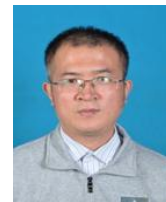# The Hyperfine Coupling Radical Pair Mechanism of Biological Effects on Weak Magnetic Fields

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Abstract

More recent concerns have been raised about the biological effects of all different weak magnetic fields (MFs) with the development of electric device era and information era. The biological effects due to weak MFs just like a hypomagnetic field (HMF) or near-null magnetic field is a very important subject for aerospace traveling and space station living. A large number of studies on the biological effects of other weak MFs have been carried out. The biological effects of different weak MFs can be negative or positive. Many mechanisms to explain the bioeffects of weak MFs have been given. Are there possible common mechanisms of the different biological effects in different weak MFs ? It's unbelievable and sound impossible at first sight that different bioeffects of different weak MFs have common mechanisms. But possible common mechanisms can exist. In this study, the author proposes the relations between the singlet yield of the radical pair and the weak MFs are the possible common mechanisms. Giving one possible common mechanism of bioeffects of all different weak MFs including impulsed ones is the first to the author's known. Here, the weak MFs are ones that cannot produce thermal bioeffects not only limited below 1mT.

Contents

1. Introduction

Since at least the late 1950s, the public have raised the concerns about the potential biological effects of non-ionizing radiation [1]. According to the European Commission, non-ionizing radiation are divided into static magnetic fields (0 Hz),extremely low-frequency (0 to 300 Hz), intermediate frequency (300 Hz to 100 kHz), and radio frequency (100 kHz to 300 GHz) fields [2].

The static magnetic fields (SMFs) are classified as following four grades:(1) the weak grade (<1mT); (2) the moderate grade (1mT -1T); (3) the strong grade (1T-5T); and (4) the ultrastrong grade (>5T) [3].

Untill now a lot of biological effects of weak magnetic fields have been found and studied [4]. During the evolution process, all living organisms experienced the action of the Earth's field(geomagnetic field, GMF) which is a natural component of their environment [5]. While, Interplanetary space is a natural hypomagnetic field(HMF) [5]. The range of a HMF is below 5uT [5]. Hypomagnetic field also can be called null or near-null magnetic field [6] .A hypomagnetic field(HMF) or near-null magnetic field is a very important subject for aerospace traveling and space station living [5]. Because of the difference on intensity between GMF(-50uT) and a HMF(<5uT) [5] many effects appear when animals, plants and microorganisms are in the HMF [5-16]. For example, a significant increase in anxiety-related behaviors was found when adult male C57BL/6 mice was in short-term HMF for 72h [8]. Usually, GMF and HMF are considered as part of static magnetic fields (SMFs). Because of their ranges of intensity, they are the entire weak grade. The biological effects of other SMFs (except for GMF and a HMF)are reported [17-20]. More recent concerns have arisen about the potential effects of all different weak magnetic fields with the development of electric device era and information era [1]. For example, more and more people have been attracted by the small increases in childhood leukemia for children living near power lines and possible increases in brain tumors for heavy use of cell phones [1]. The biological effects of extremely low-frequency (0 to 300 Hz) magnetic fields (ELF-MFs) are presented [21-34]. The biological effects of intermediate frequency (300 Hz to 100 kHz) magnetic fields(IMF-MFs)are discussed [35-38]. The biological effects of radio frequency (100 kHz to 300 GHz) magnetic fields (RF-MFs) are talked about [39-42]. The biological effects of pulsed magnetic fields are reported [43-47]. The biological effects of weak MFs can also be positive. For example ,a single session of Pulsed magnetic fields (parameters: 0.5 mT, 12 Hz, and 30 min) produced significantly greater increase in peripheral blood flow velocity in the dorsal foot [43]which may be used to treat some peripheral diseases.

Many mechanisms to explain the bioeffects of weak MFs have been given. Electromagnetic induction,ferrimagnetism and radical pair mechanisms of biological effects of a GMF are introduced [48-54]. Radical pair and magnetic moment mechanisms of biological effects of a HMF are suggested [7]; [55-57]. The mechanisms of biological effects of ELF-MFs which are cyclotron resonance theory and it's new interpretation,the ion parametric resonance model and an interference of ions bound within proteins are proposed [58-61]. The radical pair mechanism of biological effects of RF-MFs are outlined [1]; [62, 63]. Because magnetic fields in the band of 300 Hz through 10 MHz between ELF-MFs and RF-MFs have not been sufficiently explored so far [64] the mechanisms of biological effects of an intermediate frequency magnetic fields(IMF-MFs) have not been reported to the author's known. From the mechanisms of different biological effects of different magnetic fields, one can see the mechanisms are different too. Is there one common mechanism among the different biological effects of different weak magnetic fields? The study gives one possible answer. The hyperfine coupling radical pair mechanism in bird navigation is demonstrated [65]. The author thinks that the hyperfine coupling radical pair mechanism in bird navigation can be extended to explain biological effects of other weak magnetic fields. That is to say the hyperfine coupling radical mechanism or the relations between the singlet yield of the radical pair and the weak MFs may be common ones among the different mechanisms to explain different biological effects of different weak magnetic fields. In this study, the weak MFs are ones that cannot produce thermal bioeffects not only limited below 1mT. The reason is given in part 4.

The presentation order of the contents of this paper is as follows. General radical pair model and the hyperfine coupling radical pair mechanism in bird navigation is shown in part 2; the hyperfine coupling radical pair mechanism of biological effects on weak MFs is presented in part 3; Part 4 is discussions of several questions on the hyperfine coupling radical pair mechanism of weak MFs; and the main contents are summarized in part 5.

2. General Radical Pair Model and the Hyperfine Coupling Radical Pair Mechanism in Bird Navigation

A radical can be a molecule that contains an odd number of electrons. A radical pair consists of two radicals that have been created simultaneously, usually by a chemical reaction [66]. The reaction scheme can be divided into three steps [67]. The first one is that an excited donor molecule transfers an electron to an acceptor molecule resulting in a radical pair. Once the radical pair is generated, its singlet and triplet states will be interconverted by the hyperfine interaction. The final one is that singlet and triplet pairs will react to give singlet or triplet products [67, 68].

The hyperfine coupling radical model in bird navigation is given as followed [65]. When considering that the vertical hyperfine coupling A_z is relatively strong compared with γB_0, and the horizontal hyperfine coupling $A_x = A_y = 0$ is assumed, the singlet yield

$$\phi_S^0(\theta) \approx \frac{1}{2} - \frac{1}{4}\sin^2\theta - \frac{\gamma^2 B_0^2}{A_Z^2}(\frac{3}{4}\sin^2\theta - \sin^4\theta), \quad (1)$$

can be obtained under the influence of the geomagnetic field with the corresponding eigenvalue,here,which is equal to γB_0, where B_0 is the intensity of the Earth's magnetic field, and θ describes its orientation to the basis of the hyperfine tensor and γ is one constant [65]. When considering the horizontal hyperfine coupling $A_x = A_y \neq 0$,the results are similar to that without considering it Xu, et al. [65].

When considering the influence of an additional weak oscillating field, the singlet yield is given in Xu, et al. [65]

$$\phi_S \approx \begin{cases} \phi_S^0(\theta) & \omega \neq 2\omega_0 \\ \phi_S^0(\theta) + \dfrac{1}{2}(\phi_+'(\theta) + \phi_-'(\theta)) & \omega = 2\omega_0 \end{cases} \qquad (2)$$

with
$$\phi_{\pm}'(\theta) \approx -\frac{1}{4}\frac{\gamma^2 B_{rf}^2}{k^2}\sin^2\varphi\cos^2(\theta_{\pm}-\theta), \omega_0 = \gamma B_0. \qquad (3)$$

Where, $1/k$ is the radical pair lifetime. $\theta_{\pm}$ is determined by the surrounding magnetic field of electron and the hyperfine coupling A_z, and B_{rf} is the strength of additional oscillating field with frequency ω. From Equation 3, it can be seen that if the radio frequency field is parallel to the geomagnetic field, i.e., $\varphi = 0, \phi_{\pm}'(\theta) = 0,$ it means that the parallel radio frequency field has no influence on the singlet yield. If the radio frequency field is not parallel to the geomagnetic field, i.e., $\varphi \neq 0,$ the radio frequency field influences the singlet yield [65].

3. The Hyperfine Coupling Radical Pair Mechanism of Biological Effects on Weak MFs

3.1. The Hyperfine Coupling Mechanism of Biological Effects on GMF

Magnetic sensing to detect the Earth's magnetic field, is still one of the most controversial animal senses because the exact molecules to sense GMF have not been found [51]. Some models have been proposed to solve the controversy [51]. The author thinks the primary physical mechanism of the ability to detect the Earth's magnetic field is Equation 1 or 2 just as the same as the bird navigation in part 2. From Equation 2 and Equation 3 one can see when the time-dependent field is parallel to the geomagnetic field, i.e., $\varphi = 0, \phi_{\pm}'(\theta) = 0,$ or it's frequency is not equal to two folds of the corresponding eigenvalue, the biological effects are caused only by the geomagnetic (static)field. Only when the time-dependent field is not parallel to the geomagnetic field, i.e., $\varphi \neq 0,$ and it's frequency is equal to two folds of the corresponding eigenvalue, the biological effects are caused by both it and the geomagnetic (static)field.Here, the time-dependent field can either be external one made by human beings or one of the ambient alternating fields, because the wireless electromagnetic noise frequency of the surroundings can be below 1Hz [69] from 1Hz to 100KHz [70] from 9KHz to 10GHz and above 10GHz [71] and sometimes, the noise can be very important [72].

3.2. The Hyperfine Coupling Mechanism of Biological Effects on a HMF

Because of the difference on intensity between GMF(~50uT) and a HMF(<5uT) [5] many effects appear when animals, plants and microorganisms are in the HMF [5-16]. For example, a HMF can significantly suppress Arabidopsis flowering in light [14]. Because of the HMF as a key environmental factor when long-term and long-distance space mission in outer space, and also in some magnetic shielding conditions on the ground,the biological effect of the HMF should be seriously considered [73]. Some studies on the mechanisms underlying the biological effects of a HMF have been carried out [6]. These studies give the mechanism of the biological effects of a HMF at the cellular level [74-80] the mechanism at the molecular level [11]; [47]; [81-88] the mechanism at the tissue level [89, 90] and the physical mechanism respectively [55-57]. However, the underlying mechanisms remain unclear. In Ouyang and Li [7] the author and his partner gave the point: Equation 1 may be one quantum mechanism of biological effects on a HMF. Ambient alternating fields always exist [73, 74] can they influence the biological effects on a HMF ? The author thinks ambient alternating fields can influence the biological effects on a HMF just like on GMF as discussed in part 2.That is to say Equation 2 may be one possible quantum mechanism of the biological effects of a HMF when considering ambient alternating fields. In Zhang, et al. [73] the HMF(B_0) is $0.19 \pm 0.08(uT)$ or $0.14 \pm 0.07(uT)$.According to $\omega_0 = \gamma B_0, \omega = 2\omega_0$,the frequency of ambient alternating fields that can influence the biological effects is from 3076(Hz) to7550(Hz) or from1958(Hz) to5872(Hz). In Zhang, et al. [73] the ambient alternating fields is 2200-2700(Hz) or 2300-2900(Hz). Based on Equation 2, together with common range between 1958-5872(Hz) and 2300-2900(Hz), the biological effects are results of a HMF combined with ambient alternating fields.That is to say, ambient alternating fields can influence the biological effects of a HMF when the double eigenvalue $\omega_0 = \gamma B_0, \omega = 2\omega_0$ is included in the frequency of ambient alternating fields. Choleris, et al. [91] also gave the point that ambient alternating fields can influence the biological effects of a HMF. To the contrast ,if the double eigenvalue $\omega_0 = \gamma B_0, \omega = 2\omega_0$ is not included in the frequency of ambient alternating fields , the ambient alternating fields can not influence the biological effects of a HMF. Because Equation 2 is obtained based on the time-dependent perturbation theory [65] when ambient alternating fields is not much weaker compared with B_0, it can not be used.

3.3. The Hyperfine Coupling Mechanism of Biological Effects on Other SMFS (Except for GMF and A HMF)

Weak static magnetic field (500uT) increased total lipid content , including polar lipids, among them glycolipids and phospholipids was given in Novitskii, et al. [17]. Tenuzzo, et al. [92] results found apoptosis increased in some cells and decreased in the other when the cells were exposed in 6 mT static magnetic fields. Wang, et al. [93] results showed that 1.00 T and 1.13 T SMFs could increase cellular adenosine triphosphate (ATP). The biological effects of other SMFs(except for GMF and a HMF) were shown in Novitskii, et al. [17]; Sullivan, et al. [18]; Tolosa, et al. [19]; Martino [20].

The wireless electromagnetic noise frequency of the surroundings can be below 1Hz [69] from 1Hz to 100KHz [70] from 9KHz to 10GHz and above 10GHz [71]. Sometimes, the noise can be very important [72].

Based on $\omega_0 = \gamma B_0, \omega = 2\omega_0$, when B_0 equals 0.01mT, $\omega = 2\omega_0$ is about 300KHz; when B_0 equals 1mT, $\omega = 2\omega_0$ is about 30MHz ; when B_0 equals 100mT, $\omega = 2\omega_0$ is about 3GHz; when B_0 equals 10T, $\omega = 2\omega_0$ is about 300GHz.

Because of the frequency richness of the wireless electromagnetic noise of the surroundings and the weakness of it's intensity,usually the double eigenvalue $\omega_0 = \gamma B_0, \omega = 2\omega_0$ is included in the frequency of ambient alternating fields and the ambient alternating fields is much weaker compared with B_0.

From these that can be seen, the biological effects of other SMFs(except for a HMF and GMF) can be explained by Equation 2. That is to say,the biological effects of other SMFs(except for GMF and a HMF) are caused by both the wireless electromagnetic noise of the surroundings and the SMFs usually. Here, because of no external alternating field, the wireless electromagnetic noise of the surroundings is the alternating field, B_0 is the sum both GMF and SMFs when GMF and SMFs have the same directions. When they have different directions, B_0 is smaller than the sum both GMF and SMFs.

3.4. The Hyperfine Coupling Mechanism of Biological Effects on ELF-MFs

Because of industrialization, characterized by an increasing production, distribution, and consumption of electricity, occupational exposure to ELF-MFs in the frequency range of 3 Hz to 300 Hz is common and many workers are occupationally exposed to these fields Jalilian, et al. [94]. Bawin, et al. [95]; Bawin and Adey [96] provided important initial findings of non-thermal ELF-MFs that Ca^{2+} efflux from chick embryo brain tissue was influenced by ELF-MFs.Importantly, Blackman, et al. [97] later confirmed these results. An increased risk of amyotrophic lateral sclerosis (ALS) in workers occupationally exposed to ELF-MFs were observed in Huss, et al. [21]. Kleijn, et al. [22]; Zhang, et al. [23]; Schüz, et al. [24]; Tang, et al. [25]; Fixler, et al. [26]; Wang, et al. [27]; Prato, et al. [28]; Corbacio, et al. [29]; Vanderstraeten and Gillis [30]; Bowman, et al. [31]; Prato, et al. [32]; Burda, et al. [33]; Burger, et al. [34] reported the other biological effects of ELF-MFs (0 to 300 Hz) fields. Smith, et al. [58]; Lednev [59]; Blanchard and Blackman [60]; Binhi [61] proposed the mechanisms of biological effects of ELF-MFs which are cyclotron resonance theory and it's new interpretation,the ion parametric resonance model and an interference of ions bound within proteins. These mechanisms can not explain the role of light in the course of biological effects appearing [82]. The radical pair mechanism is valid for static MFs, but is also applicable to power frequency MFs: for radical recombination times, which are in the order of tens of nanosecond to few microseconds, 50/60 Hz fields may be regarded as static [98]. Based on this, the author thinks almost ELF-MFs effects can be explained through Equation 2.

Here, B_0 is the sum both GMF and amplitude of ELF-MFs. Just like the case of GMF or HMF, the author thinks ambient alternating fields can influence the biological effects on ELF-MFs. That is to say, ambient alternating fields can influence the biological effects of ELF-MFs when the double eigenvalue $\omega_0 = \gamma B_0, \omega = 2\omega_0$ is included in the frequency of ambient alternating fields.

To the contrast, if the double eigenvalue $\omega_0 = \gamma B_0, \omega = 2\omega_0$ is not included in the frequency of ambient alternating fields, the ambient alternating fields can not influence the biological effects of ELF-MFs. Because Equation 2 is obtained based on the time-dependent perturbation theory [65] when ambient alternating fields is not much weaker compared with B_0, it can not be used just like the case of GMF or a HMF.

3.5. The Hyperfine Coupling Mechanism of Biological Effects on an IMF-MFs

The intermediate frequency magnetic fields in the context of protecting human exposure have received public concerns in recent years because of the growing emergence of technology or products using those fields and a number of studies have been carried out Yamazaki, et al. [64]. Kumari, et al. [35] findings suggest that exposure to a 7.5 kHz, 120 µT MF may lead to mild learning and memory impairment possibly through an inflammatory reaction in the hippocampus. From Navarro, et al. [37] results, it seems that a low intensity 2 kHz exposure modifies short-term working memory, as well as perception, binary decision, motor execution, and sustained attention. Barbault, et al. [38]; Capstick, et al. [39] reported that cancer cell growth may be altered by very low level magnetic fields modulated at specific frequencies in humans.

Because IMF-MFs is 300 Hz through 100KHz or10 MHz [2]; [64] ELF-MFs is 0Hz through 300Hz and the author thinks ELF-MFs may be regarded as static and corresponding effects can be explained through Equation 2 in part 3.4, and one band of IMF-MFs (near ELF-Mfs) may be regarded as static and can be explained through Equation 2 just like the case of ELF-MFs.

When the frequency is so larger that IMF-MFs may not be regarded as static, how corresponding effects can be explained? This problem can be conquered together with RF-MFs.

3.6. The Hyperfine Coupling Mechanism of Biological Effects on RF-MFs

With the development of the globally advancing digitalization, the use of mobile communication systems and the mobile devices is more and more, which results in a rise of RF-MFs exposure of the human body Köhler, et al. [99]. Valentini, et al. [100] concluded that mobile phone RF-MFs may influence normal physiology. Apollonio, et al. [101] reported the other biological effects of RF-MFs. For a long time, there have been substantial concerns over the possible effects of RF-MFs at exposure levels that do not lead to significant increases in temperature [62]. Possible health effects of RF-MFs on the human body are still in discussion and have not finally been verified [100, 101]. Thermal effect which leads to temperature increase in cells and tissue and is based on dielectric heating is the undisputed and possibly only interaction of RF-MFs with biological cells and tissue [99]; [101]. However, the occurrence of non-thermal effects within cells, tissue and organism are still one controversial discussion [63]; [99-101]. Nevertheless, one mechanism that explains the observed effects with certainty is not known [40-42].

Based on $\omega_0 = \gamma B_0, \omega = 2\omega_0$, when B_0 equals 0.01mT, $\omega = 2\omega_0$ is about 300KHz; when B_0 equals 1mT, $\omega = 2\omega_0$ is about 30MHz ; when B_0 equals 100mT, $\omega = 2\omega_0$ is about 3GHz; when B_0 equals 10T, $\omega = 2\omega_0$ is about 300GHz. The wireless electromagnetic noise frequency of the surroundings can be below 1Hz [69] from 1Hz to 100KHz [70] from 9KHz to 10GHz and above 10GHz [71]. Sometimes, the noise can be very important [72].

From these the author thinks , the biological effects of an IMF-MFs or a RF-MFs can be explained by Equation 2.

Here, because of IMF-MFs or RF-MFs as external field, the wireless electromagnetic noise of the surroundings and external field all can be the alternating field, and B_0 is the sum both GMF and amplitude of low frequency part of the wireless electromagnetic noise that may be regarded as static just like the case of part 3.3.

3.7. The Hyperfine Coupling Radical Pair Mechanism of Biological Effects on Pulsed Magnetic Fields

Chen, et al. [44] results suggested that early an impulsed electromagnetic field therapy produced early and significant benefit in central nervous regeneration. Sun, et al. [43]; Hei, et al. [45]; Zhai, et al. [46]; Martino, et al. [47] reported other biological effects of an impulsed magnetic field. Because an impulse signal can be divided into different frequency parts, an impulsed MF is combined with ELF-MFs, IMF-MFs and RF-MFs, and the biological effects of an impulsed MF is comprehensive results with ELF-MFs, IMF-MFs and RF-MFs. That is to say, the biological effects of impulsed MFs can be explained by Equation 2. Here, because of impulsed MFs as external field, the wireless electromagnetic noise of the surroundings and external field all can be the alternating field, and B_0 is the sum both GMF and amplitude of low frequency part of the wireless electromagnetic noise plus the base or harmonics of the impulsed MFs that may be regarded as static. Prato [82] showed that induction of analgesia could be very significantly increased if an impulsed magnetic field was used rather than a sinuidal field. The result can be explained very well using the hyperfine coupling radial pair mechanism.Because the harmonics of the impulsed MFs satisfied the double eigenvalue $\omega_0 = \gamma B_0, \omega = 2\omega_0$,the difference of results between a pulsed magnetic field and a sinuidal field is caused based on Equation 2.

4. Discussion

Some references [1]; [25]; [29]; [36]; [42]; [62]; [87]; [94]; [101]; [102] discussed the problems of the irreproducible bioeffects of weak magnetic fields. Some references [1]; [36]; [62]; [101]; [102] explained the reasons in different view points. What are the primary physical mechanisms of the problems? In this study the author gives one possible common mechanism of bioeffects of weak magnetic fields. In this mechanism, the noise can be very important sometimes. Because of the differences of the noise in different time and different place, some bioeffects experimental results on weak magnetic fields may be not same.

In the different bioeffects experiments of different weak magnetic fields, only ones of hypomagnetic(or near-null magnetic) fields are good in reproduction to the author's knowledge. Why is this? It is one aim of next research. In part 2, B_{rf} is much weaker compared with B_0 is assumed, so the time-dependent perturbation theory can be used to calculate the yield of the singlet state. When B_{rf} is not much weaker compared with B_0,that is to say the noise is not very much weak compared with external magnetic fields, what is the influence of the noise accordingly? It is the the other aim of next research.

In part 2, A_z is assumed relatively strong compared with the external field in Xu, et al. [65] Equation 2 is given. When A_z is not relatively strong compared with the external field, Equation 2 is not the mechanism of bioeffects of weak magnetic fields.

In part 1,the arthor gives that in this study, the weak MFs are ones that can not produce thermal bioeffects not only limited below 1mT.Why? Though [67] expressed that for strong magnetic fields (>100mT) singlet-triplet interconversion can occur by virtue of the different Zeeman interactions,that is to say,the hyperfine coupling radical pair mechanism may have weaker influence in biological effects compared to the magnetic fields below 1mT, Hore and Mouritsen [66] pointed out that tiny interactions can have profound effects but only if the system has previously been brought into an appropriate state. The author thinks the weaker influence of the hyperfine coupling radical pair mechanism may be the tiny interaction when the magnetic fields is stronger than 1mT.

When the static magnetic field is stronger than 200mT, water can be magnetized [103]. Magnetized water maybe have some magnetic bioeffects along with above hyperfine coupling radical pair mechanisms in organisms. When the magnetic field is so strong that it can produce thermal bioeffects, the bioeffects produced through above hyperfine coupling radical pair mechanisms may be mixed with thermal ones.

5. Summary

The primary physical mechanism which can be related to the biological effects of weak magnetic fields is one key problem and has not been clarified. In this article,the author builds one bridge that has connected the bird navigation and bioeffects of other magnetic fields in possible common explanatory mechanisms, because the author expands Equations 1 and 2 to be used to other weak magnetic fields including impulsed ones.That is to say the author proposes one hyperfine coupling radical pair mechanism in all weak magnetic fields and explains the reasons of the irreproducible bioeffects of them . Giving one possible common mechanism of bioeffects of all different weak MFs including an impulsed ones is the first to the author's known. Here, the weak MFs are ones that can not produce thermal bioeffects not only limited below 1mT.

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