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Is magnetic resonance imaging of human brain is harmful?

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ABSTRACT

In human brains, there are a lot of macroscopic (~100 nm) magnetite granules. Exposure of the patient's head in high strength magnetic fields could lead to penetrance of those particles into brain neurons and their staying there for a long period. That conclusion is the consequence of calculations based on the equations describing the dynamics of those particles under the action of ponderomotive magnetic, elastic and viscous forces. The role of iron in brain metabolism is not conclusively clear but there is evidence of the connection between excess iron and neurodegenerative diseases. In this regard, we consider it necessary to look more carefully at the matter of safety for brain magnetic resonance imaging.

1. Introduction

20 years ago J.L. Kirschvink established, with the help of ultra-sensitive magnetometric investigations, the existence of ferromagnetic inclusions in human brain tissues [1]. Electron microscopy and diffraction along with the element analysis showed that those are magnetite nanocrystals Fe_3O_4 (or $Fe^{2+}Fe_2^{3+}O_4$) with typical sizes of $\ell = 10$–200 nm. The concentration of such granules varies from $\sim 5 \cdot 10^6$ per gram in the brain itself to $\sim 10^8$ per gram in dura and pia mater. The latter links closely on to the brain surface and penetrates deep into brain sulcuses.

According to observations, magnetic nanogranules are accumulated in groups of 50–100 crystals. They are likely natural products of biomineralization and dispersed uniformly within all celebral lobes, cerebellum, basal ganglia and midbrain. Later, those examinations have been confirmed by other authors too (see, for instance, [2], where magnetite nanogranules of $\ell \lesssim 100$ nm size have been revealed in hippocampus with TEM-technique, and [3], where synchrotron X-rays have been used).

It is the large granule volume which is crucial for strong effect of magnetic field H. In fact, the necessary condition for strong interaction is $MH \gg kT$, where $M \sim \mu_B(V/a^3)$ is the magnetic moment of the particle (μ_B is the Bohr magneton, V is its volume, $a \sim 0.5$ nm is the lattice constant), and kT is the thermal energy. For $H \sim 3$ kOe we need $V \gg 1000$ nm^3 that corresponds to the particle size of $\ell \gtrsim 20$–30 nm. Ferromagnetic granules in brain just meet that condition. The question might be asked why we concern only with ferromagnetic particles in the brain but not anywhere else? The thing is that large magnetic moments (being proportional to the volume of ferromagnetic particle) is really crucial, and we do not know some other examples of such large ferromagnetic entities in human organism.

Mentioned ferromagnetic granules are situated in the inter-cell brain space. With their high (due to the single-domain magnetic structure) magnetic moment, they could experience strong mechanical forces and/or mechanical moments under external magnetic field [4,5]. As a result, they would tend to move or turn, having an effect on the neighboring brain elements (neurons, ganglion cells, axons, etc.). That is especially important in high magnetic fields which are used in diagnostic apparatus like magnetic resonance tomograph (MRT) with the field of $H \approx 10^3$–10^4 Oe.

For the last 10 years we observed the successive transition from $\sim 10^3$ to $\sim 10^4$ Oe resulting in corresponding increasing the spatial resolution. The higher the magnetic field, the higher mechanical forces and torques affecting ferromagnetic granules. So, the problem becomes more and more actual with rising MRT-generations.

Below, we will be interested in the question "Could magnetic granules in magnetic field have so strong impact on the brain elements that some of those elements turn out to be injured?". We hold an interest in a qualitative answer to that question, so we consider some simplified qualitative model. All quantitative results are numerical estimates.

Our goal is once again to draw attention to the problem of the potential negative effect of high magnetic field on a human being. Our estimates (cf. below) give grounds for that.

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2. Ferromagnetic granule in brain

Granule material (magnetite) is the ferrite (or ferrimagnetic) which has two nonequivalent sublattices of magnetic ions (Fe^{3+} and Fe^{2+}) occupying the tetrahedral (A) and octahedral (B) positions, respectively [6,7]. The main magnetic interaction constitutes antiferromagnetic interaction between Fe^{3+}-ions of different sublattices, which causes an antiparallel state of their magnetic moments. In that case, the net magnetization, produced by Fe^{2+}-ions, exists at temperatures, lower than the Curie temperature $T_C = 858$ K. At room temperature, the saturation magnetic moment of bulk magnetite equals $I_s = 480$ G. Though I_s-value drops with reducing nanoparticle dimensions, for $\ell \gtrsim 20$ nm that effect is negligible.

In cubic magnetite crystals, there is the intrinsic magnetic anisotropy which makes the magnetic energy W_M be dependent on the direction of the magnetic moment relative to crystal axes [6]:

$$W_I = K_1 V(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2), \tag{1}$$

where $K_1 \approx -1.1 \cdot 10^5$ erg/cm^3 is the room-temperature anisotropy constant, V is the crystal volume, α_i are direction cosines of the magnetization vector relative to the three crystal axes ($i = 1,2,3$). As $K_1 < 0$, the easy magnetization axes are the $\langle 111 \rangle$ directions. In that case, the energy gain is maximum and equals ($\alpha_i^2 = 1/3$)

$$W_I^{<111>} = \frac{1}{3}K_1 V. \tag{2}$$

Apart from the crystal magnetic anisotropy, characterized by the energy W_M, there is the additional source of the anisotropy – the shape anisotropy, that makes the magnetic moment be directed along the long size of a non-spherical particle. For the particle, which is the ellipsoid of revolution with axes $a > b = c$ (see Fig. 1), the relevant shape anisotropy magnetic energy reads

$$W_s = \frac{1}{2}I_s^2 V \nu \sin^2(\beta - \gamma), \tag{3}$$

where β, γ are angles between the external magnetic field and, correspondingly, the long ellipsoid axis or the particle magnetic moment. As for ν, it is the form-factor depending on the particle non-sphericity. It equals to the difference between demagnetizing factors along the two extremal ellipsoid axes b and a. Remarkably, even at small granule non-sphericity, when the axes ratio equals just $a/b = 1.25$, the parameter ν turns out to be ≈ 1 (the maximum value, for strongly elongated ellipsoidal granules, $\nu \approx 6$).

Small magnetite granules are single-domain particles, so their magnetic moment is proportional to the saturation magnetization and equals $M = I_s V$. Such a single-domain granule is the two-level system which, due to the magnetic anisotropy, has two stable states of the magnetic moment relative to the magnetization easy axis. Magnetic characteristics of magnetite are such that for $\nu \gtrsim 1$ (i.e., even for slightly non-spherical granules) $\nu I_s^2/2 \gg K_1/3$. This means that the shape anisotropy, resulting from the granule non-sphericity, is the most important out of the two outlined magnetic anisotropy types.

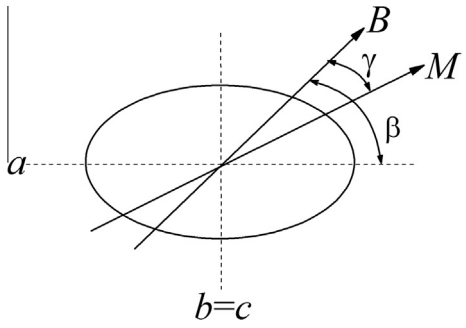

Fig. 1. Ellipsoidal single-domain magnetite granule in magnetic field.

Now, with neglecting crystal anisotropy, the problem of ferromagnetic granule magnetization is significantly simplified. To calculate its magnetic energy W in external magnetic field H one needs to add Zeeman enehgy in the right-hand side of Eq. (3):

$$\frac{W}{V} = \frac{1}{2}I_s^2 \nu \sin^2(\beta - \gamma) - HI_s \cos\gamma. \tag{4}$$

The latter equation could be written in the dimensionless form

$$w = \sin^2(\beta - \gamma) - h_\nu \cos\gamma, \tag{5}$$

where $w \equiv 2W/\nu I_s^2 V$ is the reduced energy, $h_\nu \equiv 2H/\nu I_s$ is the reduced magnetic field. (If $\nu = 1$, the value $h_\nu = 1$ corresponds to the field $H \approx 250$ Oe).

In zero magnetic field, the direction of the granule magnetic moment coincides with the easy magnetic axis, whose role the big ellipsoid axis plays. Because initially granules orientate randomly, after the switching the field on angles β between its direction and big granules' axes take random values too. For each specific value of that angle, Eq. (5) describes how the equilibrium (corresponding to the minimum of the magnetic energy w) angle γ between the granule magnetic moment and the field direction changes. That angle is very important because it is just the angle that determines the value of the mechanical moment

$$L_H = MH \sin\gamma, \tag{6}$$

affecting the granule.

In magnetic field, under the action of that moment the granule begins to turn, its big axis approaches to the field direction and the angle β reduces. Simultaneously, the angle γ drops being always less than β. Herewith, from Eq. (5) follows that in relatively weak fields ($h_\nu \lesssim 1.5$) the relation between those angles is practically linear:

$$\gamma \approx s_H \beta, \quad s_H = \frac{2}{2 + h_\nu}. \tag{7}$$

Therefore, Eq. (6) could be written in the form

$$L_H(t) = MH \sin[s_H \beta(t)], \tag{8}$$

where s_H is the coefficient which (in a given field H) keeps constant in the process of the granule motion. That equation describes non-decaying granule oscillations and should be adjusted by taking into account other forces, as well.

Granule rotation leads to the local deformation ζ of the membrane of a neighboring neuron. This results in appearing the elastic force $F_\zeta \sim k_{\text{eff}}\zeta$, that is expressed via the effective elastic coefficient k_{eff} and prevents the granule movement. The moment L_ζ, corresponding to that force, can be expressed via the granule turning angle β (see Fig. 1):

$$L_\zeta(t) \sim k_{\text{eff}} \ell^2 [\beta_0 - \beta(t)], \tag{9}$$

where β_0 is the angle between the field direction and the big granule axis in the initial point of time.

One could estimate the coefficient k_{eff} value applying the known result of the elasticity theory. Concentrated force F applied to the shell of the thickness Δ, the radius R and material of the Young's modulus E induces the inflection $\zeta \sim FR/E\Delta^2$ [8]. Herefrom, it follows $k_{\text{eff}} \sim E\Delta^2/R$, that for neuron membrane of the thickness $\Delta \sim 10$ nm, the radius $R \sim 10$ μm and Young's modulus $E \sim 10^4$ dn/cm^2 [9] gives $k_{\text{eff}} \sim 10^{-7}$ dn/cm. At that, the size of the inflection area amounts to $d \sim (R\Delta)^{1/2} \sim 10^{-5}$ cm. Hence,