THE EARTH'S GEOMAGNETIC FIELDS OR ELECTROMAGNETIC FIELDS CAN EXPLAIN BERGMANN'S, COPE'S, AND RENSCH'S RULES

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(Abstract)
A number of ecological and evolutionary patterns or 'rules' dealing with body size have been proposed over the years, the most prominent being Bergmann's rule, Cope's rule, and Rensch's rule. The mechanisms underlying these patterns remain enigmatic. We focused on the relationship between magnetic field (MF) exposure and animal body size because Bergmann's rule holds that organisms tend to be larger at higher latitudes, where the geomagnetic field is more than twofold stronger than at lower latitudes. We researched the relationship between electromagnetic field (EMF) exposure and change in animal body weight using data in the literature. We conducted a meta-regression analysis to examine the impact of EMF exposure on animal weight as compared with the weight of unexposed controls. Meta-regression showed that EMF exposure had a statistically significant positive association with relative weight in males but not in females. The increase in body weight would explain Rensch's rule. The increase in the relative weights of males would explain Bergmann's and Cope's rules. Over successive generations, animals would gradually gain a considerable amount of body size if environmental MF and/or EMF become stronger over the course of time, which explains Cope's rule.

(Keywords)
Bergmann's rule, Cope's rule, Rensch's rule, SSD, magnetic field, MF, EMF, ELF, evolution, body size, body weight

1. Introduction

A number of ecological and evolutionary patterns or 'rules' dealing with body size have been proposed over the years, the most prominent being Bergmann's rule (the tendency towards size increase with increasing latitude) [1-15], Cope's rule (the tendency towards size increase within phyletic lineages) [16-25], and Rensch's rule (which states that in many animal groups, when the male is larger than the female, sexual size dimorphism (SSD; the ratio of male to female size) increases with body size, but in groups in which the male is smaller than the female, SSD decreases with body size) [26-30]. The mechanisms underlying these patterns remain enigmatic.

In the present study, we focused on the relationship between magnetic field (MF) exposure and animal body size because according to Bergmann's rule organisms tend to be larger at higher latitudes, where the geomagnetic field (typically around 50 μT; range 20-90 μT)[31] is more than twofold stronger than at lower latitudes. We researched the relationship between extremely low frequency electromagnetic field (ELF-EMF) exposure and change in body weight using data in the literature. Although humans have been exposed to ELF-EMF in their daily lives from electrical appliances and power lines for about a century, ELF-EMF are also generated by geomagnetic storms [32], volcanic activity [33], earthquakes [33], and Schumann resonance [34]. Thus, ELF-EMF may have an effect on evolutionary processes among animals. Although static magnetic fields (SMF) and ELF-EMF differ in terms of frequency, SMF and ELF-EMF reportedly have similar effects on growth in plants and blood pressure in animals [35-38]. Furthermore, the clinical and hygienic effects of exposure to alternating and direct current MFs (of tens of mT) on human beings have been found to be very similar [39]. As described above, geomagnetic fields are always in a state of flux, the fluctuations are larger at higher latitudes where the geomagnetic field is stronger, and animals are always moving, so we believe that SMF and ELF-EMF are likely to have similar effects on animal body size.

We hypothesize that a stronger MF and/or electromagnetic field (EMF) causes animals to become larger during evolution. In addition, we propose that Bergmann's rule, Rensch's rule, and Cope's rule are all underpinned by one common factor, MF and/or EMF exposure.

2. Materials and Methods

2. 1. Search strategy and inclusion criteria

For our meta-analysis, we focused initially on high-quality animal studies conducted by the National Toxicology Program (NTP), which is made up of four charter agencies of the US Department of Health and Human Services. The NTP has conducted studies to assess the risks, especially with respect to carcinogenicity, of long-term exposure to ELF-EMF. We identified trials conducted according to the methods of the NTP study by performing a search of the MEDLINE database (1990–April 2007). The search terms used were 'carcinogenicity' and 'magnetic field', and the search was restricted to papers in English that described animal studies. The titles and abstracts of the articles identified using this process were scanned to exclude any trials that were clearly irrelevant. The full text of the remaining articles was read to determine whether they contained information on the topic of interest. The reference lists of the selected articles were reviewed for additional pertinent articles. In our analyses, we included only studies that were conducted by the NTP or according to the methods of the NTP study, which ran for 2 years, and in which animals exposed to ELF-EMF and the sham-exposed control animals (more than ~50 in each group) were dealt with in the same way, in the same room and at the same time. We did not assess the quality of the methods used in the primary studies; because the studies were conducted by the NTP or according to the methods of the NTP study, we presumed that these studies were of high quality. Two of the authors extracted the data independently. The following data were collected for each article: publication data (first author's last name, year of publication, country in which the study was performed); study design; number of animals; animal characteristics (sex, age); interventions (magnetic flux density, duration of exposure, exposure hours/day); and weights of animals and number of survivors at each assessment time point. Differences in data extraction were resolved by consensus after referring back to the original article. Publication bias was not assessed because long-term studies conducted by the NTP or according to the methods of the NTP study tend to be published whether the results are positive or negative.

2. 2. Statistical analysis

We conducted a meta-regression analysis [40] to examine the impact of ELF-EMF exposure on relative weight (percentage of control weight). We defined the relative weight as the weight of animals exposed to ELF-EMF divided by the weight of control animals at the same assessment time point in the same study. We defined ELF-EMF exposure as magnetic flux density × duration of the study (weeks) × exposure hours per day. We logarithmically transformed all ELF-EMF exposure values to achieve a more symmetric distribution of values. The natural logarithm of the relative weight was the response (dependent) variable, and ELF-EMF exposure was the explanatory (potential effect modifier) variable. We used a weighted regression model so that more precise trials had a greater influence on the result of the analysis. To correspond to a meta-regression analysis, studies were weighted using the number of survivors. A *P*-value of 0.05 indicated statistical significance. Statistical analyses were performed using SAS ver. 8 (SAS Institute Inc., Cary, NC, USA).

3. Results

Our search of the MEDLINE database initially yielded nine articles; however, some of these did not specifically address the topic of our analysis and were excluded, which left six potentially relevant articles. We read the full text of these articles and checked the reference lists for other relevant articles. We identified four trials that were conducted by the NTP or according to the methods of the NTP [41-45]. We obtained detailed data on weight changes for the four trials from a report [46] and book [47]. The general characteristics of the trials are described in Table 1. A total of 1288 rats and 1576 mice (50% female) were involved in these controlled trials: 992 rats and 1184 mice in the ELF-EMF exposure groups, and 296 rats and 392 mice in the control groups. The details of the studies are as follows.

The study of Yasui et al. [41] was a carcinogenicity test in rats using a 50 Hz sinusoidal ELF-EMF. In that study, male and female F344 rats, 48 per exposure group, were sham exposed (sham control) or exposed to 500 µT (Group 1) or 5000 µT (Group 2) ELF-EMF for 2 years. Animals were exposed from 5 to 109 weeks of age. The average exposure time was 22.6 h/day. No significant increases in the incidence of leukemia were observed. Similarly, incidences of brain and intracranial tumors did not increase in the exposed groups. The incidences of both benign and malignant neoplasms did not differ significantly between the exposed and sham exposed groups, with one exception: fibroma of the subcutis occurred slightly more commonly in exposed male rats than in sham exposed male rats. However, this difference was considered to be not statistically significant when evaluated with respect to historical control data from the laboratory of Yasui et al.

Table 1. Details of the studies included in our meta-analysis and the populations studied

Paper	Animal	Sex	Average age of animals when study began	Duration of exposure	Frequency (Hz)	Sham control (µT)	Group 1 (µT)	Group 2 (µT)	Group 3 (µT)	Group 4 (µT)	Centre where the study was conducted
Yasui[41] and Takebe[47]	F344 rats	Male Female	5 weeks	107 weeks	50	0 N=48 N=48	500 N=48 N=48	5000 N=48 N=48			Ibaraki, Japan
Boorman[43] and National Toxicology Program[46]	F344/N rats	Male Female	6-7 weeks	18.5 hours per day, 7 days per week, for 106 weeks	60	0 N=100 N=100	2 N=100 N=100	200 N=100 N=100	1000 N=100 N=100	1000 N=100 N=100	Chicago, US
McCormick[44] and National Toxicology Program[46]	$B6C3F_1$ mice	Male Female	6-7 weeks	18.5 hours per day, 7 days per week, for 106 weeks	60	0 N=100 N=100	2 N=100 N=100	200 N=100 N=100	1000 N=100 N=100	1000 N=100 N=100	Chicago, US
Mizuki[45]and Takebe[47]	AKR mice	Male Female	5 weeks	21.5 hours per day, until all animals died	50	0 N=96 N=96	500 N=96 N=96	500 (ellipsoid) N=96 N=96			Unknown location, Japan

The study of Boorman et al. [43] was a 2-year whole-body exposure study that was conducted to evaluate the chronic toxicity and possible oncogenicity of a 60 Hz (power frequency) ELF-EMF in rats. Groups of 100 male and 100 female F344/N rats were exposed continuously to a pure, linearly polarized, transient-free 60 Hz ELF-EMF at flux densities of 0 µT (sham control), 2 µT (Group 1), 200 µT (Group 2), or 1000 µT (Group 3). An additional group of 100 male and 100 female F344/N rats received intermittent (1 h on/1 h off) exposure to a 1000 µT ELF-EMF (Group 4). Mortality patterns, and the total incidence and number of malignant and benign tumors in all groups exposed to ELF-EMF were similar to those found in sex-matched sham controls.

The study of McCormick et al. [44] was a 2-year whole-body exposure study that was conducted to evaluate the chronic toxicity and possible oncogenicity of a 60 Hz (power frequency) ELF-EMF in mice. Groups of 100 male and 100 female $B6C3F_1$ mice were exposed to a pure, linearly polarized, transient-free 60 Hz ELF-EMF at flux densities of 0 µT (sham control), 2 µT (Group 1), 200 µT (Group 2), or 1000 µT (Group 3). An additional group of 100 male and 100 female $B6C3F_1$ mice received intermittent (1 h on/1 h off) exposure to a 1000 µT ELF-EMF (Group 4). A small but statistically significant increase in mortality was observed in male mice exposed continuously to the 1000 µT ELF-EMF, but mortality patterns in all other groups of mice exposed to ELF-EMF were comparable to those found in sex-matched sham controls. Body weight gains and the total incidence and number of malignant and benign tumors were similar in all groups.

The study of Mizuki et al. [45] was a whole-body exposure study that was conducted to evaluate the effect of a 50 Hz (power frequency) ELF-EMF on cancer rate in mice. Groups of 96 male and 96 female AKR mice were exposed to 50 Hz ELF-EMF at flux densities of 0 µT (sham control), 500 µT (Group 1: linearly polarized horizontal), or 500 µT (Group 2: ellipsoidal). No significant difference was detected between the exposed and sham exposed groups for each kind of tumor. Hematologically, there was no difference between the exposed and sham-exposed animals that were euthanized.

To investigate the impact of ELF-EMF exposure on relative weight, we performed a meta-regression analysis. The regression included 294 data points from four trials for both males and females. For males, we obtained an estimate that was statistically significantly different from zero for the regression coefficient of the relative weight on log ELF-EMF exposure (coefficient 0.23, standard error [SE] 0.067, $p = 0.0007$, intercept 97.4) (Fig. 1). The regression coefficient is the estimated increase in the relative weight per unit increase in the covariate. Thus, the relative weight is estimated to increase by 0.23 per unit increase in log ELF-EMF exposure. The estimated relative weight of the covariate can be derived from the regression equation: relative weight = 97.4 + 0.23 ×log ELF-EMF exposure. Fig. 1 shows the relative weight estimates according to log ELF-EMF exposure and shows that ELF-EMF exposure is positively associated with weight.

In females, the regression included 294 data points from four trials. For females, we obtained an estimate that was statistically significantly different from zero for the regression coefficient of the relative weight on log ELF-EMF exposure (coefficient 0.06, standard error [SE] 0.05, $p = 0.25$, intercept 99.5) (Fig. 2). The relative weight is estimated to increase by 0.06 per unit increase in log ELF-EMF exposure. The estimated relative weight of the covariate can be derived from the regression equation: relative weight = 99.5 + 0.06 × ELF-EMF exposure. Fig. 2 shows the relative weight estimates according to log ELF-EMF exposure and shows that ELF-EMF exposure was not associated with weight in females.

4. Discussion

We reviewed the results of four studies in which

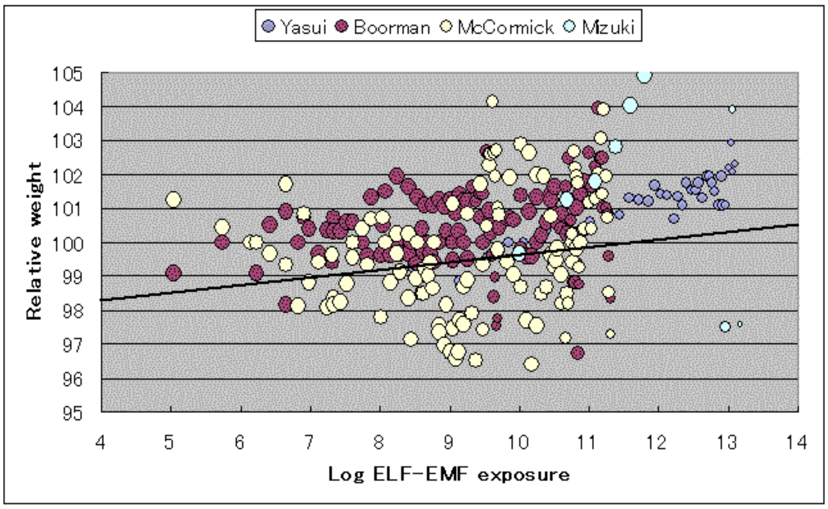

Figure 1. Meta-regression of change in relative weight on log ELF-EMF exposure for males. The circles on the graph represent the experimental groups in the studies included; the size of the circles indicates the weighting according to the number of survivors.

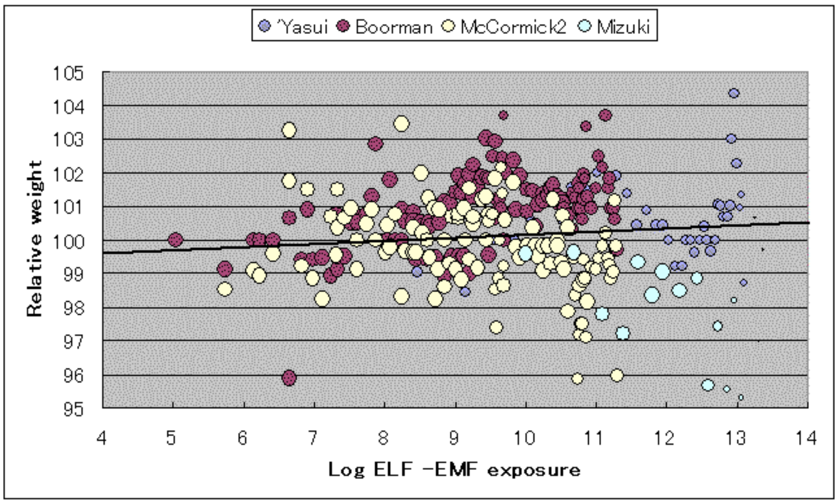

Figure 2. Meta-regression of change in relative weight on log ELF-EMF exposure for females. The circles on the graph represent the experimental groups in the studies included; the size of the circles indicates the weighting according to the number of survivors.

animals exposed to ELF-EMF and animals that were sham exposed were compared over a period of 2 years. Meta-regression revealed that ELF-EMF exposure had a statistically significant positive association with weight in males ($p = 0.0007$), but not in females ($p = 0.25$). It seems clear that these body weight gains in males were caused by the effects of ELF-EMF, because food consumption did not differ between the ELF-EMF and sham exposure groups in the studies of Yasui's and Mizuki's groups [47], although the other studies did not present data on food consumption.

Regarding the mechanism of weight gain, it is interesting that mild increases in plasma thyroid hormones (e.g., thyroxine) [48] and prolactin [49] have been found in pregnant lactating dairy cows that were exposed to ELF-EMF. Thyroxine is known to play key roles in growth, metabolism, reproduction, and somatic differentiation in developing and adult animals. Also in pregnant lactating dairy cows, exposure to the electric component of these fields alone (10 kV/m) did not affect either prolactin or thyroxine [50]. It is possible that MFs exert an effect on body size via plasma thyroxine and/or prolactin. In fact, injections of prolactin and thyroid hormones have been found to promote weight gain in male reindeer [51].

It is also possible that EMFs exert an effect on skeleton size via alteration of the proliferation and activity of bone cells. In support of this hypothesis, pulsed EMF stimulation has been used clinically for more than twenty-five years for the treatment of patients with delayed fracture healing and non-unions [52-57]. Furthermore, a substantial number of in vitro studies have shown that EMFs have positive effects on the proliferation and activity of bone cells [58-61].

Our results correspond with previous findings that ELF-EMF causes an increase in the body weight of mice and cattle [62-65]. Electrical fields alone did not produce any change in the body weight of pregnant lactating cows relative to unexposed controls [50], whereas MF did [66]. These results suggest that MF impact on the weight gains of animals.

Our finding that ELF-EMF exposure had a statistically significant positive association with weight in males with the evidence for sex differences in a variety of effects of various types of magnetic fields [67-72]. This result would explain Rensch's rule, which states that when the male is larger than the female, SSD increases with body size, but when the female is larger than the male, SSD decreases with body size. That is, the mean body weights of animals that are sensitive to MF would increase depending on magnetic flux density and frequency. In many mammals and birds, the male is larger than the female, which may be caused by a difference in sensitivity to MF.

Our finding that there was an increase in relative weight in males would explain Bergmann's and Cope's rules. The mechanism underlying Bergmann's rule has remained a mystery to date, but at higher latitudes the geomagnetic field is more than twice as strong as at lower latitudes. Our hypothesis is that, these changes in geomagnetic fields might cause organisms to grow in size. This would explain Bergmann's rule (the tendency towards size increase with increasing latitude). These animals would gain a considerable amount of body size over generations, if their surrounding environmental MF and/or EMF become stronger. This would explain Cope's rule (the tendency for body size to increase over evolutionary time). We believe that the ELF-EMF generated by geomagnetic storms, volcanic activity, earthquakes, or Schumann resonance have influenced animal body size during the course of evolution. In addition, the vulnerability to extinction of animals that adhere to Cope's rule would be explained by loss of the MF and/or EMF that supports animal body size.

Recent studies suggest that Bergmann's rule holds not only for endothermic vertebrates [3,4,73], but also for some ectothermic vertebrates; specifically, Bergmann's rule applies to most turtles [7] and

Table 2. Proportions of different animal groups that adhere to Bergmann’s rule and have larger males

	Do not adhere to Bergmann’s rule and do not have larger males	Adhere to Bergmann’s rule and have larger males	P value (Fisher's exact test))
Mammals and birds N=23	5 (21.7%)	18 (78.3 %)	
Reptiles N=14	10 (71.4%)	4 (28.6%)	0.004
Other animals N=57	46 (80.7%)	11 (19.3%)	<0.0001

salamanders [5]. Squamate reptiles (lizards and snakes) are a clear exception: the converse Bergmann’s rule applies to most species of squamates (i.e., they are smaller in cooler climates)[7]. In contrast, recent studies suggest that Cope’s rule holds for a variety of taxa, including Cenozoic mammals [74-76] and dinosaurs [77]. Rensch’s rule describes a pervasive macroecological pattern that has been observed in a wide range of taxa, including mites, water striders, lizards, snakes, turtles, hummingbirds, songbirds, and primates [27,29,30,78,79]. Given the fact that Cope’s rule applies to dinosaurs, which were endothermic, but not reptiles, which are generally ectothermic, it seems that endothermy is an important factor in MF effects. Of vertebrates, only mammals and birds are endothermic. If our hypothesis is correct, mammals and birds are endothermic should meet following conditions: 1) males should be larger than females; 2) they should adhere to Bergmann’s rule; and 3) their ancestors should have adhered to Cope’s rule. In fact, mammals and birds both meet all three of these conditions (if dinosaurs are regarded as the ancestors of birds). In fact, we evaluated the relationship between 1) and 2) by using data published by Blanckenhorn et al. [80] (Table 2). The number of classes that adhere to Bergmann’s rule and that have larger males is 18 of 23 (78.3%) mammal and bird classes, 4 of 14 (28.6%) reptile classes, and 11 of 57 (19.3%) classes of other animals. There was a statistically significant difference between the mammals and birds combined and reptiles (p=0.004; Fisher's exact test), and between the mammals and birds combined and the other animals (p <0.0001; Fisher's exact test). These results show a strong relationship between 1) and 2) for mammals and birds.

As outlined above, we believe that MF and/or EMF are fundamentally connected with animal evolution, and we have named this new field of study ‘magneto-evolution’. Because MF and/or EMF may have influenced not only animal body size but also many other characteristics, more research is needed in this new field.

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