Response

Response to Comments by Frank Barnes and Ben Greenebaum on "A Physical Mechanism of Magnetoreception: Extension and Analysis"

We appreciate the opportunity to respond to the comment by Dr. Frank Barnes and Dr. Ben Greenebaum. We limit our response to those statements that directly relate to our recently published model on magnetoreception [Binhi and Prato, 2017].

While not directly criticizing our model, Barnes and Greenebaum (B&G later) point to a limitation that does not take into account an arbitrary angle between AC and DC magnetic fields (MFs), as we only considered the parallel configuration. Besides the reasons presented in our publication, here we consider another that is relevant to this discussion. Any angle between AC and DC MF would mean that there is an AC MF component perpendicular to the DC one. This results, in general, in a magnetic moment that periodically changes in energy as transitions occur between quantum levels. When out of resonance, these transitions are negligible in terms of our model and do not affect our results and statements. At resonance, even in the case of a long thermal relaxation, the motion of moments is complicated. In a classical view, the end of a moment vector begins to follow a spiral trajectory on a sphere instead of a perfect precessional circle. This requires an additional averaging over the polar angle. Such averaging would lead, in our rough estimate, to an order of magnitude decrease in the probability of possible biological outcome. Thus, our mechanism persists in a non-parallel AC-DC MF, unless a magnetic resonance occurs that significantly reduces the effect we describe. Remember that we are speaking about weak extremely low frequency (ELF) MFs, i.e., those less than about 100 microT and 100 Hz. In these conditions, as we stated in Binhi and Prato [2017], our model's prediction is in line with many experimental observations of bioeffects in parallel AC-DC MFs. We agree that more intense and frequent MF oscillations, particularly in the non-parallel configuration, could, in principle, "awaken" other mechanisms of magnetoreception. However, it is unlikely that they would also be effective in weak ELF MFs for the following reasons.

In our work, we have avoided a model that is dependent on quantum transitions as most of the literature on effects has been associated with exposures that do not meet the needed resonance prescription. Contrary to this, B&G argue that this would not be enough and promote another approach where quantum transitions play the main role. However, we suggest that implicit in their letter are three underlying assumptions with which we disagree: (1) that quantum transitions are necessary for a magnetic biological effect, (2) such transitions are associated with downstream biochemical events, and (3) there is a workable example for the two statements above: the radical pair mechanism (RPM).

First, why should quantum transitions necessarily cause a biological response? (i) As we said above, a complicated motion of magnetic moments in non-parallel AC-DC MFs decreases the biological effect significantly. (ii) Nuclear quantum transitions extensively utilized in hundreds of millions of MRI procedures have shown no biological effects. (iii) Inducing a significant difference in populations of magnetic moment quantum levels in the geomagnetic field (GMF) by means of ELF MFs would be impossible, as this would require months of a coherent excitation, even in the absence of dissipation.

Second, B&G note that we did not show "how the cessation of precession creates a molecular change that would result in downstream differences." Our response is that adding quantum transitions changes nothing as argued by (iii) above. Furthermore, any such transitions

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will result in magnetic moment oscillations that are distributed over a sphere rather than the circle, which makes them even less likely to connect to downstream events. In our model, we explicitly connect motion peculiarities with subsequent biophysical events, though in an abstract way. That is, we specify that oscillations of the precessional circular motion should be accompanied by oscillations in the induced biophysical process, which has allowed us to build an effective model.

Third, B&G indicate the RPM as one relevant to magnetoreception, where quantum transitions in singlet-triplet states lead to a chemical shift. However, we argue that this does not ensure that a similar chemical shift will occur with other quantum mechanical transitions that do not involve spin-coherent pairs of radicals such as proton transitions that form the basis of MRI. In addition, by fundamental physical constraints, RPM is effective only in the mT range. Available indirect evidence of its possible involvement in biological effects at the microT level remain unconvincing. That it apparently works in some bird's magnetic orientation in the GMF is probably because RP-carrying cryptochromes form an ordered array in the bird's eye retina, so that the bird's brain can significantly enhance the signal-to-noise ratio and get a suitable sensitivity even with an mT-sensitivity of single RP sensors. With respect to organisms, where there is no evolutionary-developed magnetic receptors such ordered arrays are unlikely to occur by chance.

In regard to the DC-only hypomagnetic field effect — which our model predicts numerically along with the AC-DC effects — this effect could be, of course, described by different theoretical approaches. In the classical approach that we used, a zero MF means a stop of precession of all magnetic moments. In the quantum approach, it corresponds to a level crossing of the associated states. B&G prefer this latter terminology, adding that thermal transitions are required for the hypomagnetic (HMF) effect to occur. Regardless of their nature, magnetic or thermal, any transitions will cause, as we saw, the magnetic moments to move in an intricate manner, which should minimize possible connection to subsequent biophysical events and hence biological output.

For all these reasons we prefer our explanation, which does not require quantum transitions. What is needed are reliable and well-reproduced experiments undertaken during HMF exposure that are designed to reveal characteristics of the MF target, such as the gyromagnetic ratio and coherence time.

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REFERENCE

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