Association Between Stroke Occurrence And Changes In Atmospheric Circulation

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Abstract

Background: The impact of weather on morbidity from stroke was analysed in previous studies. As the risk of stroke was mostly associated with changing weather, the changes in the daily number of strokes may be associated with global changes in atmospheric circulation. The aim of our study was to detect and evaluate the association between daily numbers of ischaemic stroke (IS) and haemorrhagic stroke (HS) and the teleconnection pattern.

Methods: The study was conducted in Kaunas city, Lithuania, from 2000 to 2010. The daily numbers of IS, subarachnoid haemorrhages (SAH), and intracerebral haemorrhages (ICH) were obtained from Kaunas Stroke Register. We evaluated the association between these types of stroke and the teleconnection pattern by applying Poisson regression, adjusting for the linear trend, month, and other weather variables.

Results: During the study period, we analysed 4,038 cases (2,226 men and 1,812 women) of stroke. Of these, 3,245 (80.4%) cases were IS, 533 (13.2%) cases were ICH, and 260 (6.4%) cases were SAH. A change in mean daily atmospheric pressure of >3.9 hPa was associated with the risk of SAH (RR=1.49, 95% CI 1.14-1.96), and a stronger El Niño event had a protective effect against SAH (RR=0.34, 95% CI 0.16-0.69). The risk of HS was positively associated with East Atlantic/West Russia indices (RR=1.13, 95% CI 1.04-1.23). The risk of IS was negatively associated with Arctic Oscillation indices (RR=0.97, 95% CI 0.94-0.99). During November-March, a positive North Atlantic Oscillation (NAO) was associated with HS (RR=1.29, 95% CI 1.03-1.62), and a negative association between the NAO index and IS (RR=0.92, 95% CI 0.85-0.99) was found.

Conclusions: The results of our study provided new evidence that the North Atlantic Oscillation, Arctic Oscillation, East Atlantic/West Russia, and El Niño-Southern Oscillation pattern may affect the risk of stroke. The impact of these teleconnection indices is not identical for different types of stroke. Emergency services should be aware of the fact that specific weather conditions are more likely to prompt calls for more severe strokes.

Background

During the recent decade, many studies have focused on the impact of weather on the morbidity from stroke, and several meta-analyses or reviews were carried out [1-5]. Air temperature (T) and atmospheric pressure (AP) are among the most closely studied weather variables; increases, decreases, and fluctuations in both have been significantly linked to numerous stroke subtypes. A statistically significant negative association has been observed between T and the incidence of ischaemic stroke (IS) [6-8], haemorrhagic stroke (HS) [9,10], intracerebral haemorrhage [11-14], and subarachnoid haemorrhage [15-17]. The results of a meta-analysis [4] have also shown a negative association between daily T and all stroke subtypes. The associations between stroke incidence and T were stronger in Europe and were non-significant in North America [4]. The daily T changes have also been associated with the risk of stroke.

The results of a meta-analysis have shown that a daily increase in T was a protective factor against HS, and an increase as well as a decrease in daily T acted as a risk factor for IS [1].

Studies have shown both a negative association [1,12,18] and a positive association [14,15,19] between the risk of stroke and AP. Studies conducted predominantly in Europe have shown an increase in the incidence of stroke associated with AP changes, adjusting for T or seasonality [19-22]. According to the study conducted in Germany, rapid decreases in ambient temperature and rapid changes in relative humidity and AP increase the risk of IS under temperate climate conditions [23]. These results showed that the risk of stroke was associated with changing weather. It is possible that the risk of stroke was associated with some patterns of atmospheric variability.

The changes in atmospheric circulation are regulated through teleconnections – large-scale patterns of pressure and circulation anomalies that cover vast geographic areas. These patterns reflect large-scale changes in the atmospheric waves and influence T, rainfall, storm tract, and jet streams [24]. The most important teleconnection pattern in the Atlantic-European region is the North Atlantic Oscillation (NAO), characterised as a dipole in the sea-level pressure between the Azores high and Icelandic low [25]. Other teleconnections such as Arctic oscillation (AO), Scandinavian pattern (SCA), and East Atlantic/West Russia pattern (EA/WR) also determine weather variability in the Northern hemisphere [26-27]. Several studies have also suggested a consistent and statistically significant impact of the El Niño-Southern Oscillation (ENSO) over the North Atlantic and Europe [28].

The NAO is the most prominent and recurrent pattern of atmospheric variability over the middle and high latitudes of the Northern Hemisphere, especially during the cold season months (November-March) [25]. During winter, in Northern Europe, the positive NAO phase was associated with a stronger westerly wind flow, a higher T, and increased storminess and precipitation, whereas the negative NAO phase lead to a weakened westerly wind, a lower temperature, and decreased storminess and precipitation [25]. Apart from NAO, other teleconnections such as AO, SCA, EA/WR, and ENSO also determine climate variability in the Northern hemisphere and regulate the frequency and intensity of significant weather events [29,30,31,32,33].

As the risk of stroke has been associated mostly with changing weather, it is probable that the changes in the daily number of strokes are associated with global changes in atmospheric circulation. The teleconnections affecting the variability in atmospheric circulation in the Baltic region are likely to determine certain weather pattern or event that are potentially associated with the risk of stroke. The aim of the study was to detect the complex association between the daily numbers of IS and HS in patients aged 25-64 years and teleconnection indices – daily NAO, AO, and ENSO indices and monthly indices of EA/WR and SCA, adjusting for weather variables. In the authors' previous study [34], the impact of T, AP, relative humidity (RH), and wind speed (WS) on the risk of stroke was evaluated. As over the middle and high latitudes of the Northern Hemisphere the most prominent and recurrent pattern of atmospheric variability is the NAO especially during the cold season months [25] – we assessed the associations between NAO indices and the risk of strokes separately during November-March and April-October.

Methods

Patients

Data on stroke patients were obtained from the Kaunas population-based Stroke Register database. The registration of stroke cases among middle-aged (25-64 years old) Kaunas residents has been carried out since 1986 to the present day. Data collected for the period of 2000-2010 were used in this study. Stroke registration was conducted according to the WHO MONICA project protocol and established quality control procedures, and was described in detail elsewhere [35, 36]. Multiple sources of information (hospital discharge records, records of outpatient departments, necropsy, medico-legal records, and death certificates) for the stroke event register were used. According to the study protocol, every stroke event 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 considered as a single event. All patients suspected of having died from stroke or having had a non-fatal acute stroke was registered. The codes for the specific types of stroke were confirmed by specific diagnostic examinations. For subarachnoid haemorrhage (SAH) (ICD-10 codes I60.0-I60.9), necropsy (for fatal events), brain computer tomography (CT), or cerebrospinal fluid containing blood was required to determinate the diagnosis; for intracerebral haemorrhage (ICH) (ICD-10 codes I61.0-I61.9), the diagnosis had to be confirmed by CT or by necropsy. IS (ICD-10 codes I63.0-I63.9) was diagnosed when CT and/or autopsy could verify the infarction and/or exclude haemorrhage and non-vascular disease.

Environmental variables

Based on the results of other authors, the weather variables linked to the cardiovascular health were used as predictors in the regression model for stroke. In this case, teleconnections associated with changes in weather pattern of the Baltic region were chosen as predictors. The environmental variables used in our study are routinely collected in certain publicly available databases.The values of daily NAO and AO indices (NAOI and AOI) and the monthly EA/WR and SCA indices (EA/WRI and SCAI) were obtained from the database of National Oceanic and Atmospheric Administration (NOAA) (https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml). We included the daily NINO3.4 index (Equatorial Pacific Sea Surface Temperature), which indicates the effect of ENSO. NINO3.4 indices were taken from the NOAA database (https://climexp.knmi.nl/data/inino34_weekly.dat). Data of mean daily T (ºC), AP (hPa), RH (%), cloud cover (CC) (okta), and WS (m/s) for the studied period were obtained from the Lithuanian Hydrometeorological Service Kaunas Meteorological Station located in the suburb of Kaunas city.

Statistical analysis

The independency in the daily number of SAH, ICH, and IS was tested by calculating the autocorrelation function. As no significant autocorrelations was detected, the associations between teleconnection indices and the daily number of IS, SAH, and ICH were evaluated by applying multivariate Poisson regression. First, we assessed the univariate associations between the risk of all types of stroke and

weather variables, teleconnection indices, and daily changes (Δ) of T, AP, RH, and WS. As the non-linear and U-shape associations between weather variables and the risk of acute events were found, the weather variables were used as continuous variables or were categorised. The thresholds of categorical variables were detected by using the classification and regression tree (CRT) method [37]. Apart from this, we analysed the risk of strokes in the tertiles of environmental variables. The weather variables were included one by one in the regression model with predictors: the linear trend, T, and the day of the week and the month (the day of the week and the month were used as categorical variables). In the analysis, we used the environmental variables on the day of the stroke and on previous 1–2 days (with a lag of 0, 1, and 2 days, respectively). The choose of the weather variable (categorical or continuous) and optimal lag was selected using the Akaike information criterion. Second, we analysed the impact of teleconnection indices by including the corresponding variables in the multivariate regression model with the linear trend, month, the day of the week, T, and other significant weather variables. In the analysis, we used teleconnection indices as continuous and categorised by the tertiles and by using the CRT method. The optimal models were created using the Akaike information criterion. We checked the autocorrelations of the residuals using partial autocorrelation functions for the created model. Third, we analysed the impact of NAOI on the risk of strokes separately for November-March and April-October. To assess the impact of environmental variables, we presented adjusted rate ratios (RRs) in the multivariate Poisson regression model. Statistical analysis was performed using SPSS 20 software.

Results

During the study period, we analysed 4,038 cases with stroke (2,226 (55.1%) men and 1,812 (44.9%) women). Of these, 3,245 (80.4%) cases were IS, 533 (13.2%) cases – ICH, and 260 (6.4%) cases – SAH. The analysis of demographic characteristics showed that all types stroke were more prevalent in the older age group (55-64 years). Two thirds of all IS were occurred in the age group of 55-64 years. Both ICH and IS had a higher prevalence among men. The distribution of strokes by sex, age, and stroke types is presented in Table 1.

Table 1. Distribution of strokes by sex, age and stroke types

Sex/age groups	Total	SAH	ICH	HS (SAH+ICH)	IS
All, n (%)	4038 (100.0)	260 (6.4)	533 (13.2)	793 (19.6)	3245 (80.4)
Men, n (%)	2226 (55.1)	118 (5.3)	306 (13.7)	424 (19.0)	1802 (81.0)
Women, n (%)	1812 (44.9)	142 (7.9)	227 (12.5)	369 (20.4)	1443 (79.6)
25-54, n (%)	1521 (37.7)	164 (10.8)	224 (14.7)	388 (25.5)	1133 (74.5)
55-64, n (%)	2517 (62.3)	96 (3.8)	309 (12.3)	405 (16.1)	2112 (83.9)

SAH - subarachnoid haemorrhage, ICH - intracerebral haemorrhage, HS - haemorrhage stroke, IS - ischemic stroke

Over the study period, the mean daily temperature was 7.5°C, the daily change in air temperature ranging from -14.1 to 17.7 °C. Mean daily atmospheric pressure was 1015 hPa, the daily change in atmospheric pressure ranging from -36.8 to 32.9. All descriptive characteristics of environmental variables are presented in Table 2.

Table 2. The descriptive characteristics of weather variables

Variable	Mean (SD)	Minimum	Percentiles			Maximum
			25th	50th	75th	
Air temperature, °C	7.5 (8.9)	-2.52	1.0	7.8	14.8	26.6
Daily change in air temperature	0 (2.4)	-14.1	-1.4	0	1.4	17.7
Atmospheric pressure, hPa	1015 (9.6)	976	1009	1015	1021	1050
Daily change in atmospheric pressure	0 (6.0)	-36.8	-3.4	0	3.5	32.9
Relative humidity, %	80.4 (12)	37	73	82	89	100
Daily change in relative humidity	0 (7.8)	-34	-5	0	4	39
Wind speed, m/s	5.3 (2.0)	1	4	5	6	15
Cloud cover, okta	3.5 (1.6)	0.3	2.4	3.3	4.5	11.5
AO index	-0.12 (1.5)	-5.80	-0.95	-0.06	0.79	4.70
NAO index	-0.06 (0.8)	-3.25	-0.58	-0.02	0.51	2.39
NINO3.4 index	-0.07 (0.8)	-2.20	-0.60	0.00	0.50	1.90
EA/WR indices	-0.17 (0.9)	-2.05	-0.85	-0.25	0.46	1.79
SCA indices	0.06 (0.9)	-2.33	-0.53	0.00	0.68	2.11

AO - Arctic Oscillation, EA/WR - East Atlantic/West Russia, NAO - North Atlantic Oscillation, NINO3.4 - Equatorial Pacific Sea Surface Temperature, Scandinavian pattern (SCA)

In the multivariate Poisson regression model, a change in daily AP of >3.9 hPa from the previous day, RH >96.5% on the previous day, CC >3.95, and NINO3.4≤1.14 were statistically significantly associated with

an increased rate ratio of SAH (Table 3). In other words, a stronger El Niño (NINO3.4>1.14) had a protective impact on SAH (RR=0.34, 95% CI 0.16-0.69). A dose-response association between NINO3.4 and SAH was found. 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%, CC >1.35 on the previous day, and EA/WRI were associated with an increased RR of ICH. The rate ratio of HS was associated with daily increases in AP and CC >3.95, and was positively associated with the EA/WR index. In addition, a dose-response association between NINO3.4 and EA/WRI and ICH was detected. The RR of IS was positively associated with an increase in daily T over 2.2 °C as compared with the previous day, RH over 53.5% with a lag of 1 day, a strong positive SCAI, NINO3.4<-1.60, and a strongly negative EA/WR (EA/WRI<-1.81). Apart from this, the risk of IS was negatively associated with AOI (dose-response association was detected) in the model without other teleconnections but was statistically non-significant in the multivariate model (p=0.053) (Table 3).

Table 3. Associations* of environmental variables with different types of stroke.

Variable	Lag	RR	95% CI	p	RR	95% CI	p
			Univariate association			Multivariate model	
SAH							
ΔAP (per 10 hPa)	0	1.20	0.98-1.47	0.082			
ΔAP >3.9 hPa	0	1.48	1.12-1.94	0.005	1.49	1.14-1.96	0.004
RH >96.5%	1	1.93	1.14-3.28	0.015	2.05	1.21-3.50	0.008
CC >3.95	0	1.36	1.05-1.76	0.022	1.42	1.09-1.84	0.008
NINO3.4	0	0.87	0.75-1.01	0.065			
NINO3.4>1.14	0	0.32	0.16-0.67	0.002	0.34	0.16-0.69	0.003
ICH							
ΔT >2.6 °C	0	1.27	0.98-1.63	0.071			
ΔAP >9.55 hPa	1	1.48	1.08-2.02	0.014	1.51	1.10-2.06	0.010
RH >66.5%	1	1.39	1.00-1.93	0.051			
ΔRH <7.5%	0	1.39	1.06-1.83	0.017	1.42	1.08-1.87	0.013
CC >1.35	1	2.17	1.16-4.06	0.016	2.17	1.16-4.07	0.016
EA/WRI	0	1.16	1.05-1.30	0.005	1.16	1.04-1.29	0.006
NINO3.4>0.11	0	1.23	1.04-1.46	0.017			
HS							
ΔAP >3.9 hPa	0	1.27	1.08-1.49	0.003	1.25	1.06-1.46	0.008
ΔAP >9.55 hPa	1	1.40	1.07-1.82	0.013	1.36	1.04-1.77	0.023
ΔRH <7.5%	0	1.32	1.06-1.64	0.015	1.28	1.03-1.46	0.028
CC >3.95	0	1.20	1.03-1.39	0.017	1.21	1.04-1.41	0.012
EA/WRI	0	1.13	1.04-1.23	0.006	1.13	1.04-1.23	0.006
IS							
ΔT >2.2 °C	0	1.13	1.03-1.25	0.009	1.12	1.01-1.23	0.024
RH >53.5%	1	1.46	1.12-1.90	0.005	1.41	1.09-1.84	0.010
AOI (per 1)	0	0.97	0.94-0.99	0.008	0.98	0.95-1.00	0.053
AOI (per 1)	1	0.97	0.95-1.00	0.034			
AOI (per 1)	2	0.98	0.96-1.00	0.092			
SCAI	0	1.04	1.00-1.08	0.089			
SCAI>0.25	0	1.12	1.04-1.21	0.002	1.10	1.02-1.18	0.015
NINO3.4<-1.60	0	1.25	1.09-1.44	0.002	1.24	1.08-1.43	0.003
EA/WRI<-1.81	0	1.73	1.41-2.12	<0.001	1.59	1.29-1.96	<0.001

* adjusting for the linear trend, the month, the day of the week, and air temperature.
ΔAP = (mean daily AP on the same day) – (mean daily AP on the previous day).

The effect of EA/WR on the risk of HS was similar in men and women. However, the effects of teleconnection variables on the risk of IS were stronger in women.

No significant associations between the NAOI and the rate ratio of strokes were found throughout the period of the study. The analysis of the RRs of strokes in NAOI quartiles, (adjusting for the month, air temperature, and other environmental variables included in the multivariate model (Table 3)) during the

period of November-March and April-October showed some impact of NAOI on the risk of stroke (Figure 1). During November-March, a positive NAO was associated with the RR of HS, and a negative association between NAOI and the RR of IS was found. During April-October, only NAOI <-0.5 was associated with the RR of HS (Table 4). Moreover, during the colder period, the effect of the NAOI on the risk of IS was stronger than that of the AOI. The ENSO variable negatively correlated with the risk of SAH during November-March and with the risk of IS during April-October (Table 4).

Table 4. Associations* of the NAOI with different types of stroke during November-March and April-October.

Variable	Lag	RR (95% CI)	P	RR (95% CI)	P
		November-March		April-October	
SAH NINO3.4	0	0.74 (0.61-0.90)	0.002	1.15 (0.89-1.49)	0.282
NAOI >-0.92	0	2.48 (0.98-56.28)	0.055	0.95 (0.61-1.48)	0.809
ICH EA/WRI	0	1.25 (1.05-1.48)	0.013	1.09 (0.95-1.25)	0.209
0<NAOI <0.5	0	1.43 (1.08-1.90)	0.012		
NAOI<-0.5	0			1.25 (0.98-1.59)	0.078
HS EA/WRI	0	1.14 (0.99-1.32)	0.064	1.10 (0.99-1.23)	0.089
NAOI >0	0	1.29 (1.03-1.62)	0.030		
NAOI <-0.5	0			1.25 (1.02-1.53)	0.028
IS (1) SCAI>0.25	0	1.08 (0.96-1.21)	0.189	1.12 (1.02-1.24)	0.024
NINO3.4<-1.60	0			1.54 (1.19-2.00)	0.001
EA/WRI<-1.81	0	1.92 (1.34-2.75)	<0.001	1.58 (1.22-2.04)	0.001
NAOI (per 1)	0	0.92 (0.85-0.99)	0.028	1.04 (0.98-1.11)	0.166
IS (2) SCAI>0.25	0	1.07 (0.96-1.21)	0.221	1.12 (1.01-1.24)	0.027
NINO3.4<-1.60	0			1.55 (1.19-2.01)	0.001
EA/WRI<-1.81	0	2.00 (1.40-2.87)	<0.001	1.59 (1.23-2.05)	<0.001
NAOI <0.5	0	1.25 (1.10-1.41)	0.001	0.91 (0.81-1.02)	0.097

* adjusting for the linear trend, the month, the day of the week, and T, RH, and CC variables

Discussion

In this 11-year study of 260 patients with SAH, 533 patients with ICH, and 3,245 patients with IS, we found that some patterns of RH and CC and daily changes in AP and RH were associated with the risk of some types of stroke. In addition, we used NAO, AO, EA/WR, SCA, and ENSO indices as predictors for the

evaluation the risk of stroke. For the first time, we detected a protective effect of warmer ENSO (a stronger El Niño) on the risk of SAH, a positive association between the risk of HS and the EA/WR, a negative association between the rate ratio of IS and the AOI, and a negative impact of a strong positive SCA on the risk of IS. Apart from this, during November-March, a higher risk of HS was related to a positive NAO, and a negative association between the risk of IS and NAOI was found. In the analysis, an impact of teleconnection indices was detected, adjusting for seasonal variation, T, and other weather variables.

In our study, the risk of HS was associated with daily change in AP above the threshold of 3.9 hPa for SAH and 9.55 hPa for ICH. These results are in line with those obtained by other authors who found a significant association between SAH and ICH and changing AP. The daily change in AP with a lag of 1 day positively correlated with daily number of SAH in the English Midlands [19], and the daily change in AP >10 hPa was association with the risk of SAH in the UK [38] and in Germany [20].

To our knowledge, the risk of SAH was associated with a higher RH and CC level, and the risk of ICH – with a higher CC level on the previous day and with a lower daily RH change. Some authors found a significant association between stroke and RH and daily hours of sunshine, which is the opposite variable to cloud cover. A decrease in daily sunlight hours was positively associated with the risk of SAH [17,39]. A positive association between SAH and RH was found in area of humid subtropical zone [16] and in the Rhein Main area [20], while in the southern regions of France and in the area with various climatic condition (41 states of USA), a negative association between SAH and RH was observed [17, 39]. ICH negatively correlated with sunshine hours [40] and positively correlated with amount of precipitation [6], which coincident with our results.

We found a positive effect of a strong warm ENSO on human health. In our study, most of these events (NINO3.4>1.14) fell into colder months. Therefore, the protective effect of a warmer ENSO on SAH may be explained by the effect of ENSO on the weather pattern during autumn and winter. Studies have shown that the warm and the cold phase of ENSO have different impacts on the pattern of weather regimes during the colder season in Europe [33]. Strong El Niño events were related to a higher sea level pressure, a lower T, and dry air in the Baltic countries [41,33,42]. According to our data, during the second half of autumn, the period of NINO3.4>1.14 was characterised by a lower mean AP, a higher amount of precipitation and RH, and a very significantly lower diurnal temperature range (DTR) (by 1.3 °C, p<0.001). In winter, the period of NINO3.4>1.14 was characterised by a lower T, WS, and CC and a higher AP and DTR. These weather patterns may be associated with a lower risk of SAH. Some studies have shown that a higher DTR is significantly associated with higher mortality, and this effect was stronger during autumn [43,44]. Therefore, a lower DTR during autumn may have a positive effect on human health.

We found a positive association between the EA/WRI and HS and an increase in the risk of IS during a strong negative EA/WR phase. These effects were similar during both the colder and the warmer periods, and the additional inclusion of the NAOI in the model did not reduce the significance of the EA/WRI. In the studied region, in winter, the positive EA/WR produced cold advection from the north and was characterised by a lower air temperature, a lower precipitation level, and stronger atmospheric circulation

[45]. In the south-eastern region of Baltic Sea, the EA/WRI negatively correlated with air temperature in spring [46], with lake water temperature in spring-autumn [47], and with precipitation amount in summer [45]. According to our data, during the positive EA/WR phase, a higher mean WS and AP in winter and a lower mean T and a higher mean AP both in spring and summer were observed. Apart from this, a higher variation was found in the daily change of AP both in winter and spring. Thus, it can be said that a higher EA/WRI was related to a stronger variation in AP, colder air flow in winter, and colder air in other seasons. The complex of these weather patterns may be associated with a higher risk of HS.

For the first time, negative associations between IS and AO and between IS and NAO only during November-March were found. According to the results of studies by other authors, AO was associated not only with tropospheric, but also with stratospheric variability and changes in weather pattern in Lithuania and nearby regions [48,49]. During January-March, positive AO brings a higher surface T and a lower precipitation in middle-latitude regions [50]. In the region of the Baltic sea, a positive correlation between T and AO was observed during January-March [51], March-May [52], July and October [46], and September-March [53]. According to our data, the AOI positively correlated with T in all seasons excluding summer and negatively correlated with RH excluding winter. It is possible that this complex of weather patterns (a higher T and a lower RH during the equinox, a lower RH in summer, and warmer winters) related to days of a higher AOI had a protective effect against the risk of IS.

The SCAI positively correlated with T in summer and negatively correlated with T and positively correlated with AP over the region of the Baltic Sea in winter [26,31,46]; the same associations were found in our study. The positive phase of SCA indicates more likely anti-cyclonic conditions and a lower level of atmospheric circulation over the Baltic Sea region during autumn-spring [26], and the anticyclonic conditions over Scandinavia substantially suppress westerly zonal airflow in summer [54]. It is possible that cold outbreaks during the colder period and the atmospheric variations related to a stronger positive SCA are associated with the risk of IS.

During the colder period, the positive NAO had a protective effect against IS, but, vice versa, a negative NAO had a protective effect against HS. During wintertime, in the Baltic Sea region, a positive NAOI was associated with a higher T and with altered weather: a higher WS, a lower AP, and a north-eastward shift in the Atlantic storm activity with enhanced activity from Newfoundland into Northern Europe [25] As a positive NAO during the winter was associated with more changing weather, a positive NAO was risky for HS, whereas a change in T was more relevant for IS. Studies in Northern and Middle Europe have shown a higher risk of HS associated with changing weather but not with T [19,20,22,38]. A study conducted in the UK showed a significant impact of changes in T only on IS, whereas changes in AP had a significant impact only on the risk of HS [55].

According to literature, both positive and negative NAO phases are associated with worse health outcomes. [56] found a positive association between the daily AOI with a lag of 3 days and the incidence of and mortality from acute myocardial infarction in Northern Sweden. An inverse association between the climate index (which represents winters with a strong negative phase of the NAO) and the level of

mortality from ischemic heart disease were found in England [57]. In addition, a negative association between the NAO index and systolic and diastolic blood pressure during spring-autumn was found [58].

The pathophysiological mechanisms underlying the correlation between stroke and weather conditions have been discussed. Factors that increase the risk of stroke include high blood pressure, some diseases, and the lack of regular exercise. Blood pressure is influenced by cold, stress and physical activity [58]. Donkelaar et al. [22] hypothesized that AP changes trigger the inflammation process in the aneurysm wall. Variations in AP may influence on vessel walls and their endothelial function by endogenous inflammatory mechanisms [21]. Studies about thrombosis in air travels suggesting that prothrombin fragments and the thrombin-antithrombin complex are activated in hypobaric conditions [59,60] could be another clue to the underlying mechanism.

Studies on the associations between physical activity in the elderly and weather conditions in Europe showed that physical activity decreased with increasing WS, precipitation, humidity, and a shorter duration of sunshine [61,62]. These weather conditions are associated with a negative AO and NAO excluding winter months – therefore, it can be assumed that negative AOs are associated with fewer physical activity opportunities for the elderly, who are likely to be stressed. This can explain the fact a negative AO increased the risk of IS.

The present study has several **strengths**: the large number of included patients with various types and subtypes of stroke, the long study period, and standardised methods and criteria used for stroke register. In addition, it analyses daily stroke incidence data by stroke subtypes, daily meteorological data, the variation of these data with respect to the previous day, and uses the teleconnections such as NAO, AO, EA/WR, SCA, and ENSO. Moreover, the fact that the included patients come from a small geographical area (Kaunas city) contributes to the homogeneity of weather conditions. In our study, associations between atmospheric circulation patterns such as NAO, AO EA/WR, SCA, and ENSO 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. In our region infections are strongly related to the season with a highest prevalence during winter [63]. Despite the fact that in our study, the analyses were controlled for the month and T, residual confounding by short-term respiratory epidemics remains a possibility. Moreover, we did not consider weather-related physical activity that may have had an impact on individual exposure to outdoor T and humidity.

In our study, the influence of air pollution, which is a known trigger for cardiovascular diseases, has not been examined. We did not have air pollution data for the entire study period, but the additional inclusion of the daily concentrations of PM_{10}, NO_2, or O_3 did not change the association between the risk of strokes and teleconnection indices. Based on the results published by other authors [64], we can assume that the short-term effect of PM_{10}, NO_2, or O_3 on the risk of stroke was not significant enough to affect the results of our study. First, the level of air pollution in Kaunas is not high. Second, our stroke patients were

relatively young (<65 years of age), whereas in other studies presenting a positive association between air pollution and stroke (except for those performed in subtropics or in regions with high levels of pollutants), the mean age of the patients was over 70 years [68]. Third, we did not evaluate other comorbidities such as acute myocardial infarction, ischemic heart disease, arterial hypertension, heart failure or other risk factors such as atrial fibrillation, diabetes, dyslipidemia, or renal or malignant diseases, which may also be associated with a higher risk of ischemic and hemorrhagic stroke. Fourth, harmful lifestyle factors such as alcohol consumption or smoking, which increase the risk of haemorrhagic stroke, cannot be ruled out either.

Conclusion

A protective effect of a stronger El Niño on SAH was found. The risk of HS was associated with an increase in daily AP, a higher CC, and a higher EA/WR index. The risk of IS was negatively associated with the AO index, and a negative impact of a strong positive SCA on the risk of IS was found. During the colder period, a positive NAO had a protective effect against IS, but, vice versa, a negative NAO had a protective effect against HS. The results of our study provided new evidence that the NAO, AO, SCA, EA/WR, and ENSO pattern may affect the risk of stroke. The impact of these teleconnection indices on different types of stroke is not identical. As U-shaped or J-shaped relationship between daily changes in weather variables and stroke events were found, we recommend using the weather variables as categorical factors in the regression models. Emergency services should be aware that specific weather conditions are more likely to prompt calls for more severe strokes.

Abbreviations

IS: ischaemic stroke; SAH: subarachnoid haemorrhages; ICH: intracerebral haemorrhages; EA/WR: East Atlantic/ West Russia pattern; HS: haemorrhagic stroke AO: Arctic Oscillation; NAO: North Atlantic Oscillation; T: Temperature; AP: atmospheric pressure; SCA: Scandinavian pattern; ENSO: El Niño-Southern Oscillation; RH: relative humidity; WS: wind speed; WHO: World Health Organization; CT: computer tomography; AOI: Arctic Oscillation index; NAOI: North Atlantic Oscillation index; EA/WRI: West Russia index; SCAI: Scandinavian pattern index; CC: cloud cover; CRT: classification and regression tree.

Declarations

Acknowledgements

Authors' contributions

JV conceived the idea for this study, designed the analysis plan, perform a statistical analysis, and interpreted the data; RR conceived the idea for this study, designed the analysis plan, interpreted the data,

and drafted and revised the manuscript for important intellectual content; **AT** conceived the idea for this study, designed the analysis plan, and revised the manuscript for important intellectual content; **DR** conceived the idea for this study, interpreted the data, and revised the manuscript for important intellectual content; **DKB** and **VV** conducted the data analysis, interpreted the data, and drafted the manuscript. The authors had full access to the data and take responsibility for their integrity. All authors have read and agreed to the manuscript as written. The author(s) read and approved the final manuscript.

Availability of data and materials

Data can be made available from the corresponding author on reasonable request

Ethics approval and consent to participate

All patient data were analysed anonymously and de-identified prior to analysis. All methods were performed in accordance with the relevant guidelines (MONICA project) and regulations (Lithuanian Bioethics Committee). All of the patients who participated in the study signed their informed consent. The study protocol was approved by the Lithuanian Biomedical Research Ethics Committee No 14-27. We also state that study ethics comply with the Declaration of Helsinki.

Consent for publication

Not applicable.

Competing interests

The authors declared no conflict of interest.

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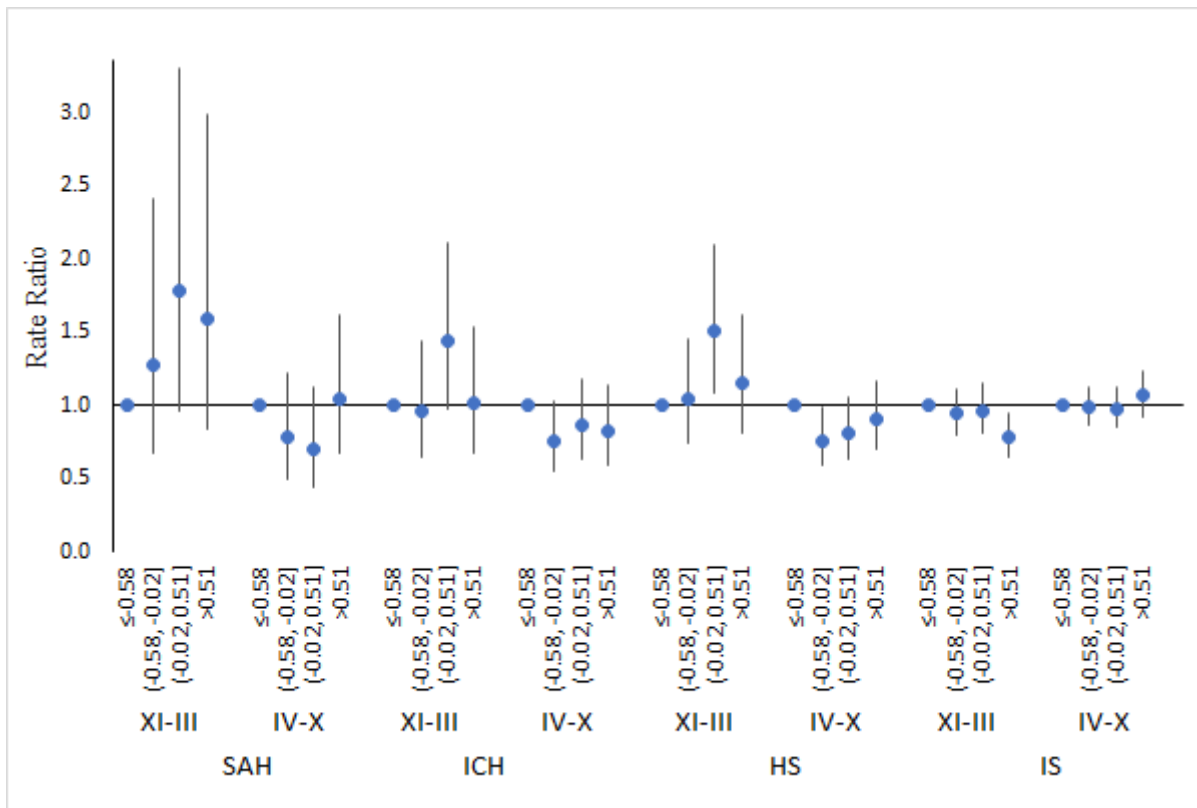
Figures

Figure 1

Rate ratios of strokes in the quartiles of the NAOI (reference category − NAOI<-0.58).