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Magnetometric Measurements of Low Concentration of Coated Fe_3O_4 Nanoparticles

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A modified RF SQUID system with the 2^{nd} order gradiometer has been tested for the purposes of detecting the magnetic nanoparticles as potential carriers of biological medicament. The paper presents basic information about the sensitivity of the system and its use for quantification of low concentration of coated Fe_3O_4 magnetic nanoparticles. Model measurements provided information that enabled us to define the parameter influencing the experimental results. The volume of the biological object and its distance from the antenna appear to have the significant influence on the measurement accuracy.

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1. Introduction

The principle of measurement of the presence of magnetic nanoparticles (MNPs), located in the specific organ of an animal or human, is in the detection of the magnetic response B_a of MNPs to applied magnetic field. Due to very low signal response it is necessary to use the most sensitive magnetic field sensor - SQUID [1, 2, 3]. Besides the very weak signal detected, the additional complication is the fact that various organs of the body do not have well defined dimensions and configuration, which means that the values of the magnetic response should be corrected primarily to the volume of the measured object (organ). Another important parameter is the position of the object with respect to the sensor, especially when the sensor is close to the measured object. Therefore we have investigated what kind of errors of the measured signal may occur depending on the volume of the measured object and its position with respect to the sensor.

2. Method

Our SQUID system (SQS) consists of the RF SQUID, 2^{nd} order gradiometer, electronic modules, an acrylic platform for moving models and the magnetization system with Helmholtz coils generating the AC magnetic field of $B_{pp} = 2.85 \times 10^{-4}$ T in the direction of the gradiometer. The magnetization system is driven by current with the frequency of 2.8 Hz. The spectral sensitivity of SQS is $\approx 2 \times 10^{-14}$ T·Hz$^{-1/2}$.

SQS detects the changes in the axial magnetic induction B_a, which depends on the amount of MNPs in a carrier liquid, volume of the measured object and its position with respect to the sensor. To determine the effect of these parameters we performed the model measurements with eight cuboid shaped acrylic containers which volume V_M increases from 2×10^{-6} m^3 to 1024×10^{-6} m^3. The containers were filled with distilled water as a calibration liquid or with MNPs (Fe_3O_4, mean diameter 85 nm, covered with a citric acid) in the aqueous suspension of the concentration $c_{MNP} = 10$ μg/ml. The models were centered to the gradiometer axis. The distance between surface of the model and bottom of the cryostat d_M has been changed from 0.002 m to 0.052 m with step of 0.01 m. Dependences of the output voltage $U_{PP} \sim B_a$ on V_M and distance d_M were obtained (Fig. 1).

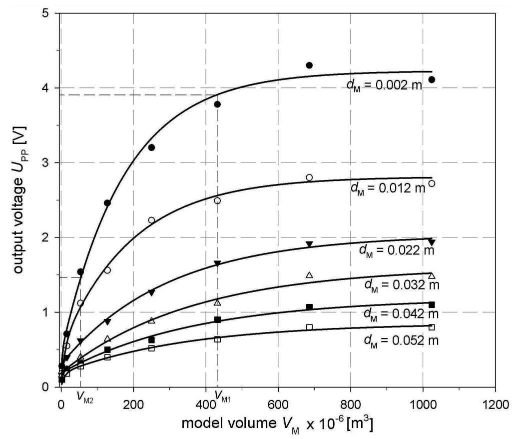

Fig. 1. The measured values of U_{PP} for models with $c_{MNP} = 10$ μg/ml and various volumes V_M. The distance d_M between the sensor and the measured object is a parameter.

In order to determine the content of MNPs, it was necessary to measure the dependence of U_{PP} on c_{MNP}. For example, the model with $V_{M2} = 54 \times 10^{-6}$ m^3 at $d_M = 0.002$ m was measured with various c_{MNP} 3, 6.2, 12.5, 25 and 50 μg/ml. U_{PP} was recorded by the oscilloscope in XY regime and compared with the signal of the applied magnetic field. By considering the tilting of the elliptical image on the oscilloscope the para- or diamagnetic properties of suspensions could be determined (Fig. 2).

In order to obtain information about the magnetic properties of MNPs in the suspension with the same

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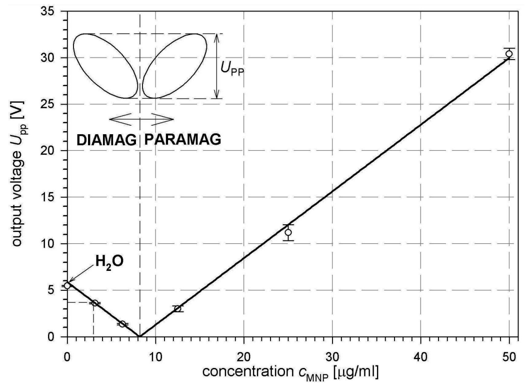

Fig. 2. The dependence of U_{PP} on c_{MNP} for d_M = 0.002 m, $V_{M2} = 54 \times 10^{-6}$ m^3.

c_{MNP}, $M(H)$ measurements on microsamples of the volume of 80 μl were performed on Quantum Design MPMS XL SQUID magnetometer (Fig. 3).

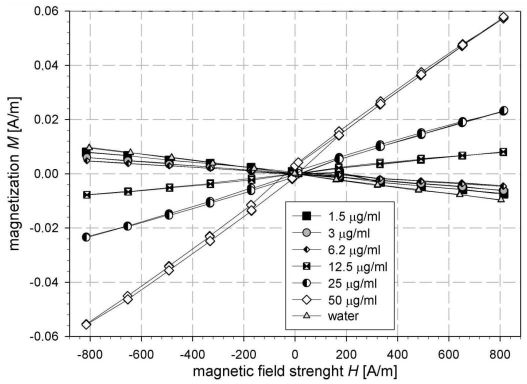

Fig. 3. Magnetization curves of suspensions containing MNPs with various concentrations.

3. Results and discussion

Based on obtained results it is clear that the quantification of the deposited MNPs in different biological organs will depend not only on the level of detected signal but also on the accuracy of the volume and position determination. An incorrect determination of the volume produces error of U_{PP}, Fig. 1. It is evident that the smaller volume of an object, the greater the error is. Let us assume that in measurement of the object (organ) at $d_M = 0.002$ m, the error in determination of the volume of $V_{M1} = 432 \times 10^{-6}$ m^3 is $\pm 10\%$. Then the error of U_{PP} is $\pm 2\%$. In the case of eight times smaller object (of the volume of $V_{M2} = 54 \times 10^{-6}$ m^3) in the same position and again incorrect determination of the volume with error $\pm 10\%$, the error of U_{PP} is already $\pm 8\%$. Similarly, U_{PP} errors occur if d_M is set incorrectly, for example in repeated measurements. Let us compare measurements on two models V_{M1} and V_{M2} at the distance $d_M = 0.002$ m (Fig. 1). In case of incorrect determination of d_M, e.g. increasing by 0.002 m, the error of the U_{PP} will be for V_{M1} around 8.5% and for V_{M2} around 7%.

The recorded dependence in Fig. 2 allows to define the minimum detectable level of c_{MNP} for this type of MNPs. Using the model with $V_{M2} = 54 \times 10^{-6}$ m^3 and $d_M = 0.002$ m, knowing that the SQS background noise is $U_{PPN} \approx 200$ mV, $U_{PPWater} = 5.9$ V, for chosen 20 dB SNR this level of c_{MNP} is ≈ 3 μg/ml. From Fig. 1, the minimum detectable level of c_{MNP} for model with $V_{M3} = 2 \times 10^{-6}$ m^3 and $d_M = 0.002$ m, whose detected signal is approx. 5.5 times weaker than that from model with V_{M2}, can be estimated to be 18–20 μg/ml. This information is particularly important for the measurement of c_{MNP} in small experimental animals in which the volume of the organs under test (liver, lungs, kidneys, etc.) generally does not exceed the above values.

From $M(H)$ measurements (Fig. 3.), the volume magnetic susceptibility χ was determined and the linear dependence between c_{MNP} and χ was obtained. Also the transition point from dia- to paramagnetic properties of the suspension was proved to be approximately 8 μg/ml.

Concerning the shape of the model, these measurements were made for only one type – cuboid. In the future research we shall also aim at other shapes – sphere and ellipsoid.

3. Conclusion

Using the SQUID system, the model measurements allow to analyze the process of determination of low concentrations of MNPs and to point out some important circumstances and errors that may significantly affect the accuracy of quantification. It was shown that special attention to the position of the object with respect to sensor should be paid. Successful quantification can be provided only if the volume of the object is defined as accurately as possible.

Acknowledgments

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References

[1] A.A.O. Carneiro, J.P. Fernandes, M.A. Zago, D.T. Covas, I.L. Angulo, O. Baffa, *Rev. Sci. Instrum.* **74**, 3098 (2003).

[2] F. Boháková, I. Šimáček, *J. Magn. Magn. Mat.* **267**, 357 (2003).

[3] S. Della Penna, C. Del Gratta, S. Di Luzio, V. Pizzella, K .Torquati, G.L. Romani, *Phys. Med. Biol.* **44**, N21 (1999).