Noninvasive Detection of Magnetic Particles in Biological Nanomaterials using Magnetic Field Sensors

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Introduction

The vital activity of an organism is accompanied by flowing of very weak electrical currents (biocurrents) inside it. These currents are induced by electrical activity of cells, mainly muscle and nerve. Biocurrents have very low values and induce magnetic fields of $B \sim 10^{-15}$–10^{-11} T. In addition, weak magnetic fields can be induced inside an organism by ferromagnetic particles, which were accidentally trapped or purposefully introduced into it. The external magnetic field discloses inhomogeneities of the magnetic susceptibility of organs, which work as sources of magnetic fields close to the boundary of magnetic vacuum ($B \leq 10^{-16}$ T). In view of the aforesaid, the development of magnetic field sensors (MFSs) for detecting ultraweak magnetic fields ($B \leq 10^{-10}$ T) is of great practical importance.

Particular attention should be paid to magnetic particle detection methods and tools, which are widely used in medical practice. The materials used for this purpose contain magnetic particles of micron, submicron, and nanometer sizes. A special place is held by carbon nanotubes (CNTs) and nanomaterials based on them. In particular, CNTs can include catalytic ferromagnetic particles (iron, nickel, etc.), as well as other magnetic particles encapsulated therein. CNTs can be functionalized by magnetic nanoparticles and vector fragments, which will ensure targeted drug delivery to a desired organ. Superparamagnetic nanoparticles (e.g., iron particles 5–30 nm in size) encapsulated in CNTs can significantly improve the contrast of magnetic resonance imaging, which is extremely important for diagnostics. Three-dimensional (3D) nanocomposites containing bovine serum albumin (BSA, matrix) and CNTs (filler) or their aqueous suspensions are promising for application in different bioresorbable bone tissue implants or biofuels for laser welding of biological tissues [1, 2]. Note that BSA is a biological material widely used in medicine. The BSA/CNT nanocomposite characterized by the sufficiently high strength and biocompatibility is promising for creating different implants, including bone or cartilage tissue substitutes. Certainly, an implant located inside a human body can only be controlled noninvasively. Therefore, of great interest is nondestructive control of CNT-containing biological objects using MFSs. This technique makes it possible to monitor noninvasively the conditions of implants or laser biological tissue welding sutures.

Here, we estimate the sizes of magnetic particles that can be detected by MFSs with different magnetosensitivities.

Calculation Technique

In the calculations, we used the characteristics of modern ultra-weak magnetic field sensors operating in the differential magnetometer (gradiometer) mode. The minimum size of an iron magnetic particle detected by a differential magnetometer against the Earth's magnetic field background was estimated using the equation [3]

$$r \approx \left[\frac{2B_0}{\Delta B} \left[\left(\frac{1}{l} \right)^3 - \left(\frac{1}{l+l_0} \right)^3 \right] \right]^{-\frac{1}{3}}. \quad (1)$$

Here, r – is the minimum radius of a spherical iron magnetic particle, ΔB is the resolution of the differential magnetometer (the minimum detected magnetic field), l is the distance between the nearest part of the magnetometer and the particle center, and l_0 is the magnetometer base, i.e., the distance between its receiving parts. The axis of differential magnetometer receiving coils and the detected magnetic particle lie in the same line.

Estimate (1) was obtained under the obvious assumptions of the magnetic permeability of the background (air) negligible with respect to the magnetic permeability of an iron particle and $B_0 \approx 50$ μT. The minimum detected magnetic field is at a level of the magnetometer resolution ($B \approx \Delta B$).

Results

Figure 1 shows the $r(l)$ dependences obtained at different magnetometer resolutions. It can be seen that the high resolving power of the magnetometer ($\Delta B \sim 10^{-15}$ T) and its proximity to a magnetic particle ($l \sim 1$ mm) make it possible to detect particles of submicron sizes ($r \sim 0.1$ μm). In addition, as the l value decreases, the r value drops to nanometers. However, the above-mentioned values ($\Delta B \sim 10^{-15}$ T, $l \leq 1$ mm) can be attained using a SQUID (Superconducting Quantum Interference Device) magnetometer or a combined MFS (CMFS) [4,5]. Equation (1) was derived under the condition that the magnetometer receiving coil diameters are negligible as compared with the size l, which is not valid for SQUIDs in the range of $l \leq 10$ mm. This degrades the r resolution. Therefore, it is more advantageous to use CMFSs with a nanostructured active band, which are based on a magnetic field concentrator formed from a superconducting (niobium) film and giant magnetoresistance layers (permalloy) as a magnetosensitive element [6]. In such CMFSs, the receiving coil diameter (≤ 2 mm) can be several times smaller than in commercial SQUIDs at a resolution of $\Delta B \sim 10^{-14}$–10^{-15} T [7].

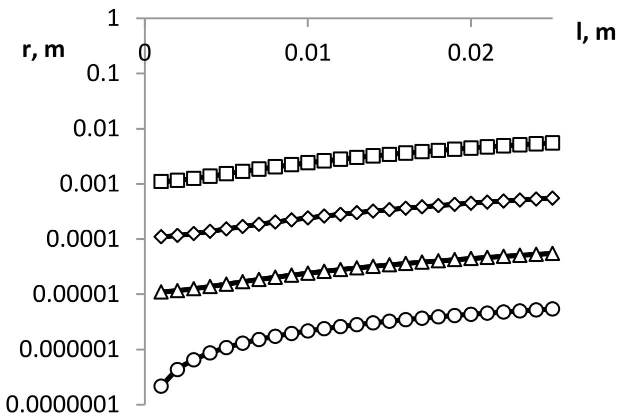

Figure 1. $r(l)$ dependence at different ΔB values, T: o – 10^{-15}; Δ – 10^{-12}; ◊ – 10^{-9}; □ – 10^{-6}

At $\Delta B \sim 10^{-12}$ T, magnetic particles with $r \sim 1$ μm can be detected at a distance of $l \leq 1$ mm. In this case, SQUIDs and CMFSs, as well as nuclear magnetic resonance magnetometers with laser pumping (NMR LP) and magnetomodulation sensors (MMS) containing high-temperature superconducting ceramic materials [8] can be used. At $\Delta B \sim 10^{-9}$ T and $\Delta B \sim 10^{-6}$ T at a distance of $l \leq 1$ mm, magnetic particles 0.1 and 1 mm in size, respectively, can be detected. In this case, MFSs based on the giant magnetoresistance (GMR) and Hall effects, respectively, can be used.

SQUIDs, CMFSs, and MMSs are the most highly sensitive magnetic field sensors, which allow magnetic particles 0.1–10 μm in size to be detected; however, they require cryogenic cooling (operation temperatures of 4–77 K). The NMR LP magnetic-field sensors based on the GMR and Hall effects have the lower sensitivity, but can operate at room temperature and detect coarser particles ($r \sim$ 0.01–1 mm).

Conclusions

The estimated values $r \geq 0.1$ μm are much higher than the approximate diameter of a catalytic iron particle (~1 nm) in a single CNT; therefore, the discussed MFSs cannot be used for detecting single nanotubes. However, in nanomaterials they are often aggregated in bundles, clusters, or globules. In particular, in a BSA/CNT nanomaterial, globule aggregates 1–5 μm in diameter are formed, which contain a great number of nanotubes, which are apparently fixed by the considered MFSs. The latter can probably feel the CNT framing.

The highly sensitive MFSs are applied also in production of very-large-scale integrated circuits. They serve as basic components of magnetic microscopes (Neocera type) used for controlling microcircuit design faults by remote measurements of weak currents between elements [9, 10]. In future, this control will be relevant for CNT-based data storage. Indeed, the nanotube walls can work as separators of magnetic particles located at their ends. This promises high data storage densities (over 10^{12} bit/cm^2).

Thus, the highest magnetic-field sensitivity is characteristic of SQUID magnetometers and combined magnetic field sensors with nanostructured active bands. The estimated sizes of iron particles detected by these devices at a distance of ≤ 1 mm lie in the submicron and nanometer regions (≤ 0.1 μm). The same MFSs can be used to detect carbon nanotube aggregates ≤ 5 μm in size.

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