

Article

Possible Associations between Space Weather and the Incidence of Stroke

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Abstract: The aim of our study was to detect the possible association between daily numbers of ischemic strokes (ISs) and hemorrhagic strokes (HSs) and space weather events. The daily numbers of ISs, subarachnoid hemorrhages (SAHs), and intracerebral hemorrhages (ICHs) were obtained from Kaunas Stroke Register during the period of 1986 to 2010. We used time- and season-stratified multivariate Poisson regression. We analyzed data of 597 patients with SAH, 1147 patients with ICH, and 7482 patients with IS. Strong/severe geomagnetic storms (GSs) were associated with an increase in the risk of SAH (by 58%) and HS (by 30%). Only GSs occurring during 6:00–12:00 UT were associated with the risk of IS. Low geomagnetic activity (GMA) was associated with the risk of ICH, HS, and IS (Rate Ratios with 95% CI were 2.51 (1.50–4.21), 2.33 (1.50–3.61), and 1.36 (1.03–1.81), respectively). The days of \geq X9 class solar flare (SF) were associated with a 39% higher risk of IS. The risk of HS occurrence was greater than two times higher on the day after the maximum of a strong/severe solar proton event (SPE). These results showed that GSs, very low GMA, and stronger SFs and SPEs may be associated with an increased risk of different subtypes of stroke.

Keywords: geomagnetic activity; solar flares; solar proton event; ischemic stroke; hemorrhagic stroke

1. Introduction

Numerous studies have reported that geomagnetic activity (GMA) affects humans—especially their cardiovascular system [1–5]. GMA has been observed to be positively associated with arterial blood pressure [6], some blood coagulation parameters [7], the marker of inflammation, C-reactive protein level [8], and it is negatively associated with heart rate variability [1,9] and melatonin concentration [10]. It has been indicated that low GMA was associated with an increase in electrical heart instability [11,12]. These effects of GMA have been explained by the effects of the magnetic field on ions and protons in the human body [2,13–15].

The impacts of GMA, especially the impact of geomagnetic storms (GSs) on the risk of myocardial infarction have been discussed during the past 50 years [1,2,5,16]. Some studies have analyzed statistical associations between GS and stroke [17–22]. An increase in the daily rate of strokes during moderate and strong GSs [18,19,22] has been observed.

Previous studies have shown that space weather phenomena—such as solar proton events (SPEs), stream interaction regions (SIRs), solar flares, $Pc1$ and $Pc4$ – $Pc5$ geomagnetic pulsations, ionospheric parameters, solar wind speed, and solar wind dynamic pressure—might be associated with the risk of acute cardiovascular events [16,23–29]. During days of SPEs and 1–2 days after, a higher rate of acute myocardial infarction has been observed [23,27]; besides, SPEs have been positively associated with the number of arrhythmias [30]. The risk of ventricular fibrillation during hospital admission due to acute coronary syndromes (ACSs) was associated with SIRs with a lag of 0–3 days; the risk of ACS in patients with chronic atrial fibrillation was associated with high-speed solar wind (HSSW) (≥ 600 km/s) (lag 0–3 days) and with days of SPEs (lag 0–3 days) occurring in conjunction with SIR (lag 0–3 days) [29]. HSSW and 1–2 days after were associated with an increase in the risk of ACS in patients with diabetes; also, the impact of GSs was stronger if they coincided with HSSW [31]. Apart from this, statistical associations between solar wind speed and the parameters of heart rhythm variability [32] were found. Stronger solar flares (SFs) (M-class or X-class) were positively associated with the number of arrhythmias [30].

Arrhythmic disorders are risk factors for stroke. It is possible that not only stronger GS, but also low GMA, SPEs, SIRs, and a stronger SF may be associated with the risk of stroke. It is probable that GS in conjunction with a negative B_z (the z component of the interplanetary magnetic field), SPE, SIR, SF, or HSSW had a stronger possible effect on the risk of various subtypes of stroke.

The aim of the study was to detect the potential associations between the daily numbers of ischemic strokes (ISs), subarachnoid hemorrhages (SAHs), and intracerebral hemorrhages (ICHs) in patients aged 25–64 years and space weather events, adjusting for weather variables.

2. Methods

2.1. Patients

During the study period, from 1986 to 2010, data about patients aged 25–64 from the population of Kaunas city have been analyzed. The data were derived from Kaunas population-based Stroke Register database. Multiple records from health care organisations (hospitals, outpatient departments) and different sources of information (hospital discharge documents, death certificates, autopsy protocols, etc.) were evaluated to form the Stroke Register, where stroke events were registered in accordance with the WHO MONICA project protocol and established quality control procedures [33]. All stroke cases were registered on special forms suggested by the WHO MONICA project. Stroke was defined according to the WHO MONICA protocol and was described in detail elsewhere [34]. During the study period, stroke types were coded according to ICD-9 and ICD-10 classifications: ICD-9 codes (430—subarachnoid hemorrhage (SAH), 431—intracerebral hemorrhage (ICH), 433—ischemic stroke (IS)) and ICD-10 codes (I60—Subarachnoid hemorrhage (SAH), I61—intracerebral hemorrhage (ICH), I63—ischemic stroke (IS)). All patients suspected of or having had a nonfatal acute stroke or death from stroke were registered. According to the study protocol, every stroke event (SAH, ICH, IS) must have its apparent onset within the study period and more than 28 days from any previously recorded stroke event in the same case. Multiple stroke attacks occurring within 28 days from the onset were regarded as a single event. Special diagnostic procedures were used for the confirmation of codes for specific types of stroke (SAH, ICH, IS). Brain computer tomography (CT) or cerebrospinal fluid containing blood or autopsy (in fatal events) was required to determine the diagnosis of SAH. The diagnosis of ICH had to be confirmed either by CT or by autopsy. IS was diagnosed when CT and/or autopsy could verify the infarction and/or exclude hemorrhage and nonvascular disease.

2.2. Environmental Variables

Data on X-class SFs, SPE, HSSW, defined as Solar wind speed ≥ 600 km/s, B_z components of the interplanetary magnetic field presented in GSM coordinates, and geomag-

netic activities were used in the study. The planetary 3-hourly Kp and daily Ap indexes were used as a measure of the level of geomagnetic activity. We analyzed the effect of GSs defined by the National Oceanic and Atmospheric Administration's (NOAA) Space Weather Prediction Centre (SWPC) and the Australian Space Weather Services (ASWS). GS defined by NOAA/SWPC were based on the 3-hourly Kp index (Kp = 5—a minor GS, Kp = 6—a moderate GS, and Kp ≥ 7—a strong/severe GS). GS defined by ASWS (also used by NOAA/SWPC) were based on the Ap index: a minor GS occurs when $30 \leq \text{Ap} < 50$, a major GS occurs when $50 \leq \text{Ap} < 100$, and a severe GS occurs when $\text{Ap} \geq 100$ [35]. In the analysis, the effect of low GMA was also assessed. The data of GMA were downloaded from World Data Centre for Geomagnetism, Kyoto homepage (<http://wdc.kugi.kyoto-u.ac.jp/kp/index.html#LIST> (accessed on 4 March 2021)).

Moreover, we analyzed the daily rate of stroke on days of a maximum of strong and severe SPE event, defined as the proton flux ranged in the interval of, respectively, 1000–9999 pfu, and ≥10,000 pfu (pfu = protons/(cm²·day·sr), and on days of X-class SFs, depending on their intensity. To identify days linked with these events, we corrected the date of the event, adjusting for local time. The data on the SPE onset and maximum were downloaded from (<https://www.ngdc.noaa.gov/stp/space-weather/interplanetary-data/solar-proton-events/> (accessed on 4 March 2021)) and the data on the intensity of X-class SF were downloaded from the NGDC database (<https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-flares/> (accessed on 4 March 2021)). The data on the daily proton >10 MeV flux and solar wind parameters were downloaded from NASA/GSFC's OMNI data set through <http://omniweb.gsfc.nasa.gov/> (accessed on 4 March 2021). The effect of HSSW and a negative B_z were assessed since 1995, because about 30% of the daily values of these parameters were missing before 1995.

In our previous work [36], we detected a statistically significant effect of the variables of air temperature (T), atmospheric pressure (AP), relative humidity (RH), the daily Arctic oscillation indices, and the monthly East Atlantic/West Russia (EA/WR) pattern, Scandinavian (SCA) pattern, and ENSO indices [36]. The corresponding weather variables for subtypes of stroke were included in the multivariate regression models as predictors.

2.3. Statistical Analysis

The possible associations between space weather variables and the daily number of strokes were evaluated by using a multivariate Poisson regression. To control for the inter-annual trend in the rate of stroke occurrence arises due to changes in population size, prevention, and treatment during the 25-year period, a time-stratified model [36] was used. This approach creates indicator variables that are assigned to each year across the entire study period (the year was included in the models as a categorical variable). To exclude the impact of a seasonal variation, the calendar month was included in the multivariate models as a categorical predictor. The space weather variables were used as categorical predictors. The level of GMA was detected by using daily data (Ap index or maximal value of all 3-hourly Kp) and by using 3-hourly Kp. We assessed the risk of stroke occurrence on days of space weather events and 1–2 days after these events (with a lag of 0, 1, and 2 days, respectively).

First, we analyzed the daily mean values of SAH, ICH, haemorrhagic stroke (HS) (SAH or ICH), IS, and all strokes depending on the level of GMA, SPE, or SF. The significance of the difference between the means was assessed by using univariate Poisson regression. Secondly, we analyzed the impact of space weather variables by including them into the stratified multivariate regression model with other predictors, affecting the risk of stroke: the day of the week as a categorical variable and variables of air temperature, atmospheric pressure, relative humidity, and teleconnection indices, which were defined in [37]. In the model for SAH, were included a change in daily AP of >3.9 hPa from the previous day, RH > 96.5% on the previous day, and strong El Niño; in the model for ICH were included a change in daily AP of > 9.55 hPa from the previous day with a lag of 1 day, daily change in RH < 7.5%, and EA/WR index; and in the model for IS and all strokes were included

an increase in daily T over 2.2 °C compared with the previous day, RH over 53.5% with a lag of 1 day, a strong positive SCA pattern, a strong La Nina, and a strongly negative EA/WR [37]. Since 1995, we assessed the effects of HSSW, a negative B_z , and combined effects of GMA, SPE, and SF with HSSW or a negative B_z .

For the assessment of the impact of space weather variables, we presented adjusted rate ratios (RRs) in the multivariate Poisson regression model with 95% confidence interval (95% CI) and p -value. To avoid overloading the tables with excessive information, we marked the p -value > 0.5 as ns (nonsignificant). Statistical analysis was performed using SPSS 20 software (IBM Corp. Released 2011. IBM SPSS Statistics for Windows, Version 20.0. IBM Corp.: Armonk, NY, USA).

3. Results

During the study period (1986–2010), 9277 cases of stroke were identified and verified (5230 (56.4%) in men and 4047 (43.6%) in women). Of these, 7482 (80.7%) cases were IS, 1147 (12.4%) cases were ICH, 597 (6.4%) cases were SAH, and 51 (0.5%) were other types. The distribution of strokes by sex and stroke types is presented in Table 1.

Table 1. Distribution of strokes by sex and stroke type. SAH: subarachnoid hemorrhage; ICH: intracerebral hemorrhage; IS: ischemic stroke.

Sex/Groups	Total	SAH	ICH	HS (SAH + ICH)	IS	Other
All, n (%)	9277 (100.0/100.0)	597 (6.4)	1147 (12.4)	1744 (18.8)	7482 (80.7)	51 (0.5)
Men, n (%)	5230 (56.4/100.0)	281 (5.3)	631 (12.1)	912 (17.4)	4294 (82.1)	24 (0.5)
Women, n (%)	4047 (43.6/100.0)	316 (7.8)	516 (12.7)	832 (20.5)	3188 (78.8)	27 (0.7)

According to the ASWS definition, during 1986–2010, minor GS occurred at 504 days, major GS at 186 days, severe GS at 46 days, and very low GMA ($A_p = 0$) was observed at 49 days (Table 2). According to the NOAA/SWPC definition, minor GS (maximal 3-h $K_p = 5$) occurred at 1103 days, moderate GS (maximal 3-h $K_p = 6$) at 450 days, and strong/severe GS (maximal 3-h $K_p \geq 7$) at 273 days (Table 2). During the studied period, 31 strong and 9 severe SPE events were occurred. As the maximum of severe SPE occurred on 25 September 2001, at 22:35 UT, we regarded both that day and next days as days of severe SPE. One or a few X-class SF were observed at 246 days; among them, 24 days were with X5.0–X8.9 intensity, and 16 days were with $\geq X10.0$ intensity.

A higher daily rate of all types and subtypes of stroke on days of $A_p = 0$ was found. Days of severe and strong/severe GS were associated with a higher rate of SAH and HS. A higher daily rate of ICH was observed on days of strong and severe SPEs. On days of $\geq X9$ class solar flare or on the days after if this flare took place in the afternoon, a higher daily rate of IS was detected (Table 2).

Table 2. The daily mean values of cases of stroke (SD) in groups of different levels of space weather conditions and p -values in the univariate Poisson regression model.

Variable	N	SAH	ICH	HS	IS	All Types
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
The effects of geomagnetic activity level defined by the A_p index						
$A_p = 0$	49	0.12 (0.3)	0.33 (0.5)	0.45 (0.6)	1.04 (0.9)	1.49 (1.0)
$0 < A_p < 30$	8346	0.06 (0.3)	0.12 (0.4)	0.19 (0.4)	0.82 (0.9)	1.01 (1.0)
Minor GS ($30 \leq A_p < 50$)	504	0.05 (0.2)	0.13 (0.4)	0.19 (0.4)	0.83 (0.9)	1.02 (1.0)
Major GS ($50 \leq A_p < 100$)	186	0.08 (0.3)	0.15 (0.4)	0.23 (0.5)	0.86 (0.9)	1.09 (1.0)
Severe GS ($A_p \geq 100$)	46	0.17 (0.4)	0.17 (0.4)	0.35 (0.5)	0.78 (0.9)	1.13 (1.1)
p		0.023	0.002	<0.001	0.485	0.015

Table 2. Cont.

Variable	N	SAH	ICH	HS	IS	All Types
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
The effects of GS, defined by 3-h Kp index (days of Ap = 0 excluded)						
All 3-h Kp < 5	8359	0.07 (0.3)	0.13 (0.4)	0.19 (0.4)	0.82 (0.9)	1.02 (1.0)
Minor GS * (Kp = 5)	1103	0.06 (0.3)	0.12 (0.3)	0.18 (0.4)	0.82 (0.9)	1.01 (1.0)
Moderate GS * (Kp = 6)	450	0.05 (0.3)	0.13 (0.4)	0.18 (0.4)	0.82 (0.9)	0.99 (1.0)
Strong/severe GS * (Kp ≥ 7)	273	0.10 (0.3)	0.14 (0.4)	0.23 (0.5)	0.86 (1.0)	1.09 (1.1)
<i>p</i>		0.108	ns	0.273	ns	ns
The effects of the maximum of SPE						
Other days	9090	0.07 (0.3)	0.13 (0.4)	0.19 (0.4)	0.82 (0.9)	1.02 (1.0)
Strong event (1000–9999 pfu)	31	0.10 (0.3)	0.19 (0.4)	0.29 (0.4)	0.84 (0.9)	1.13 (1.1)
Severe event (≥10,000 pfu)	10	0	0.40 (0.5)	0.40 (0.4)	0.70 (0.9)	1.10 (1.0)
<i>p</i>		ns	0.039	0.151	ns	ns
The effects of the X-class solar flare						
X ≥ 9.0 lag 0–1 **	34	0.03 (0.2)	0.15 (0.4)	0.18 (0.4)	1.21 (1.12)	1.38 (1.2)
Other days	9048	0.07 (0.3)	0.12 (0.4)	0.19 (0.4)	0.82 (0.9)	1.01 (1.0)
<i>p</i>		0.426	ns	ns	0.013	0.034

* defined by maximal 3-h Kp. ** the days of ≥X9.0 class solar flare or the day after if this flare took place in the afternoon. ns (nonsignificant).

The analysis of the effects of GS occurring at different times of the day showed that stronger effects of GS were observed during the period of 6:00–9:00 UT; only GS occurring at this time were associated with a higher rate of IS (Figure 1). The GS occurring at 6:00–18:00 UT had a stronger effect on SAH; besides, GS occurring at 15:00–21:00 UT had a stronger impact on ICH (Figure 1).

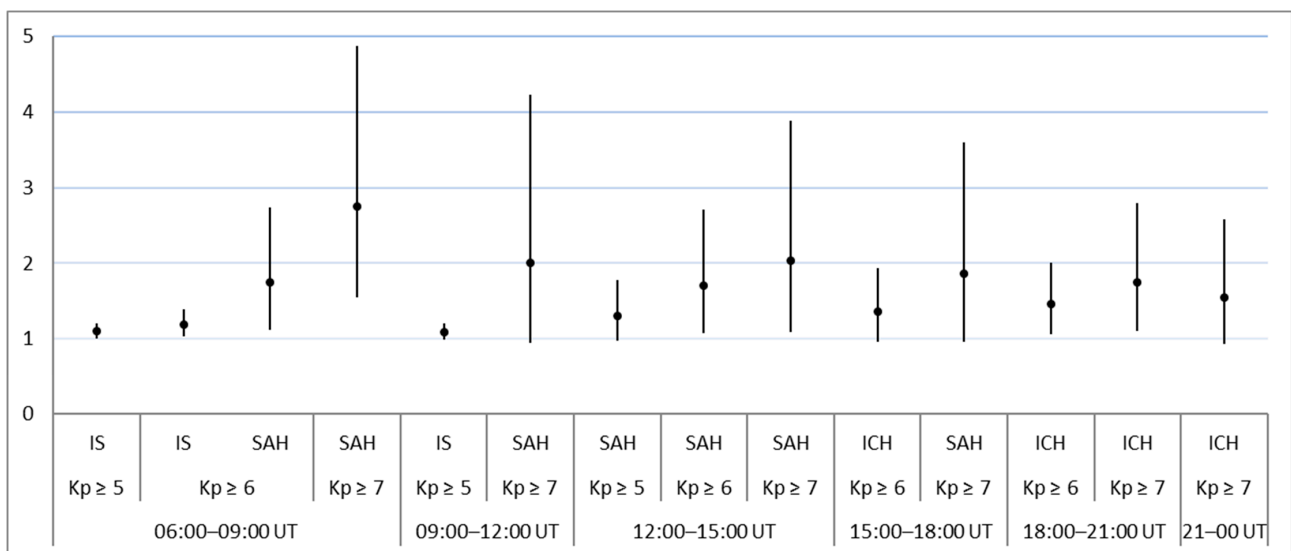


Figure 1. Univariate associations between GS occurring at different times (UT) and the risk of stroke (Rate ratio with 95% CI).

After adjusting for the time interval, seasonality, the day of the week, and weather variables, the days of severe GS ($Ap \geq 100$) were associated with a more than two-fold increase in the risk of SAH and HS occurrence ($p < 0.01$). The strong/severe GS were associated with a 58% increase in the risk of SAH occurrence and with a 30% increase in the risk of HS occurrence. Low GMA was associated with a more than 2-fold increase in the risk of ICH and HS. Only moderate+ GS occurring at 15:00–21:00 UT were associated with the risk of ICH. The multivariate models showed a significant effect of both low and high GMA and strong SPEs on the risk of the occurrence of HS (Table 3). The risk

of HS occurrence was by more than two times higher on the day after the maximum of strong/severe SPE.

Table 3. Rate Ratios \diamond , 95% Confidence Intervals (CI), and p -values for the associations between the occurrence of haemorrhagic stroke and space weather variables in a time-stratified multivariate model.

Model	Variable	RR (95% CI)	p	RR (95% CI)	p
Subarachnoid hemorrhages				Haemorrhagic stroke	
I	Ap = 0	1.88 (0.81–4.34)	0.142	2.33 (1.50–3.61)	<0.001
	50 ≤ Ap < 100	1.17 (0.68–2.00)	ns	1.26 (0.92–1.71)	0.152
	Ap ≥ 100	2.75 (1.35–5.59)	0.005	2.04 (1.24–3.35)	0.005
II	Strong/severe GS, defined by daily Kp	1.58 * (1.07–2.35)	0.023	1.30 * (1.01–1.68)	0.041
III	Kp = 6 at 06:00–09:00 UT	1.21 * (0.60–2.45)	ns		
	Kp ≥ 7 at 06:00–09:00 UT	2.65 * (1.49–4.72)	0.001		
IV	Extreme GMA (Ap = 0 or Ap ≥ 100)	2.30 (1.33–3.96)	0.003		
Intracerebral hemorrhages					
V	Ap = 0	2.51 (1.50–4.20)	<0.001		
	30 ≤ Ap < 50	1.13 (0.88–1.45)	0.359		
	50 ≤ Ap < 100	1.34 (0.89–1.92)	0.168		
	Ap ≥ 100	1.63 (0.81–3.29)	0.173		
VI	Kp ≥ 6 at 15:00–21:00 UT	1.42 * (1.07–1.89)	0.016		
VII	Days of the maximum of strong SPE	1.67 * (0.74–3.77)	0.214		
	Days of the maximum of severe SPE	3.33 * (1.23–9.01)	0.018		
VIII	Ap = 0	2.51 (1.50–4.21)	<0.001		
	Days of the maximum of severe SPE	2.62 (0.95–7.27)	0.064		
	Kp ≥ 6 at 15:00–21:00 UT	1.36 (1.02–1.83)	0.039		
IX	Days of the maximum of SPE **			1.71 * (0.99–2.98)	0.056
X	1 day after of the maximum of SPE **			2.07 * (1.24–3.47)	0.006
XI	2 day after of the maximum of SPE **			1.51 * (0.83–2.76)	0.173
XII	Ap = 0			2.33 (1.50–3.61)	<0.001
	Ap ≥ 100			1.77 (1.05–2.98)	0.031
	1 day after of the maximum of SPE **			1.81 (1.06–3.10)	0.030

\diamond adjusted for month, the day of the week, and weather variables; * additionally adjusted for low GMA (Ap = 0); ** strong/severe SPE. ns (nonsignificant)

In the multivariate model, both low GMA and GS during 06:00–12:00 UT were associated with a significant increase in the risk of IS. The days of ≥X9 class solar flare or the day after if this flare occurred in the afternoon were associated with a 39% increase in the risk of IS, adjusting for the GMA level. If these days were 1–2 days after the day of GS, the risk of IS increased by 76%, and the risk of any types of stroke increased by 60% (Table 4).

Table 4. Rate Ratios \diamond , 95% Confidence Intervals (CI), and p -values for the associations between the occurrence of ischemic stroke and all strokes combined and space weather variables in time-stratified multivariate models.

	Variable	RR \diamond (95% CI)	p	RR \diamond (95% CI)	p
Ischemic stroke				All strokes	
I	Ap = 0	1.36 (1.03–1.81)	0.032	1.56 (1.23–1.98)	<0.001
	Kp ≥ 6 at 06:00–09:00 UT	1.17 (1.00–1.36)	0.047	1.18 (1.03–1.36)	0.016
II	Kp ≥ 5 at 06:00–09:00 UT and 09:00–12:00 UT	1.14 * (1.01–1.29)	0.042	1.15 * (1.02–1.28)	0.019
III	X ≥ 9 lag 0–1 **	1.41 * (1.03–1.92)	0.032	1.34 * (1.00–1.79)	0.048
IV	Ap = 0	1.36 (1.03–1.81)	0.032	1.56 (1.23–1.98)	<0.001
	Kp ≥ 5 at 06:00–09:00 UT and 09:00–12:00 UT	1.13 (1.00–1.28)	0.051	1.14 (1.02–1.28)	0.023
	X ≥ 9 lag 0–1 **	1.39 (1.02–1.89)	0.040	1.32 (0.99–1.77)	0.060
V	Ap = 0	1.36 (1.03–1.81)	0.033	1.56 (1.23–1.98)	<0.001
	Kp ≥ 5 at 06:00–09:00 UT and 09:00–12:00 UT	1.13 (1.00–1.28)	0.058	1.14 (1.02–1.28)	0.025
	X ≥ 9 lag 0–1 ** and Ap ≥ 30 lag 1–2	1.76 (1.18–2.62)	0.006	1.60 (1.09–2.35)	0.015

\diamond adjusted for month, the day of the week, and weather variables; * additionally adjusted for low GMA (Ap = 0); ** the days of ≥X9 class solar flare or the day after if this flare occurred in the afternoon.

The results of the analysis for the period of 1995–2010 showed a possible stronger effect of GS occurring in conjunction with a negative B_z or HSSW (Figure 2). No statistically significant effect of all GS ($A_p \geq 30$) on the risk of ICH or of moderate+ GS occurring at 06:00–09:00 h on the risk of IS was observed. However, if these GSs occurred in conjunction with HSSW, the risks increased by over 19% and were significant (Figure 2).

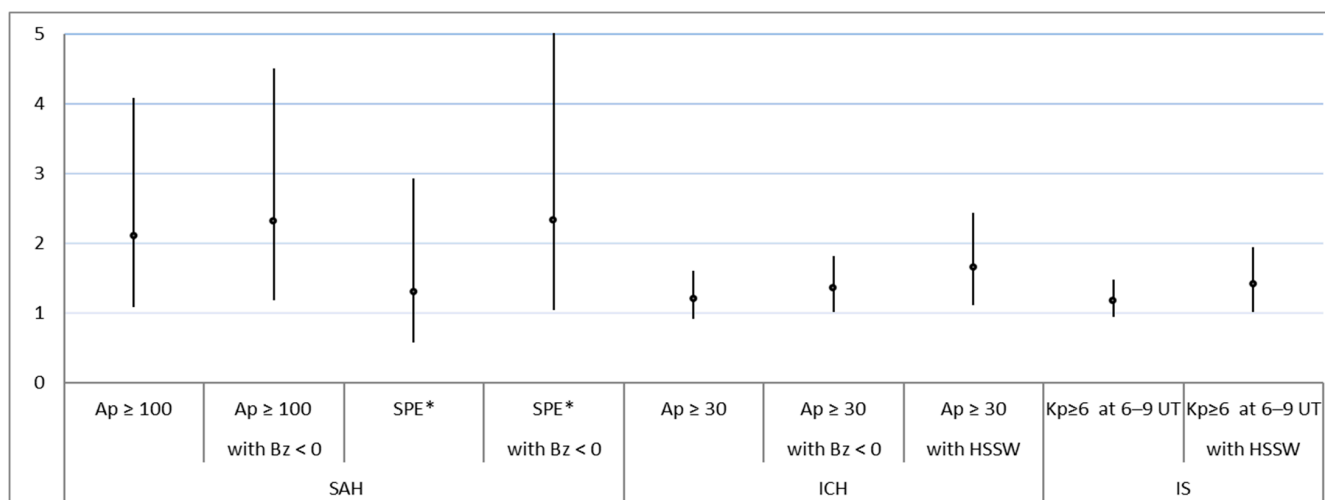


Figure 2. Associations between stroke occurrence and space weather variables in a time-stratified multivariate model since 1995 (RR adjusted for month, the day of the week, air temperature, change in atmospheric pressure, relative humidity, and low GMA). * days of the maximum of strong/severe SPE.

4. Discussion

In this 25-year study of 597 patients with SAH, 1147 patients with ICH, and 7482 patients with IS, we found that both very low GMA and stronger GS were associated with the risk of some types of stroke. For the first time, we detected the possible effect of strong/severe SPEs on the risk of HS and the effect of $>X9.0$ intensity SF on the risk of IS. These possible effects were detected by using time- and season-stratified models, adjusting for weather variables. In the study, we analyzed the possible effect of GS defined by daily A_p and 3-h Kp indices. For the first time, we detected the possible effect of GS depending on the time of the day.

Our data showed that strong/severe GSs were associated with an increased risk for SAH and HS, but not for IS or all strokes. The study of Feigin et al. [22] based on the data from several large population-based stroke incidence studies found that moderate+ GS were associated with an increase in the risk of SAH, ICH, and IS in patients aged 16–64 years. We found only the effect of moderate+ GS occurring at 6–9 UT upon IS and all strokes. These discrepancies may be explained by the difference in solar-GMA activity during study periods. In our study, 44.3% of the days fell in the minimum-ascending phase of the 11-year solar cycle (SC), 18.7%—in the SC maximum, 37%—in the period of SC descending phase, and 8.1% of the days were regarded as GS ($A_p \geq 30$). In the study of [22], these proportions were, respectively, 33.3%, 22.8%, 43.9%, and 10.4%. GSs peak in the solar maxima and the descending phase and these periods are characterized by higher rates of HSSW, ICMEs, and SPEs [38]. It is possible that a stronger effect of moderate+ GS in the study by [22] was due the strongest solar-GMA period. The analysis of the effects of GS in separate studies showed a stronger effect of GS in the studies performed during the period of an SC maximum, for example in Auckland [22]. Other studies showed positive associations between GMA and stroke. A positive association was found between monthly A_p and the number of deaths from stroke in patients aged <65 years [39].

We found an increase in RR for ICH, HS, IS, and all strokes during days of very low GMA ($A_p = 0$). Low GMA was also associated with some increase in electrical heart

instability, the number of ventricular and supraventricular extrasystoles, and a higher rate of ventricular tachycardia [11]. The effect of both very low and high GMA may be explained by their effects on some important factors in stroke pathogenesis. A rise in coagulation and blood pressure was observed during a high GMA, whereas a low GMA provoked more atrial fibrillation [39].

A trend was observed for an increased risk of stroke with increasing severity in GSs [22]. We found a stronger possible effect of GS occurring in conjunction with a negative B_z or with HSSW. According to the data since 1995, the effect of strong/severe SPE with $B_z < 0$ increased the RR for SAH. Minor+ GS with $B_z < 0$ or HSSW increased the RR for ICH.

We assessed the possible effects of GS defined by using the daily Ap and the 3-h Kp. Strong+ GS were associated with a higher RR for SAH and HS. According to the data of our study, the effect of GS defined by using the 3-h Kp index, depended on the time of the GS occurrence. A higher RR for SAH and IS was fixed on days of GS that occurred at 6–9 UT, while a higher RR for ICH was fixed on days of GS that occurred at 18–21 UT. We found an increase in RRs for all strokes on days of minor+ GS occurring both at 6–9 and 9–12 UT. GS is associated with an intensification of the sympathetic nervous system [3] and it is possible that GS occurring in the morning until before noon, when the sympathetic activity was elevated, had a stronger effect on the risk of the occurrence of IS and all strokes.

Apart from the possible effects of GS, other most powerful solar disturbances such as X-class SF and SPEs were also associated with the risk of stroke. We found a possible effect of SF with intensity $>X9.0$ on an increase in the RR for IS and all strokes. The possible effect of SF with intensity $>X9.0$ with a lag of 0–1 day was stronger if these days coincided with the days regarded as 1–2 days after GS defined as $Ap \geq 30$. Strong/severe SPEs were associated with a higher RR for HS and ICH; this effect for HS was observed after adjusting for the effect of very low GMA and strong/severe GS. The possible effect of stronger SPEs on stroke was observed by other authors as well. The study by [40] showed a significant positive correlation between the monthly space proton flux >90 MeV and mortality from stroke in patients aged 25–64 years.

The possible effect of stronger SPEs on the risk of HS may be explained by their effect on the ionosphere and on the weather pattern. It has been shown that stronger SPEs ionizes the atmosphere down to 20 km [41]. During the colder period, the onset of SPEs with energy > 90 MeV was accompanied by a distinct pressure change and an increase in atmospheric vorticity in the Baltic region [42]. The results of a meta-analysis have shown that a daily change in air temperature had a significant effect on stroke [43]. Studies conducted predominantly in Europe have shown an increase in the incidence of ICH or SAH associated with AP changes [44–47]. These results showed that the risk of stroke, especially for HS, was associated with changing weather. It is possible that stronger SPEs are the reason for rapid weather changes. The SPEs affect the ionosphere by increasing electron density in the D region of the ionosphere, and the altitude of the D region depends on particle energy. A significant correlation between some ionospheric parameters and emergency admissions due to stroke [11] and the number of deaths from brain stroke [28] was found.

One of the possible mechanisms to explain the influence of GMA, X-class SF, and SPEs on human health is the Schumann resonance [48]. Schumann resonances (SR) are resonant electromagnetic waves in the cavity between the Earth and the ionosphere. The alpha waves during human brain activity (8–13 Hz) lie in the same frequency range as the first two modes of SR (on average, 7.8 and 14.2 Hz). It was established that changes in the SR parameter were associated with stronger SPEs and SF: during the high-energy SPE, the first and the second Schumann resonance modes decreased, and the first-mode damping increased; the solar X-ray burst preceding proton precipitation was accompanied by an increase in the first-mode frequency [49].

The strengths of the present study are the large number of the included patients with various types and subtypes of stroke, the long study period, and standardized methods and criteria used for the stroke register. In this study, the analyses were performed by using

time- and season-stratified models, and therefore the effects of long-term trends arose due to the change in the volume of the population, the prevention of the stroke, and changes in lifestyle. In our study, the potential associations between stronger SPEs, X-class SF, GS occurring at different times of the day and the risk of stroke were found for the first time.

The limitation is that other potential confounders such as air pollution, influenza epidemics or other respiratory infections were not directly considered in this study. We did not have air pollution data for the entire study period, but the additional inclusion of the daily concentrations of PM₁₀, NO₂, or O₃ did not change the association between the risk of stroke and GS, SPEs, or SF. We did not evaluate other comorbidities and other risk factors such as atrial fibrillation, diabetes, dyslipidaemia, or renal or malignant diseases, which may also be associated with a higher risk of ischemic and hemorrhagic stroke. Harmful lifestyle factors such as alcohol consumption or smoking, which increase the risk of hemorrhagic stroke, cannot be ruled out either.

5. Conclusions

The days of severe GS ($A_p \geq 100$) were associated with a more than two-fold increase in the risk of SAH and HS ($p < 0.01$), and strong/severe GS were associated with a 58% increase in the risk of SAH occurrence and with a 30% increase in the risk of HS occurrence. Low GMA was associated with an increase in RRs by more than two times for ICH and HS and by more than 1.36 times for IS. The analysis of the possible effects of GS occurring at different times of the day showed that these effects were stronger if GS occurred during the period of 6:00–9:00 UT: only GSs occurring during this time were linked to a higher rate of IS and all strokes. GS occurring at 6:00–18:00 UT had a stronger effect on SAH. The risk of the HS occurrence was by more than two times higher on the day after of the maximum of strong/severe SPE. The days of $\geq X9$ class solar flare—or the day after, if this flare occurred in the afternoon—were associated with a 39% increase in the risk of IS, adjusting for the GMA level. If these days were 1–2 days after the day of GS, the risk of IS increased by 76%, and the risk of any types of stroke increased by 60%. The obtained results were found in time- and season- stratified models adjusting for the day of the week and weather variables.

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