thus, the atmospheric conditions. Enhanced SW plasma streams are associated with intensifications of a mid-latitude cyclone [50]. The effect of a positive DST was also observed in a study performed during the SC ascending phase: the heart rate was statistically significantly higher on days where DST ≥ 0 as compared with days of $-20 < \text{DST} < 0$ [51].

We found a decrease in VLF% and LF/HF and a rise in HF% on days of a very low GMA. In addition, a dose–response association between apmax and VLF% and HF% was seen. The effects of a low GMA have been found to be associated with the risk of arrhythmias in cardiovascular patients [52,53]. Additionally, lower mean SDNN, VLF, LF, and HF were observed in patients during a quiet GMA on the second day after the surgery. It is possible that these patients had a poorer cardiovascular health because postoperative atrial fibrillation (AF) was associated with a higher risk of future AF, mortality, heart failure, and ischaemic stroke [54,55]. Studies found a higher incidence AF on the second day after surgery [54], and the risk of AF was higher in patients undergoing VS [55], which is in line with our findings. We observed a stronger effect of the global GMA than the local GMA, possibly because Kp (or Ap) indices parametrise the ULF and very-low-frequency waves as well as the relativistic electron flux (REF) [46]. The REF affects the flow of Jz and the distribution of the electric charge in the clouds [49], thus affecting the atmospheric conditions and may be associated with changes in atmospheric electricity.

We have no reason to state a statistically significant association between HRV variables and CRI, even though other researchers showed a significant positive association between HRV and CRI [15]. We found a statistically significant correlation between some HRV parameters and the daily CRI, but CRI exhibited a seasonal variation, and the trend in CRI is the opposite of solar activity.

We found lower SDNN, VLF, LF, and HF on the second day after SWS < 304 km/s. This effect may be explained by the impact of a low SWS on atmospheric patterns associated with the patients' poorer psychological state and a lower parasympathetic cardiac control. The SWS minima occurred approximately 2 days before the REF minima [55], and the minima of the SWS and the deep minima of the REF occurred within a few days of the change in the IMF direction [35]. During the colder period (November–March), days of SWS minima were associated with a decrease in cyclonic activity between 60° and 80° N [56] and with a negative NAO index [35]. During negative NAO phases in Eastern Europe, cold air is more common [57]. The weather data of 2008–2012 showed that during the two-day period after SWS < 304 km/s, a negative NAO/AO and a rise in AP during November–March and a lower T and higher RH during summer and the first month of autumn were observed. The cold during winter and a lower temperature and wetter days during the warmer period may provoke a stressed situation. According to the Polyvagal theory [58], a low HRV is associated with emotional dysregulation [59]; therefore, it is possible that patients who were more stressed two days after SWS < 304 km/s due to the worse weather conditions had a lower SDNN. The effects of individual space weather variables recalculated as a percentage of the median were similar for different frequency domain components.

The effects of a low SWS and a higher DST were only observed in males. Decreases in SDNN, HF, or HF% due to these space weather conditions were linked to a decrease in the parasympathetic activity, and thus, an increase in the sympathetic activity. A predominance of the sympathetic tone over the parasympathetic tone in males and vice versa in females was observed [60]. A low GMA was associated with an increase in parasympathetic activity; therefore, the effect of a low GMA defined by Ap or ap indices was stronger in females. In females, a decrease in VLF% by 12.8% or by 25.1% as compared with the median (51%) was associated with a low apmax. Low VLF power is more strongly associated with all-cause mortality and with arrhythmic death [1].

The effect of space weather variables was non-identical for different types of surgery. A stronger effect of the quiet GMA after surgery was observed in patients who underwent

VS. It is probable that patients who underwent VS had a higher risk of arrhythmias, or these patients had a poorer psychological state, and they had a poorer time adapting to GMA changes.

We did not find any statistically significant effects of an increased GMA or geomagnetic storms (GS), although other authors stated a decrease in HRV during GS [16–19]. This may be explained due to only five surgeries being performed during GS or 2 days before/after, and only four ECGs being performed during GS; 77.6% of ECGs were performed during quiet GMA. In addition, we used the data of 5-minute ECGs performed mostly during the first half of the day, whereas in other studies [16–19] the data of 24-hour ECGs were used. Based on data on the medical control of cosmonauts' cardiac rhythm changes, substantial changes in the mean values of SDNN and normalized frequency domain parameters were observed during at different times of day [18]. The different effect of GMA during different times of day was found in another study [61]. In addition, our patients had just undergone open-heart surgery and were more sensitive to rhythmic disorders, i.e., to low GMA. Therefore, the U-shaped effect of GMA on HRV was probable.

To evaluate the cardiovascular risk, non-linear HRV indices were also used [62,63]. The effect of geomagnetic disturbances on the fractal scaling of HRV was determined [64]. We did not have any nonlinear indices of HRV and some time domain variables of HRV, which can be seen as a limitation of the study.

The absence of data on the psychological state of the patients could be another limitation of the study; only the presence of depression was included in the model. The social factors of marital status and education were analysed, but these predictors in the model were not statistically significant. The assessment of space weather variables in our study did not consider the possible effect of patients' treatments on HRV indicators.

5. Conclusions

The results of our study showed a statistically significant association between very low GMA on the day of ECG, a low SWS two days before, a positive DST, and a quiet GMA on the second day after the operation and HRV variables in patients after open-heart surgery. A lower mean SDNN and VLF, LF, and HF powers were observed in patients when Ap < 8 was observed two days after the surgery and a low SWS occurred two days before the ECG. A lower VLF% and a higher HF% were associated with a low maximal 3-hourly ap. A higher VLF% and LF/HF and a lower LF% and HF% were associated with DST > 1. During days with a positive IMF polarity, a lower NN was observed; this effect was predominant in females. The effect of space weather variables was non-identical for males and females and for various types of surgery.

Our study results confirmed that repeating a 5 min ECG is recommended to consider space weather conditions, because some HRV variables were related to space weather changes. The GMA during the surgery may affect the SDNN in short-term ECG during the longer period, especially in patients who undergo VS.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Geomagnetic activity, solar wind, and cosmic ray intensity data were obtained from Niemegk observatory (ftp://ftp.gfz-potsdam.de/pub/home/obs/monrep/ (accessed on 4 March 2021)); National Geophysical Data Center OMNIWeb database (http://omniweb.gsfc.nasa.gov/ (accessed on 4 March 2021)); World Data Centre for Geomagnetism, Kyoto homepage (http://wdc.kugi.kyoto-u.ac.jp/kp/index.html#LIST (accessed on 4 March 2021)); OULU Cosmic Ray station (http://cosmicrays.oulu.fi/ (accessed on 4 March 2021)); Leif Svalgaard's Research Page (https://svalgaard.leif.org/research/sblist.txt (accessed on 4 March 2021)); National Oceanic and Atmospheric Administration (https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml (accessed on 4 March 2021)). The HRV variables database is not publicly available.

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