Does magnetoreception mediate biological effects of power-frequency magnetic fields?

Jacques Vanderstraeten [a,*], Hynek Burda [b,c]

[a] Research Center on Environmental Health and Work Health, School of Public Health, Université Libre de Bruxelles, CP 593, Route de Lennik 808, 1070 Brussels, Belgium
[b] Department of General Zoology, Faculty of Biology and Geography, University of Duisburg-Essen, 45117 Essen, Germany
[c] Department of Forest Protection and Game Management, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences, Kamycka 129, 165 21 Prague 6, Czech Republic

ARTICLE INFO

ABSTRACT

The question of possible biological effects of power-frequency magnetic fields (PF-MF) remains controversial, notably because no valid mechanism of interaction could be proposed so far for intensities relevant to human and animal exposure (e.g. such as near high-tension power lines). In rodents, however, a few consistent effects of weak PF-MF have been reported. These are, notably, influence on spatial memory and partial inhibition of melatonin secretion under long-lasting exposure. Recent developments in study of magnetoreception in mammals justify reviving the hypothesis previously proposed of the intervention of the magnetic sense in melatonin disruption by PF-MF. We revisit this hypothesis and revise and extend it with respect to current knowledge and, particularly, with respect to reported effects on spatial memory. Proposals are made for experimental testing of the hypothesis. We argue that these tests may provide further insight into mechanisms of biological interactions of PF-MF and also, into mechanisms of magnetoreception per se.

© 2011 Published by Elsevier B.V.

1. Introduction

Since several decades, the question has been raised about possible biological (behavioral, physiological, and pathological) effects of the power-frequency (50/60 Hz) magnetic fields (PF-MF) that are generated by high-tension (high voltage) power lines. However, such effects per se have not been unambiguously identified and mechanisms of action of these fields at the concerned intensities, i.e. ≤10 microtesla (μT), upon organisms remain enigmatic (cf. WHO, 2007). It is assumed that direct unspecific effects of PF-MF on living tissues are only possible at intensities above 1 millitesla (mT), which is the threshold value for generation of significant electrical currents in human brain by electromagnetic induction (ICNIRP, 2010). Numerous experimental studies were nevertheless dedicated to the examination of possible biological effects of PF-MF of weak intensities (≤1 mT). Among these, two particular effects reported in rodents are here considered.

The first effect refers to the influence of weak PF-MF (between 0.2 μT and 1 mT) on spatial memory. Following to reports of modulation by weak PF-MF of cholinergic and opiate activity in hippocampus and other brain areas in rodents (cf. WHO, 2007), several studies dealt with the effect of PF-MF on spatial memory. In a recent review, the WHO expert group (2007) presented the results of eight such studies, of which seven have reported impairment of spatial memory. Since then, one additional study has been published on effects of extremely low frequency (10–30 Hz) MF of weak intensity (4 μT), yet with opposite findings, i.e. improvement of spatial memory (Tehranipour and Kafaee, 2010).

The second effect refers to partial inhibition of the nocturnal secretion of the hormone melatonin, the main biomarker of circadian rhythmicity in animals. Since inaugural reports in the 1980s of melatonin disruption in rodents and birds exposed to, respectively, Earth-strength (about 50 μT of intensity) static MF of artificially varying orientation and to electromagnetic fields (cf. Reiter, 1994), melatonin secretion has been studied particularly in rats exposed to weak PF-MF. Although the large majority of these studies tested short term (≤2 weeks) exposure, with predominantly negative findings, six from the seven studies that tested long term (≥4 weeks) exposure to PF-MF>1 μT (between 1.4 μT and 1 mT) reported positive findings (reviewed in Jahandideh et al., 2010; Swerdlow et al., 2006; WHO, 2007). Since 2003, however, no more experimental research has been published on melatonin secretion under exposure to PF-MF. The lack of physiological explanation, together with the predominantly negative experimental results in humans (cf. Swerdlow et al., 2006; WHO, 2007), presumably explains why this research has been put on hold.

Phillips and Deutschlander (1997) have suggested that PF-MF could disrupt melatonin secretion through the intervention of the magnetic sense, by affecting a "magnetic" Zeitgeber that is derived from the natural temporal variation in Earth's MF intensity. At the time of their proposal, however, arguments supporting it were meagre.

In particular, no data then existed in support of the existence of magnetoreception in mammals other than mole-rats and whales, and in support of effective sensing of PF-MF. Such data are now available and are here briefly reviewed. On this basis, it is thus proposed to go back on the proposal by Phillips and Deutschlander (1997), but with revising the suggested way of interaction in agreement with current knowledge, and with extending this proposal to reported effects on space memory. Finally, attempt is made to define the most appropriate methodology for testing the hypothesis of the role of the magnetic sense in biological effects of PF-MF.

2. Magnetoreception in mammals

Magnetoreception has mainly been studied in homing and migratory birds. In these and in other migratory and homing animals, this sense provides orientational and positional tools that are based on sensitivity to small variations of, respectively, the angular position (sensitivity to less than 1° variation) and the intensity (sensitivity to less than 0.5 µT variation) of the geomagnetic field (Earth's MF) vector (cf. Wiltschko and Wiltschko, 2005).

Despite being phylogenetically widespread (cf. Wiltschko and Wiltschko, 2005), magnetic compass orientation has been demonstrated in only few species of mammals representing only few orders: rodents (Burda et al., 1990; Kimchi and Terkel, 2001; Deutschlander et al., 2003; Muheim et al., 2006), bats (Holland et al., 2006; Wang et al., 2007), artiodactylans (Begall et al., 2008; Burda et al., 2009), cetaceans (Kirschvink et al., 1986; Walker et al., 1992), and carnivorans (Cerveny et al., 2011). Still, regarding the taxonomic distribution, and following Muheim et al. (2006), we suggest that magnetic sense may be a rather general feature of mammals.

While the role of the magnetic sense seems obvious (compass-sense) in mole-rats, bats, and cetaceans, it is less clear in other mammals identified as magnetosensitive on the base of exhibition of magnetic alignment. Apart from being involved in directional perception, magnetoreception could also participate in space perception and position recognition (Phillips et al., 2010). In this respect, Burger et al. (2010) observed suppression of c-Fos expression in some parts of the brain navigation circuit of mole-rats exposed to periodic changes in intensity of the MF (from 46 to 47 µT and back, at 0.5 Hz frequency) or to repeated shifts in azimuth. Based on these and other findings of the study, the authors suggested that orientation cues derived from Earth's MF are integrated with information from other sensory and motor systems into a common spatial representation of allocentric space within the navigation circuit.

Apart from the electromagnetic induction, which could explain magnetoreception in sharks and other salt-water fishes, three mechanisms have been mainly considered in vertebrates for reception and transduction of the magnetic signal into a neuronal input. Two of them are based on iron–mineral particles (IMP), one on IMP with permanent magnetic moment (single domain particles) and one on IMP with inducible magnetic moment that interact with each other. The first mechanism has been identified in some fish and is thought to provide sensitivity to Earth's MF orientation and direction (polarity) (Diebel et al., 2000; Kirschvink and Gould, 1981). The second one has been reported in several bird taxa and is thought to provide sensitivity to both Earth's MF orientation (and, possibly, direction) and intensity (Falkenberg et al., 2010; Fleissner et al., 2007; Solov'yov and Greiner, 2009). The third mechanism is based on spin-correlated radical pair reactions (RPR). It has been considered in several bird taxa and is thought to provide sensitivity to Earth's MF orientation only (Ritz et al., 2000; Wiltschko and Wiltschko, 2010). Whereas in mole-rats and in bats, the magnetic sense has been determined as a polarity compass (Marhold et al., 1997; Thalau et al., 2006; Wang et al., 2007), the proximate mechanisms underlying magnetoreception in any mammal species have not been unambiguously clarified yet.

3. Sensing of power-frequency magnetic fields

Recently, interaction of PF-MF with the magnetic sense has been observed in mammals. Burda et al. (2009) reported disruption (scatter) of the magnetic alignment of cattle and roe-deer (previously described by Begall et al., 2008) in the vicinity of high-tension power lines. The effect persisted up to distances corresponding to assumed PF-MF intensity of about 1 µT, and a specific pattern of disruption has been observed for different directions of the power lines, and thus different directions of the PF-MF relative to direction of Earth's MF.

Under exposure to PF-MF, the natural magnetic cue (Earth's MF, intensity set as 50 µT) is replaced by a cue that is the vector sum of both these fields and that oscillates at the frequency of 50/60 Hz, either in intensity or in direction, or both, according to the relative orientation of both fields (Fig. 1). The question of sensing of PF-MF has thus to be addressed in terms of sensing of this resulting, oscillating MF, or, more generally, in terms of magnetosensory disruption PF-MF cause. Already at about 0.5 µT of PF-MF intensity, and whichever the relative orientation of both fields, the amplitude of oscillations of this resulting MF exceeds the so far reported threshold of magnetosensory discrimination of MF intensity and/or orientation (Vanderstraeten and Gillis, 2010). Although Burda et al. (2009) quantified disruption of ruminants in terms of mean angular shift and its scatter, a possible and plausible interpretation for their observation is thus random alignment of the ruminants along the direction of any angular phase of the resulting oscillating MF. Such interpretation could for example be tested by experimental procedures using controlled PF-MF intensities and directions.

The frequency of the magnetic cue oscillations caused by PF-MF, however, is higher than the frequency of the faster physiological time-variations that can be experienced upon head rotation or body motion. The question of sensing of PF-MF has thus to be addressed in terms of sensing of the temporal instability of the orientation and/or the intensity of the resulting MF rather than accurate sensing of the 50-Hz frequency of its oscillations. Based on theoretical considerations, transduction of PF-MF appears possible, either for a mechanism based on IMP with inducible moment, or by a mechanism based on RPR. It appears not possible, however, for a mechanism based on IMP with permanent moment (Vanderstraeten and Gillis, 2010 and references therein). The neural transmission and processing of a 50/60 Hz time-varying magnetosensory stimulus also appears possible. Indeed, the time-scales of neural processing of diverse sensory stimuli (visual, somatosensory, postural) are in the millisecond or in the sub-millisecond range, which is to compare with the period of 16/20 ms of PF-MF (Butts et al., 2007; Jones et al., 2004; Sadeghi et al., 2007).
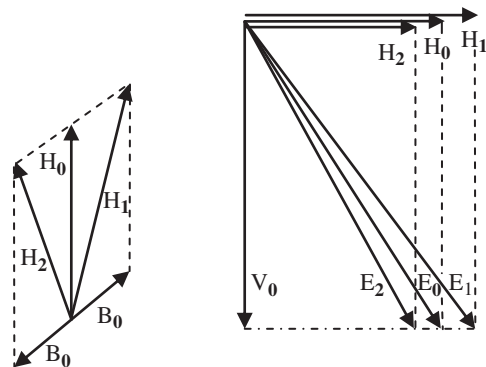
Fig. 1. Exemplative case of exposure to a PF-MF that has a horizontal, Southwest–Northeast orientation. E_0, H_0 and V_0 are the field intensity vectors of, respectively, the total Earth's magnetic field, its horizontal component, and its vertical one. B_0 is the peak intensity vector of the PF-MF. The azimuth of the resulting MF (left part) will oscillate at a frequency of 50/60 Hz between H_1 and H_2. The inclination (angle between H_0 and E_0) and the intensity (right part) oscillate at the same frequency between E_1 and E_2 (adapted from Burda et al., 2009).