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Non-photic solar associations of heart rate variability and myocardial infarction ☆

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Abstract

Alignment of serial epidemiological, physiological, including electrocardiographic data with variations in galactic cosmic rays, geomagnetic activity, and atmospheric pressure suggests the possibility of links among these physical environmental variations and health risks, such as myocardial infarctions and ischemic strokes, among others. An increase in the incidence of myocardial infarction in association with magnetic storms, reported by several investigators from Russia, Israel, Italy and Mexico, accounts in Minnesota for a 5% (220 cases/year) increase in mortality during years of maximal solar activity by comparison with years of minimal solar activity. Magnetic storms are also found to decrease heart rate variability (HRV), indicating a possible mechanism since a reduced HRV is a prognostic factor for coronary artery disease and myocardial infarction. Longitudinal electrocardiographic monitoring for a week or much longer spans in different geographic locations, notably in the auroral oval, further suggests that the decrease in HRV affects spectral regions other than that around 3.6 s (0.15–0.40 Hz), reportedly associated with the parasympathetic nervous system. Differences in some associations are observed from solar cycle to solar cycle, and as a function of solar cycle stage, a finding resolving controversies. Coordinated physiological and physical monitoring, the scope of an international project on the Biosphere and the Cosmos, seeks reference values for a better understanding of environmental effects on human health and for testing the merit of space weather reports that could prompt countermeasures in space and on earth. Physiological data being collected systematically worldwide and morbidity/mortality statistics from causes such as myocardial infarction and stroke constitute invaluable data bases for assessing changes within the physiological range, for detecting environmental effects and for recognizing endogenous as well as exogenous disease-risk syndromes. Timely and timed intervention may then be instituted to lower risk, in preference to exclusive current focus on treating overt disease. These chronodiagnostics are particularly important for those venturing into regions away from hospitals, such as astronauts in space. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Disease-risk syndrome; Heart rate variability; Magnetic storm; Myocardial infarction; Stroke

1. Introduction

Half a century ago, chronobiologists (scientists concerned with time [chronos] structures in biology) debated whether rhythms, such as about-daily (circadian) and

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about-yearly (circannual) variations in organisms, were a mere response to environmental cycles, or whether they were endogenous. After much indirect evidence for the built-in nature of the circadian system as a critical evolutionary adaptation to changes in the proximate environment (Halberg, 1969), the identification of ubiquitous "clock genes" (Plautz et al., 1997) provides direct proof. It is also no longer disputed that environmental cycles can alter the characteristics of biological rhythms, changes in phase after a transmeridian flight being perhaps the best illustrative example. Historically, biometeorology deals statically, e.g., with temperature as a so-called biotropic factor. In nature, however, temperature effects may depend on the stage of rhythmic changes in temperature along the scale of minutes, hours, days, weeks, seasons and, we add, years, as we consider a human-made greenhouse effect. Furthermore, apart from any anthropogenic effect, the effect of external cyclic components depends upon internal ones, the latter with frequencies acquired in the course of evolution, in response not only to photic but also to non-photic cycles.

Variations with a period of about a week (circaseptan) are also ubiquitous. Apart from an obvious social influence, evidence for an endogenous basis of circaseptans is also provided by Halberg (1995). A biochemical basis for them has also been proposed (Ulmer et al., 1995). After a brief review of the literature on influences of non-photic solar–heliospheric activity and geomagnetic activity upon the cardiovascular system, we summarize some of our own results linking the about-weekly and half-weekly changes in heart rate (HR) with similar changes in geomagnetic activity. A similarity in periodic variations constituting hints at best, we then turn to our studies revealing associations between magnetic storms and myocardial infarction (MI), and their effects on heart rate variability (HRV), as a putative underlying mechanism. We conclude by describing our ongoing BIOsphere and the COSmos (BIOCOS) project, which aims at a systematic, coordinated physiological and physical monitoring in different locations, to map a broad time structure (chronome) exhibited by both organisms and their environment, and to gain a better understanding of environmental effects on human physiology and pathology. Resolving the chronomes in us and around us can help detect environmental threats, while recognizing endogenous as well as exogenous disease-risk syndromes. Timely and timed interventions may then be applied prophylactically to lower an elevated risk, in preference to exclusive focus on treating overt disease. Such procedures are particularly important for those venturing into regions away from hospitals, such as astronauts in space.

2. A review of earlier work

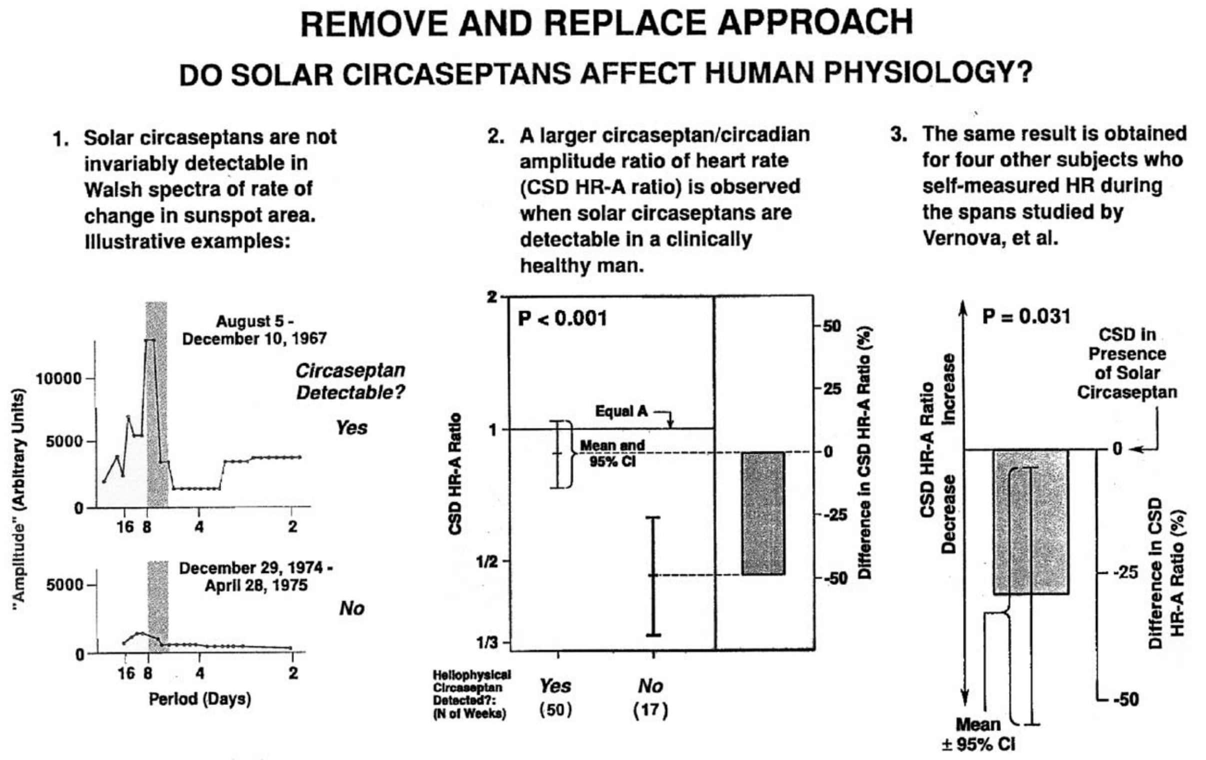
It has long been claimed, notably by Soviet scientists, that geomagnetic storms and other electromagnetic variations are associated with changes in the incidence of various diseases, MI and strokes in particular (for review see Halberg et al., 2000). Results of direct experiments are cited in which biological specimens are exposed to artificially induced electromagnetic oscillations in support of studies of correlation between geomagnetic activity and human morbidity and mortality (Gnevyshev and Novikova, 1972). Electromagnetic fields have been reported to affect blood pressure (Gmitrov and Gmitrova, 1994), baroreflex function (Gmitrov et al., 1995), and HRV (Bortkiewicz et al., 1996). Gurfinkel et al. (1995) report effects of geomagnetic disturbances on the capillary blood flow of patients with ischemic heart disease. Chibisov et al. (1995) further observe drastic changes in the circadian rhythm of various endpoints of the ultrastructure of cardiomyocytes of rabbits during geomagnetic storms.

Such effects upon the circulation may contribute to a correlation between heart attacks and magnetic activity, repeatedly affirmed (Stoupel, 1976; Malin and Srivastava, 1979; Otto et al., 1982; Stoupel et al., 1996; Halberg et al., 1991; Villoresi et al., 1994a,b; Persinger and Psych, 1995; Strestik and Sitar, 1996; Feigin et al., 1997) as well as disputed (Feinleib et al., 1975; Lipa et al., 1976; Rogot et al., 1976; Knox et al., 1979). Studies by Stoupel et al. (1996) suggest that the adverse effect of solar activity on the circulation, gauged by mortality from ischemic heart disease and stroke, may be particularly prevalent in the elderly, perhaps because of an increased susceptibility associated with old age. In his investigation of changes in the incidence of sudden cardiovascular death in the course of the synodic month, Sitar (1990) concludes that the distribution he observes cannot be attributed solely to gravitation (tides) and that the influence of solar corpuscular radiation is also involved, finding an increased cardiovascular mortality in association with an increased geomagnetic activity.

From the viewpoint of clinical cardiology, HRV has been used as a putative index of autonomic cardiovascular function (Ewing et al., 1984). A reduction in HRV has been reported to have prognostic value (Kleiger et al., 1987; Algra et al., 1993), a result supported by a 7.7-year follow-up of 1575 male participants in the Framingham study (Lauer et al., 1996). Sastre et al. (1998) reported reversible changes in HRV in humans exposed to 20 μT magnetic fields. The epidemiological study of Savitz et al. (1999) showed an association between occupational magnetic field exposure and death due to arrhythmia in acute MI, though not with chronic heart disease.

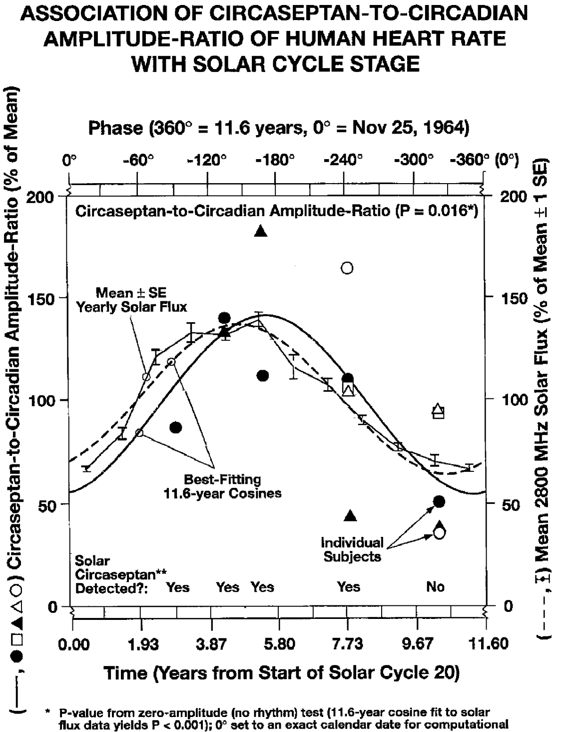
Surprisingly, several independent studies carried out by our group have found links between HR and geomagnetic activity, that all involve an about-weekly and/or half-weekly structure, that may relate, during some but not all time spans, to a sector structure of the interplanetary magnetic field (Wilcox and Ness, 1965). An approximately 6.75-day variation has been documented for the geomagnetic disturbance index, Kp, by Halberg et al. (1991), and validated for Kp by Roederer (1995) and for aa by Vladimirskii et al. (1995). It is thus possible that these variations constitute an environmental counterpart for the about 7-day (circaseptan) components documented for HR in data collected automatically around the clock at about 30-min intervals for several months in conditions of isolation from society (Halberg et al., 1991; Halberg, 1995). This proposition is supported by results from another similar study in which the HR of a 28-year-old, presumably healthy woman was monitored around the clock for about a year, bracketting a span of 267 days in isolation from society. In this study, the non-linearly resolved period of the detected about half-weekly component of HR (period = 81.2 h; 95% CI: 80.6–81.9 h) resembles that of Kp (period = 81.5 h; 95% CI: 80.9–82.1 h), both periods differing with statistical significance from exactly 84 h (3.5 days) (Cornélissen et al., 1999). Although the half week is far from being a major peak in the spectrum of Kp, it was of sufficient importance during the 267 days of the isolation study to be resolved with statistical significance by the non-linear least-squares fit of a model consisting of cosine curves with trial periods of 24 and 84 h. An association between the two variables is further supported by cross-spectral coherence analyses (Cornélissen et al., 1999). While these results stem from individual records, that do not allow generalization, their merit resides in the fact that the data were obtained automatically around the clock for several months in isolation from society.

Associations are also documented in studies on groups. In Moscow, Russia, results from 33 human newborns monitored at 20-min intervals for ~ 7–20 days during the first month of life reveal a cross-spectral coherence > 0.7 ($P < 0.05$) at periods of about 3.33 days and 8.77 h between HR and the local K index of geomagnetic activity, measured in Moscow for spans corresponding to the neonatal series. The circaseptan amplitude of neonatal HR also correlates with that of the local K index ($P = 0.012$) (Syutkina et al., 1997). These results suggest that the circaseptan structure usually prominent in early extrauterine life may be influenced by about-weekly variations in natural environmental factors. This observation is further corroborated by the fact that an about-weekly variation in human HR appears to be amplified during spans when velocity changes in solar wind are characterized by a detectable spectral peak around one cycle per 7 days. Such a peak in Walsh spectra had been identified in four of five spans in a study by



From Vernova, et al. (1983).

Fig. 1. Remove-and-replace approach. Do solar circaseptans affect human physiology? Decreases, for all (five) subjects investigated, of the normalized circaseptan amplitudes of HR during spans without vs. spans with circaseptan features in solar activity (middle and right), gauged by Walsh spectra (Vernova et al., 1983) of the rate of change in sunspot area (left). © Halberg.



* P-value from zero-amplitude (no rhythm) test (11.6-year cosine fit to solar flux data yields P < 0.001); 0° set to an exact calendar date for computational purpose only.

** Gauged by rate of change in sunspot area.

Key - Men: ● RS (28y); □ EH (48y); ▲ HL (59y); Women: △ EK (43y); ○ MH (81y)

Fig. 2. The circaseptan-to-circadian prominence in human HR follows an about-11-yr cycle similar to the solar activity cycle, as do the solar circaseptans (not shown). © Halberg.

Vernova et al. (1983). Examples of Walsh spectra are shown in Fig. 1 (left). HR had been self-measured longitudinally several times per day in some or all of these spans by five subjects, whose data were re-analyzed to assess the relative prominence of the about-weekly vs. the about-daily variation, as a ratio of amplitudes (the "circaseptan-to-circadian amplitude ratio"). The circaseptan changes in HR were found to be consistently (for all five subjects) weaker when no peak around one cycle per week was detected in the Walsh spectra of velocity changes in solar wind ($P = 0.031$) (Cornélissen et al., 1999). This is shown for one subject in Fig. 1 (middle) and as a summary of results from all the five subjects in Fig. 1 (right). The circaseptan-to-circadian amplitude ratio of human HR was further found to follow an about 10.5-year cycle similar to the solar activity cycle, Fig. 2, in keeping with the report that circaseptan features in solar activity are coupled with geomagnetic field variations and may be characterized by an amplitude that is modulated by the solar activity cycle (Ptitsyna et al., 1980). These results suggest that about 7-day cycles in human HR may still be amplified by solar circaseptans, and are in agreement with more prominent about-weekly variations in mortality from MI reported in Georgia during years of high vs. low solar activity (for review, see Cornélissen et al., 2000).

3. Associations between MIs and magnetic storms

The question whether geomagnetics represent health risks could be investigated in a data base of over 6.3 million cases requiring the call of an ambulance between January 1, 1979, and December 31, 1981, including 85,819 cases of MI. During this 3-year span, cross-spectral coherence was found for MI in association with both the geomagnetic disturbance index, Kp, and the north–south component (Bz) of the interplanetary magnetic field at the same frequency of one cycle in about 3.15 days (Halberg et al., 1991; Breus et al., 1995). Defining an "event" (thought at the time to relate to a magnetic storm or substorm) as a north-to-south daily mean of the Bz turn from $\geqslant 1$ nT to < -1.5 nT, 32 occurrences were identified. [A north-to-south Bz turn is known to trigger auroras in the earth's upper atmosphere and storms in the magnetosphere (Arnoldy, 1971). The stronger the Bz turn, the stronger the geomagnetic field disturbance, and the stronger the electric field and currents in the magnetosphere. When Bz abruptly turns from $Bz > 0$ to $Bz < 0$, the total current in the magnetosphere increases up to 10 times within 5–10 min. Concurrently, a drop in potential across the earth's polar cap increases from 10 to 100 kV.]

By superposed epochs, the incidence of MI was found to increase by 7.6% after a Bz turn ($P = 0.027$), followed, however, by a 5.9% decrease on the following day ($P = 0.029$). This result was consistent during all the three years when analyzed separately (Cornélissen et al., 1994). Using a different approach, Villoresi et al. (1994a) independently confirmed this result in the same data, also reporting an even larger effect for values of the geomagnetic disturbance index, $aa > 60$, and of Forbush decreases in cosmic ray intensity $> 1.5\%$, with additional evidence obtained from a different data base (Villoresi et al., 1994b).

These results, further corroborated by statistics in Israel, Lithuania, and Mexico (for review see Halberg et al., 2000), are not supported, however, by the thorough analyses by Feinleib et al. (1975) and Lipa et al. (1976) on another data base of over 2.75 million cases of mortality from coronary artery disease and over 1 million cases of mortality from stroke in the US in 1962–1966. These authors had compared the daily numbers of deaths from each cause with the corresponding geomagnetic Ap index using three different approaches:

(1) by computing the Pearson product–moment correlation coefficient between daily deaths and Ap with lags varying between -14 and $+14$ days;
(2) by constructing superposed epoch diagrams for deaths on days with Ap in selected ranges; and
(3) by plotting mortality vs. the magnetic index, globally and for individual metropolitan areas.

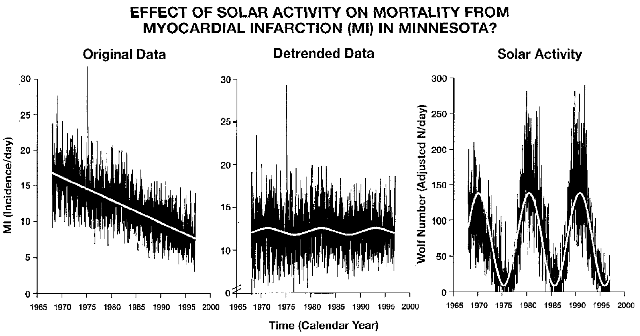


Fig. 3. Demonstration of about 10.5-yr cycle in mortality from myocardial infarction in Minnesota (1968–1996) after removal of decreasing linear trend, aligned with about 10.5-yr solar activity cycle. Fitted curves represent fundamental component as a first approximation that does not account for the asymmetry of the solar activity cycle considered in Fig. 4. © Halberg.

While concluding that the data did not support an association between solar activity and cardiovascular mortality (Feinleib et al., 1975; Lipa et al., 1976), Lipa et al. (1976) appropriately cautioned that it was necessary to determine whether any physiological–physical association is sensitive to geographical location, to the phase of the solar cycle, or to some other parameter which might distinguish the samples analyzed by them from those in which associations could be statistically validated. In their investigation of relationships between different parameters of the geomagnetic activity and daily numbers of MI in St. Petersburg, Russia, in 1989–1990, Villoresi et al. (1998) indicated the need to differentiate between morbidity and mortality data. The about 10.5 (±1.2)% increase in MI deaths during big geomagnetic storms (defined by the days of the descending phase of cosmic ray Forbush decreases) contrasts with the lack of an effect on the incidence of morbid events (Villoresi et al., 1998).

In a database of 129,205 deaths from MI recorded in Minnesota from 1968 to 1996, some of the questions posed by Lipa et al. (1976) could also be examined. After removal of a linearly decreasing trend (Fig. 3, left), an about 10.5-year component could be documented ($P < 0.001$), Fig. 3 (middle). In this figure, only the fundamental 10.5-year component is shown, while it is realized that the solar activity cycle (Fig. 3, right) is well known to be asymmetrical. In order to account more precisely for the actual waveform of the solar activity cycle, the yearly incidences of MI were further categorized by actual solar cycle stage: maximum, descending stage, minimum, and ascending stage, Fig. 4. An excess of 220 deaths per year can be seen during years of maximal vs. minimal solar activity ($P = 0.023$) (Cornélissen et al., 1999, 2000). Intra- and inter-solar cycle differences are found in mortality statistics from MI (Tables 1–3) and in longitudinal physiological data covering up to three solar cycles (Halberg et al., 2000). For the case of mortality from MI, analyzed separately for three solar cycles, statistically significant differences are found both in the average daily number of deaths and in the 10.5-year amplitude, that is in the prominence of the about 10.5-year cycle (Table 1). In the detrended data, the about 10.5-year component can be resolved by non-linear least squares during the first two solar cycles, as well as overall, but it is not validated during the years 1987–1996 (Table 2). Relying on dates of Forbush

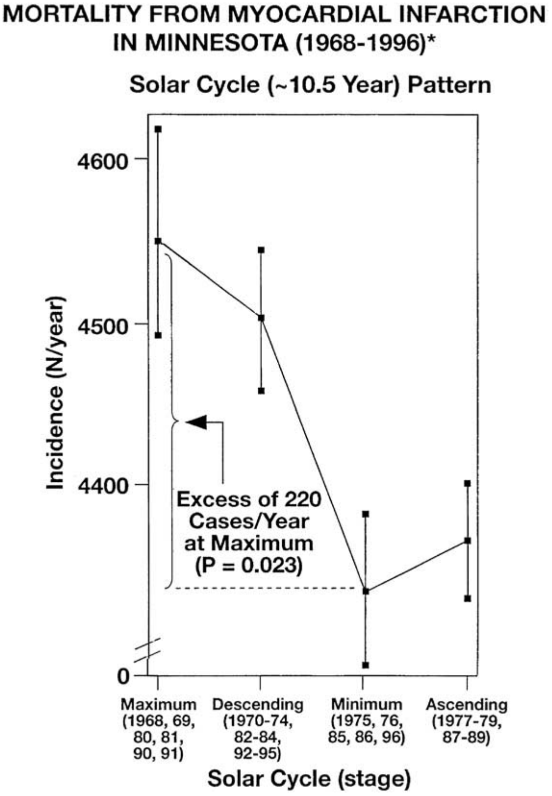


Fig. 4. During years of maximal solar activity, there is an about 5% excess mortality (220 cases per year) from myocardial infarction in Minnesota (1968–1996) as compared to years of minimal solar activity. © Halberg.

Table 1
Differences among three consecutive solar cycles found by fit of a 10.5-year cosine curve to daily mortality from myocardial infarction in Minnesota[a]

Cycle N	P ($A = 0$)	Average ±SE (cases/day)	Amplitude (A) (95% CI) (cases/day)	Relative amplitude	Phase of maximum (95% CI) (degrees)[b]
1	0.006	12.0 ± 0.1	0.36 (0.18; 0.53)	0.030	− 135 (− 105; − 164)
2	< 0.001	12.4 ± 0.1	0.76 (0.55; 0.96)	0.061	− 145 (− 132, − 158)
3	0.830	12.1 ± 0.1	0.07 ( )	0.006	− 144 (,)

Test of equality of parameters

Parameter(s)	ndf	F	P
Average	(2, 20)	11.296	0.0005
Amplitude (A)	(2, 20)	12.820	0.0003
Phase of maximum (ϕ)	(2, 20)	0.231	0.7954
(A, ϕ)	(4, 20)	6.762	0.0013
(M, A, ϕ)	(6, 20)	9.586	< 0.0001

[a] In the data analyzed after removal of a linearly decreasing trend. Average computed as a rhythm-adjusted mean (MESOR (midline-estimating statistic of rhythm)); amplitude: measure of extent of predictable change within one cycle; phase of maximum expressed in (negative) degrees, with 360° equated to 10.5 yr; phase reference: 00:00 on 1 July 1967.

[b] 95% CI: 95% confidence interval.

Table 2
Myocardial infarctions in Minnesota (1968–1996)[a]

	Average (95% CI) (cases/day)	Period (95% CI) (yr)	Amplitude (95% CI) (cases/day)[b]
Original data (10.5 *yr cosine model*)			
All 29 years (yr)	12.19 (12.06; 12.33)	9.81 (9.61; 10.00)	1.15 (0.97; 1.34)
Original data (10.5 *yr cosine* + *linear trend model*)			
All 29 yr	12.16 (12.04; 12.28)	10.83 (9.93; 11.74)	0.40 (0.22; 0.57)
1968–1977 (10 yr)	15.06 (14.83; 15.29)	8.03 (4.96; 14.76)	0.26 (0; 0.59)
1978–1986 (9 yr)	12.26 (12.05; 12.48)	12.10 (10.28; 15.17)	0.94 (0; 2.89)
1987–1996 (10 yr)	8.93 (8.75; 9.10)	—	—
Detrended data (10.5 *yr cosine model*)			
All 29 yr	− 0.04 (− 0.15; 0.07)	10.83 (10.00; 11.66)	0.40 (0.24; 0.56)
1968–1977 (10 yr)	− 0.22 (− 0.43; − 0.01)	11.48 (3.23; 19.72)	0.38 (0.09; 0.67)
1978–1986 (9 yr)	0.20 (− 0.61; 1.01)	10.64 (8.60; 13.28)	0.76 (0.45; 1.07)
1987–1996 (10 yr)	− 0.54 (− 0.71; − 0.38)	—	—

[a] Period estimated by non-linear least-squares fit of listed model. Analysis fails to resolve the about 10.5-yr component for the span 1987–1996, found overall and during 1968–1977 and 1978–1986, suggesting differences from solar cycle to solar cycle. Average computed as a rhythm-adjusted mean (MESOR (midline-estimating statistic of rhythm)); amplitude: measure of extent of predictable change within one cycle.

[b] 95% CI: 95% confidence interval.

decreases in cosmic ray intensity available on the web, a weak effect of Forbush decrease in cosmic ray intensity, found for the data as a whole (1968–1996), is not statistically significant in 1979–1981 (Table 3), when such an effect was observed prominently by Villoresi and his group in the Moscow data base (Halberg et al., 1991, 2000; Villoresi et al., 1994a).

The (detrended) data on the daily incidence of mortality from MI in Minnesota were further associated with different indices, including a coronal index of solar activity based on the total irradiance of the coronal 530.3 nm green line (Rybansky et al., 1994), Wolf numbers, Kp, aa, Dst, and Forbush decreases in cosmic ray intensity. The strongest associations were found to be with Dst (at lag zero), and with Wolf numbers (with a 3-day lag). Although statistically significant ($P < 0.001$), the correlation coefficients are relatively small. Analyses by superposed epochs in relation to Forbush decreases indicate an increase in mortality

Table 3
Effect of Forbush decrease (FD) in cosmic ray intensity on mortality from myocardial infarction (MI) in Minnesota[a]

% change in MI[a] relative to epoch mean (≡ 100%)		Day − 1	FD	+1	Difference (day +1 vs. FD)
1968–1996		− 0.275	+4.070	− 3.795	7.865
($N = 161$)		±2.128	±2.240	±1.916	±3.585
	Student t	− 0.129	1.817	− 1.981	2.194
	P	NS	(0.071)	(0.049)	(0.030)
1979–1981[b]		− 5.642	+2.801	+2.841	− 0.041
($N = 29$)		±5.614	±6.548	±4.551	±9.781
	Student t	− 1.005	0.428	0.624	− 0.004
	P	NS	NS	NS	NS

[a] 3-day epoch, the day of the FD and the preceding (− 1) and following (+1) days. NS: not statistically significant.

[b] Span for which a statistically significant effect of FD on the incidence of MI was found in Moscow, Russia.

from MI by only 4% on the day of the Forbush decrease, followed by a decrease of a similar extent on the following day ($P = 0.030$ for the difference in mortality between these two days). This effect, however, does not increase with the magnitude of the Forbush decrease, and can only be validated during years other than those corresponding to maximal solar activity, at which times mortality from MI is higher overall.

Possible reasons for the discrepancies include:

(1) The acute increase in MI seen in association with a magnetic storm may affect only susceptible individuals, being immediately compensated for by a decrease on the following day. A similar argument is presented by Stoupel et al. (1996), who found stronger associations for older subjects.

(2) The “chronic” biological response (higher mortality during years of solar maximum) may depend on other factors such as the solar cycle stage and geography. Dose and timing of exposure are factors that should be taken into consideration in future studies, notably since some investigators report a myocardial protection conferred by electromagnetic fields (DiCarlo et al., 1999).

(3) The lack of specificity of both the biological mechanism involved and the physical trigger. In this context, Otsuka, 2000 (see Proceedings, 2000) suggests that geomagnetic activity affects certain natural environmental factors such as fluctuations of atmospheric pressure in the range 0.01–0.10 Hz (10–100 s), which in turn may have more direct physiological and/or pathological effects. Unhealthy effects of atmospheric temperature and pressure on the occurrence of MI and coronary deaths have also been discussed by Danet et al. (1999).

4. Effects of magnetic storms on HRV as a putative underlying mechanism

As for the incidence of MI, inter- and intra-solar cycle differences are also observed for associations between HR and Wolf numbers in unusually long recordings from two clinically healthy men (Cornélissen et al., 1999; Halberg et al., 2000). By contrast, the relationship between HRV (gauged by the monthly standard deviation; SD) and solar activity appears to be consistent. More specifically, an about 10.5-year component characteristic of the solar activity cycle was documented for HR measured automatically, longitudinally around the clock, mostly at 15-min intervals for 11 years (Cornélissen et al., 1999). In these data, a negative association is found between the SD of HR (over 1-month intervals) and Wolf numbers, Fig. 5a (right), which was consistent. The positive association observed between HR and Wolf numbers (Fig. 5a, left), however, can be validated only during the ascending and not during the descending stage of the solar cycle, Fig. 5b. Similar results are observed in another healthy man who self-measured his HR (among other variables) about 5 times a day during waking for a span covering three solar cycles (Halberg et al., 2000). Whereas the association between HR and Wolf numbers was not consistent, either from one solar cycle stage to another, or in a given stage from one solar cycle to another, the relationship between the monthly SD of HR and Wolf numbers was consistent.

These individual results are corroborated by studies on groups. A 20% reduction in HRV (24-h SD) was observed in the 24-h Holter recording of 50 MI patients as compared to a group of 50 clinically healthy men ($P = 0.002$) (Cornélissen et al., 1990). A 20% reduction in HRV (48-h SD) is also observed in 48-h ambulatory profiles of 16 patients who are to develop coronary artery disease in the next 6 yr as compared with 281 similar patients who will not develop this condition during the same 6-yr span ($P = 0.004$). In the latter study, a too low 48-h SD of HR was associated with a 550% increase in the risk of coronary artery disease. The HRV (∼ 30-min SD) of presumably very healthy cosmonauts in space was 30% lower in those eight monitored during a magnetic storm as compared to 41 others monitored during quiet conditions ($P = 0.041$).

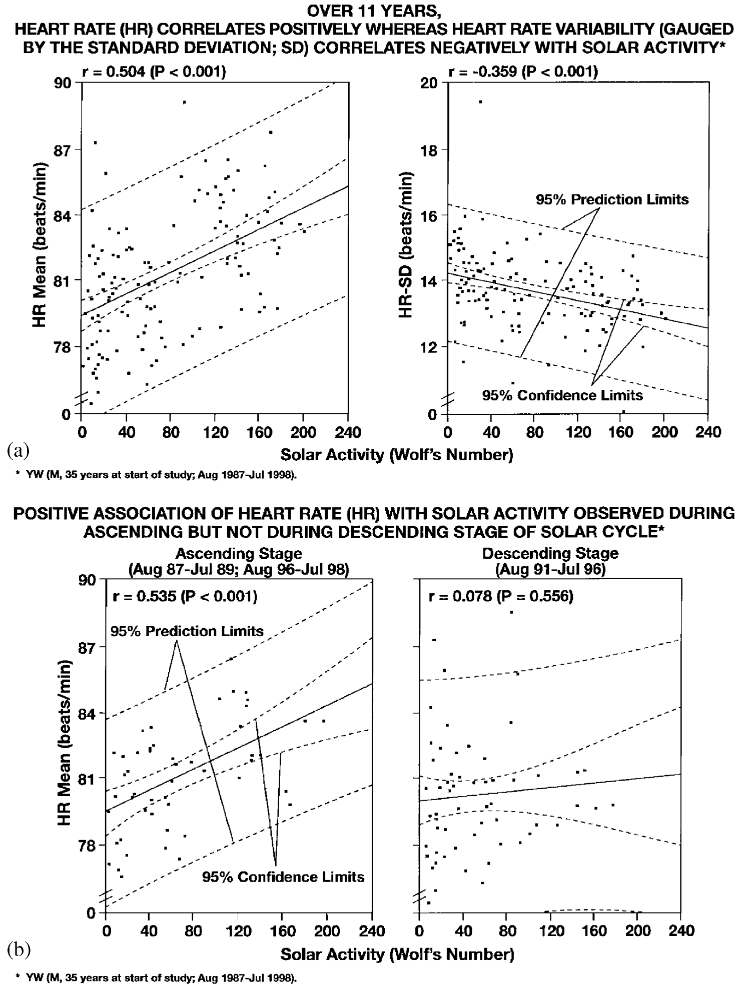


Fig. 5. (A) Over 11 yr, the monthly SD of HR (monitored automatically around the clock, mostly at 15-min intervals) correlates negatively with solar activity, gauged by Wolf numbers (right), whereas HR shows a positive correlation (left). (B) While the negative association of the SD of HR with solar activity appears to be consistent (not shown), a positive relation between HR and solar activity is found during the ascending stage (left) but not during the descending stage (right) of solar activity. © Halberg.

Geomagnetic disturbance effects on HRV were corroborated in a 7-day electrocardiographic (ECG) record provided by a clinically healthy man (Cornélissen et al., 1999). Beat-to-beat ECG records are typically analyzed over successive short intervals of 5 min to derive time-domain and/or frequency-domain endpoints of HRV, the latter by means of spectral analysis. The variations in HR can then be separated into different components that correspond to different frequency bands in the spectrum: ~3.6 s (0.15–0.40 Hz) thought to reflect the respiratory modulation of vagal nerve activity; ~10.5 s (0.04–0.15 Hz) putatively generated by the baroreceptor modulation of the sympathetic and vagal nervous tone; and frequencies below 0.04 Hz, that may relate to variations in the activity of the renin–angiotensin system and thermoregulation, the ~10.5/~3.6 s spectral power ratio being considered as a marker of sympathetic nervous tone. Analyses of the 7-day ECG record referred above revealed a statistically significant decrease in HRV during disturbed vs. quiet days, that was primarily contributed by a decrease in power in specific spectral regions, centered around one cycle in 46.5 and 10.5 s, but not in a region centered around one cycle in 3.6 s. In this 7-day record, an overall alteration of the time structure of several HRV endpoints was observed, consisting primarily of a change in prominence from the circadian to the circaseptan component. The circadian rhythm also became desynchronized, assuming a period shorter than 24 h. This altered time structure resembles that observed in the study of "Chinchilla" rabbits by Chibisov et al. (1995), in relation to a magnetic storm.

A decrease in HRV during disturbed vs. quiet days, affecting spectral regions away from one cycle in about 3.6 s, was corroborated in a study of eight clinically healthy subjects (seven men and one woman aged from 21 to 45 yr), in Alta, Norway (70°N) (Proceedings, 2000). Each subject provided a 7-day ECG record. Frequency-domain measures of HRV, obtained over consecutive 5-min spans, were compared for each subject during 24-h spans of high geomagnetic disturbance vs. quiet conditions. The 24-h SD of the local horizontal component of the earth's magnetic field was about 7 times higher on disturbed days as compared to quiet days. The decrease in HRV was found primarily in spectral regions of 0.0001–0.003 Hz (24.6% decrease; $P = 0.005$) and 0.003–0.04 Hz (23.4% decrease; $P = 0.003$). It was less pronounced around 10.5 s (16.3% decrease; $P = 0.022$) and could not be demonstrated around 3.6 s.

Among mechanisms of HRV, the autonomic nervous system comes to mind (Ewing et al., 1984). Signs of reduced vagal activity have been associated with an enhanced risk of sudden cardiac death (Algra et al., 1993). Impaired HRV has also been shown to serve as a predictor of mortality among patients with a variety of other vascular diseases (Tsuji et al., 1994). The results may point to some underlying physiological mechanism responsible for the response to changes in magnetic activity other than the parasympathetic, usually identified with spectral power centered around 3.6 s, a spectral region wherein no statistically significant differences were found.

Corroborating evidence is also found in the literature. Occupational exposure to medium-frequency electromagnetic fields has been reported to bring about impairments in the neurovegetative coordination of the cardiovascular system (Bortkiewicz et al., 1996). Although no difference in overall SD of HR was found between the exposed and non-exposed workers, a decrease with age of the spectral power in the frequency range from 0.15 to 0.35 Hz (one cycle in about 3.6 s) was reportedly observed in the control group, but not in the exposed group. The authors also report a dose-dependent reduction in the day-to-night ratio of HR (and arterial BP) for the workers exposed to radiofrequency fields as compared to controls (Bortkiewicz et al., 1996), a finding in keeping with the reduced HRV in association with electromagnetic exposure. Heart rhythm disturbances, impaired conduction, lowered ECG amplitudes, particularly of the T-wave peak, and arterial BP abnormalities have been reported in subjects exposed to low-power electromagnetic fields in another study (D'Yachenko, 1970). A survey by Hamburger et al. (1983) revealed a more frequent incidence of HR problems in subjects with a high-level exposure to radiofrequency and microwave electromagnetic fields.

An elevated risk of coronary heart disease by a factor 2.00 ±0.27 was reported among drivers exposed to ultra-low-frequency magnetic field fluctuations produced by trains powered by DC electricity as compared to drivers of electric motor units producing much lower fields (Ptitsyna et al., 1996). Because the subgroups of drivers apparently could be considered to have had equal exposure to other known risk factors, the authors attributed the elevated risk of coronary heart disease among drivers of electric locomotives to the increased occupational exposure to ultra-low-frequency magnetic fields. Exposure to electromagnetic fields has been included among environmental cardiovascular risk factors in a comprehensive review of 177 risk factors classified in 10 categories (Omura et al., 1996).

5. Coordinated physiological and physical monitoring: BIOCOS project

In view of the reduced HRV in coronary artery disease vs. health, the decrease in HRV associated with the exposure to geomagnetic disturbances may constitute a mechanism accounting for the increase in MI incidence on the day following a magnetic storm. An international project on the BIOCOS advocates the coordinated, concomitant monitoring of physiological and physical variables in different geographic locations. Reference values are thereby sought for a better understanding of environmental effects on human health and for testing the need of space weather reports (Dorman et al., 1993, 1995; Rostoker, 1998) that could prompt the initiation of countermeasures in space and on earth.

As a dividend, week-long or longer monitoring of the ECG and HR (along with blood pressure), coupled to chronobiological analyses, can help detect disease-risk elevations, as a warning of the need for a preventive pre-habilitation (Cornélissen et al., 1999), to safeguard two of the most precious features of life, independence and mobility. Within the normal range of physiological variation, computer methods resolve chronomes for the derivation of reference standards in health and the detection of disease-risk syndromes such as a reduced HRV (and an excessive blood pressure variability), associated with a very large increase in the risk of coronary artery disease, cerebral ischemic events and nephropathy (Halberg et al., 1998; Cornélissen et al., 1999). A reduced HRV and CHAT (Circadian Hyper-Amplitude-Tension; a condition characterized by an excessive circadian blood pressure amplitude) may be largely independent disease risks because when both conditions are present, the vascular disease risk is much larger than when only one of the two diagnoses is made, Fig. 6.

The resolution of variability inside the physiological range in terms of multifrequency rhythms and other chronome elements yields new endpoints that may be invaluable, not only to recognize pre-disease before the onset of overt symptoms, but also to avoid controversy and/or blunders, notably when long-term variations are involved. The systematic monitoring of physiological variables and morbidity/mortality statistics may serve to sort out meaningful associations from fleeting ones. The ubiquitous about 10.5-year changes are just starting to be mapped, along with components of even lower frequencies of one cycle in about 21 and 50 yr, no-

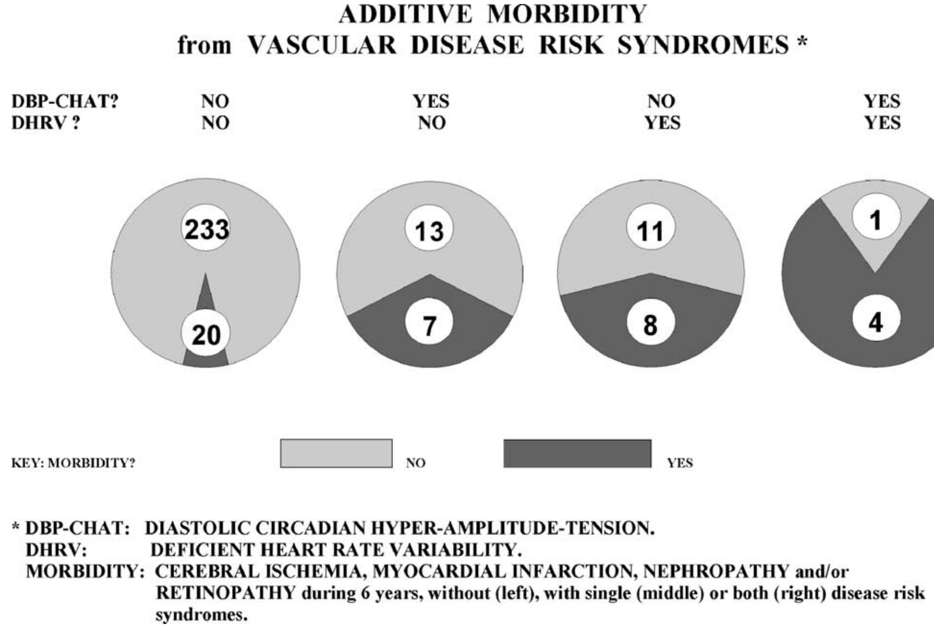


Fig. 6. Pie charts comparing the incidence of morbid vascular events among patients with an acceptable blood pressure and HRV, patients diagnosed with either an excessive circadian blood pressure amplitude (CHAT) or a decreased HRV (DHRV) alone, and patients diagnosed with both conditions. Results from a 6-yr prospective study on 297 (121 normotensive and 176 treated hypertensive) patients, who each contributed a 48-h record of blood pressure and HR measurements at 15-min intervals at the start of study. The incidence of morbid events was checked at 6-month intervals for 6 yr. Each patient's circadian characteristics of blood pressure and HR were interpreted in the light of reference standards obtained from independent studies on presumably clinically healthy subjects, matched by gender and age. CHAT (Circadian Hyper-Amplitude-Tension) was defined as a circadian amplitude of blood pressure above the upper limit of acceptability and DHRV (Decreased Heart Rate Variability) as a 48-h standard deviation below the lower limit of acceptability. © Halberg.

tably in relation to growth and development (Cornélissen et al., 1999, 2000; Halberg et al., 2000; Proceedings, 2000). Sampling over spans shorter than a full solar cycle may erroneously suggest the presence of an increasing or decreasing trend when records over longer spans readily reveal cyclic changes. Of particular interest is the incidence of stroke deaths. With the qualification that there have been changes in the classification of mortality from stroke, a non-monotonic trend over the past 50 years has been documented both in Minnesota (Halberg et al., 2000), Fig. 7a, and in the Czech Republic. This result raises the question whether the decline in stroke during the past two decades cannot be accounted for, at least in part, by a natural about 50-yr cycle, although one should not use 50 years of data to discuss an about 50-yr periodicity. An upward trend is observed in most recent years in Minnesota, Fig. 7b, as well as in the Czech Republic, in Slovakia, in Lund, Sweden (Johansson et al., 2000), and with Paul W.C. Johnson in data from Arkansas (Halberg et al., 2000), Table 4.

6. Concluding remarks

Results from the BIOCOS group and many others reviewed herein suggest that mortality from MI may be influenced by non-photic cosmo-heliospheric and geomagnetic activity. A putative underlying mechanism is offered by showing that geomagnetic storms are associated with a decrease in HRV, too low HRV being a risk factor for coronary artery disease and MI. In view of the many yet unanswered questions, longitudinal physiological monitoring is proposed in different geographic/geomagnetic locations, complementing ongoing physical monitoring.

It remains to be proved that organisms are useful to the physicist as a complex thermometer, barometer, galvanometer and radiation detector, and probably as a combination of such instruments. At the 2000 NATO Advanced Study Institute on Space Storms and Space Weather Hazards, Friis-Christensen estimated that the variations in irradiance during a solar cycle between sunspot maximum and minimum amount to 0.1%, hardly enough, as he put it, "to have a significant effect on the global temperature" ("among other variables", we may add). Turning to the ultraviolet part of the solar irradiance spectrum, Friis-Christensen finds much larger variations in the course of a solar cycle than those in visible light, with models fitting somewhat better, but not well enough. The climatic and biological associations of the Schwabe cycle are larger in extent of change. Hence, galactic cosmic ray flux and cloud formation influenced thereby also have been considered in accounting for climatic models and are found to be highly correlated.

Not only does the mapping of chronomes depend upon the density and length of the available time series, the information available at the outset and/or obtained in repeated passes over the accumulating data, as they are stepwise compacted and recycled, should not be underestimated. In defraying the cost of mapping the chronomes, science administrators should realize that with each pass repeated to assess a given component that is found to be reproducible in a time series, the number of required data points for future assessments of the same component is likely to decrease, all else being unchanged. To map long-term changes, monitoring for most of a professional human lifetime may be needed. Governmental planning is thus desirable to seek more precisely which environmental factors may more directly affect the biota. The strong influence of solar activity changes on geomagnetic disturbances notwithstanding, differences in the time structures of Wolf numbers and Kp have been noted. As a result, there may be times of stronger or weaker parallelism in the time course of these two variables, which in turn may affect the extent of physiological–physical associations. Nor should the ever-present influence of photic solar effects be forgotten; the concomitant monitoring of physiological and physical variables in different geographic locations may shed new light on this issue by the assessment of differential latitudinal effects. The proposed systematic transdisciplinary mapping is indispensable to avoid errors and essential to describe everyday physiology. It provides reference values in order to detect disease-risk syndromes, and describes the nature of things in and around us. Its systematic pursuit is cost-effective, like the building of roads or aircraft that once built need only maintenance paid for by taxes, tolls or tickets.

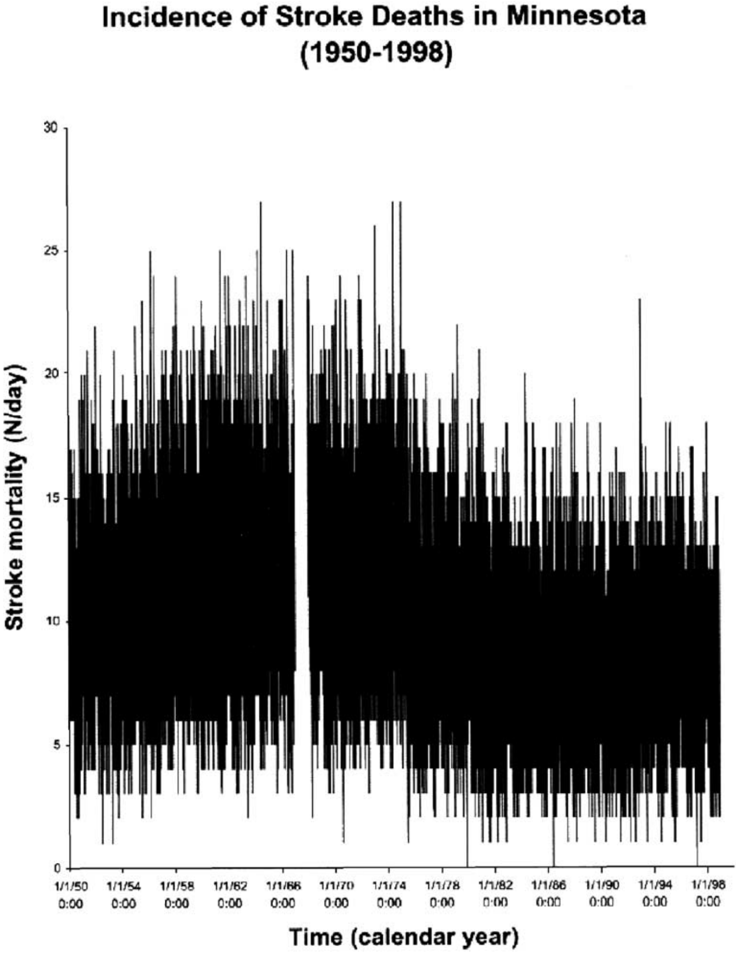


Fig. 7. With the qualification that the classification of stroke mortality has changed over the years, an about 50-yr pattern (a) may account for the recent increase in the incidence of stroke deaths, observed by the fit of a third-order polynomial to data since 1968, using the same disease classification (b). © Halberg.

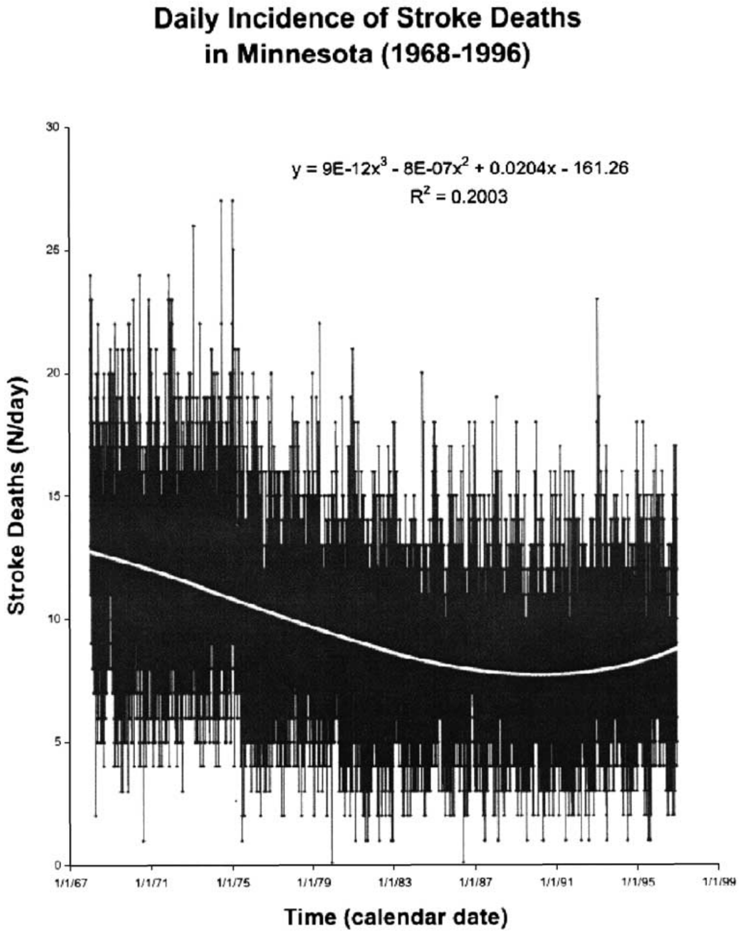


Fig. 7. (*continued*).

Table 4
Is stroke mortality increasing in recent years?

Location	Comment
Arkansas, USA (data from P.W.C. Johnson; Halberg et al., 2000)	Increase in stroke mortality from 1991 to 1998 from average 5.8 to 6.4 cases per day ($r = 0.867; P = 0.005$)
Czech Republic (data from Fiser et al., 2000)	Increase in stroke deaths detected in 1999 by self-starting cumulative sum, estimated to have started in 1997
Minnesota, USA (Fig. 7)	Increase from average 7.86 to 8.17 deaths per day between 1987–1992 and 1993–1998 ($t = 3.584$; $P < 0.001$)
Lund, Sweden (Johansson et al., 2000)	From 1983–1985 to 1993–1995, increase from 998 to 1318 patients with first-ever stroke, representing a rate per 100,000 person-years increase from 134 (95% CI: 126–143) to 158 (149–168) overall and from 94 (85–103) to 117 (108–137) for patients < 75 yr of age
Slovakia (data from Kovac and Mikulecky; Proceedings, 2000)	Statistically significant increasing linear trend from 1989 to 1993 in clinical onset of cerebral ischemia and intracerebral hemorrhage but not of subarachnoid hemorrhage

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