Quantification of Low Concentration of Ferromagnetic Particles by SQUID Magnetometric Method

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Abstract

The results of direct measurements of the remanent magnetic induction (RMI) of some powdered ferromagnetic materials (PFM) with the help of the SQUID magnetometric system (SMS) are given. The study was performed to evaluate the magnetic characteristics of the powdered PFM and the dependencies of RMI on their planar concentration. Based on measurements of the groups of samples with PFM, the minimum measurable planar concentrations for selected materials were determined. Magnetic measurements of this kind may be useful for quantifying the lung dust retention in clinical practice.

1. Introduction

Using unique facilities of SMS in the non-invasive diagnostic method of some lung diseases - magnetopneumography - are known [1, 2, 3]. The method consists of exposing the chest to a uniform DC magnetic field and subsequently measuring RMI of the ferromagnetic particles in the lungs by scanning the subject's chest under a stationary probe. Magnetopneumography usually yields correct results based on statistical comparison measurement of group of subjects with lung dust retention and controls. The problems start up when an exact information about PFM quantity in the living tissues is requested. In order to get an improvement in accuracy of the measuring method of the lung contamination the measurement with low-volume samples with PFM were accomplished.

2. Materials and methods

We set up the groups of samples with PFM whose presence in the lungs is most likely. 20 mg of Co, Ni, Fe, γ– Fe_2O_3 and Fe_3O_4, with radius of up to 80 μm, were mixed separately with 20 cm^3 of magnetically clean epoxy 1200 without a hardening agent (density of epoxy is $\rho = 1160$ kg m^{-3}, dynamic viscosity $\eta = 2.6$ Pa s). The volume of the first sample was 1 cm^3 i.e., the initial volume concentration c_v was 1 mg cm^{-3} and following samples were of the volumes 0.5, 0.25 and 0.125 cm^3. The samples were prepared from the mixtures by weighting. After the sedimentation of PFM in the polyethylene vessels with base 1 cm^2 the particles created a continuous and uniform coating without a noticeable agglomeration on the bottom. Thus we got samples with planar concentration values from c_{p1} to c_{p4} equal to 1, 0.5, 0.25 and 0.125 mg cm^{-2} of PFM, respectively. Then the samples were magnetised in stages for 30 seconds by the external uniform magnetic fields of strengths $H_{m1} = 4$ kA m^{-1}, $H_{m2} = 15$ kA m^{-1}, $H_{m3} = 47$ kA m^{-1}, $H_{m4} = 150$ kA m^{-1} and $H_{m5} = 640$ kA m^{-1}. After each magnetisation procedure the samples were measured by the SQUID system with the sensitivity of 2×10^{-14} T $Hz^{-1/2}$ at white noise level [4]. The aerial of the measuring system was the second order axial gradiometer. The stand-off distance d between the gradiometer bottom coil and the sample

was 6 cm. Magnetic flux density B_r corresponding to the measured sample was determined as difference between the magnetic flux density values with and without the sample. A 10 Hz low-pass filter was used to cut the high frequency noise. At least, three identical samples from each of the concentration PFM were measured. Finally, the output signal was calculated as the average remanent magnetic induction B_{ra}.

3. Results

The dependence of B_{ra} magnitudes on the uniform magnetic field of strengths H_m for various c_p of powered Fe is in Fig. 1. Using the linear regression fit of B_{ra} versus c_p an excellent linear relationships with r = 0.99 - 0.974 were proved. Hence, we can assume

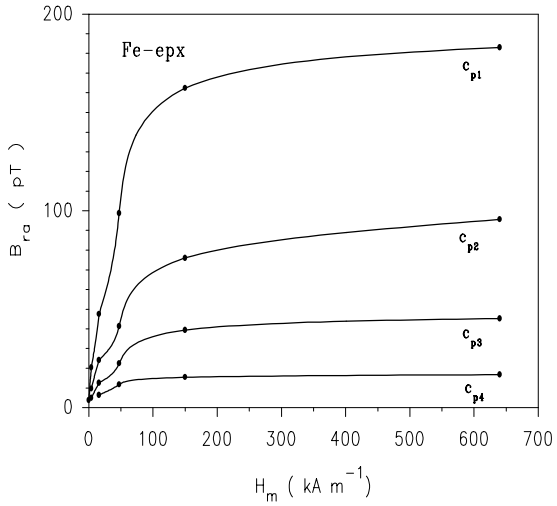

Fig. 1. The average remanent magnetic induction B_{ra} vs. uniform magnetic field of strength H_m for various planar concentration c_p

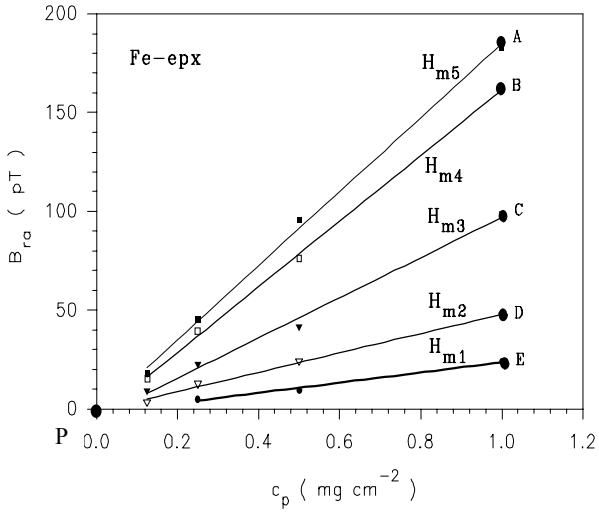

Fig. 2. The linear regression fit of B_{ra} versus c_p for various H_m.

that the linear dependence $B_{ra} = f(c_p)$ will be valid also for smaller c_p, i.e. as far as the minimum measurable concentration c_L. As the samples were measured in the static position, the dominant noise signal B_n was below the 1/f corner frequency. Figure 3 shows the real-time trace of this noise spectra. Three minutes time domain of this spectra displays B_n in the limits ± 1.5 pT, that is B_{np} = 3 pT pick to pick. Since the slopes of the regression lines define only approximately the actual slopes of the dependencies $B_{ra} = f(c_p)$, these lines were substituted for the lines p_{H1} up to p_{H5}. They are the connecting lines between the points A, B, C, D, E and the point P(0,0), Fig.4. Then, the final magnitude of c_L is the value of the x co-ordinate calculated from the point of intersection between one of the line p_H and selected level of B_{ra}. Hereby, the selected level of B_{ra} determines an eligible maximal error e_m for c_L. For example, if the signal-to-noise ratio is only 6 dB, e_m can achieve as far as ± 25%. If e_m is lower than ± 5 %, then B_{ra} must be minimally 30 pT.

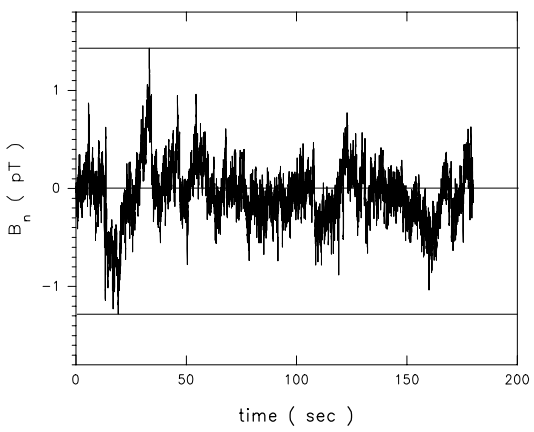

Fig. 3. The real-time trace of noise spectra.

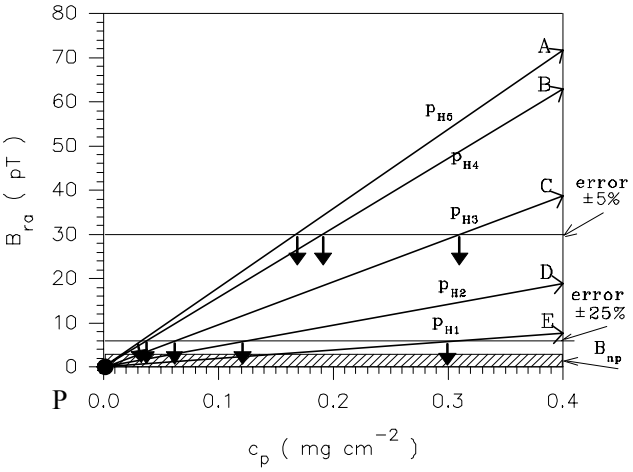

Fig. 4. The connecting lines p_{H1} to p_{H5}.

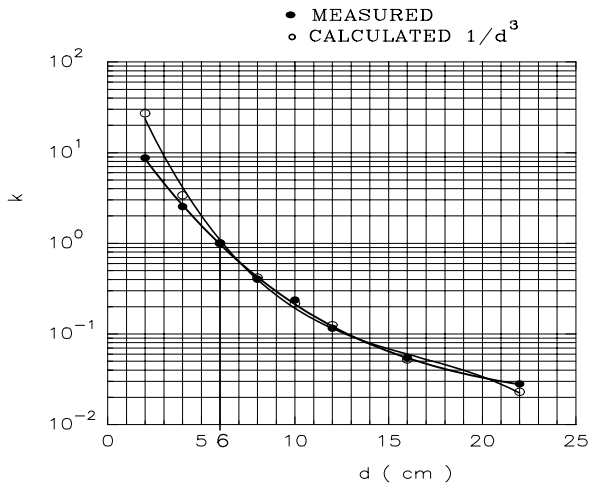

Fig.5. Stand-off distance *d* dependence of factor *k*.

These final values of c_L are in Tab. 1. This data are relevant to d = 6 cm between the first coil of the gradiometer and the bottom of the sample. It is known, that PFM in the living tissues are located in the various depth. Since magnetic field decreases as increasing the stand-off distance d, c_L is also as well depended on d. Hence, remanent magnetic induction B_{rx} was measured for some samples in different distances x and the factor $k = B_{rx}/B_{ra}$ was determined. The calculated and measured curves of factor k versus d are plotted in Fig. 5. Then, the minimum measurable concentration c_{Lx} for arbitrary d in the range from 2 to 22 cm can be calculated by formula $c_{Lx} = c_L/k$.

Table 1.

	Minimum measurable concentration c_L for powered ferromagnetic materials									
	Co (μg cm^{-2})		Fe (μg cm^{-2})		Ni (μg cm^{-2})		Fe_3O_4 (μg cm^{-2})		γ-Fe_2O_3 (μg cm^{-2})	
± e_m (%)	25	5	25	5	25	5	25	5	25	5
H_m (kA m^{-1})										
640	2.4	12	33.5	167.5	7.2	36	0.66	3.2	0.57	2.85
150	2.8	14	38.2	191	7.6	38	0.7	3.5	0.63	3.15
47	4.6	23	61.8	309	9.7	48.5	1.1	5.5	3	15
15	14.7	73.5	128	640	20	100	4.2	21	10	50
4	34.2	171	300	1500	92	460	4.6	23	13	66

4. Discussion

It is clear, that quantitative evaluation of PFM dispersed in a biological subject is complicated problem, since the final measured output signal is influenced by many disturbing signals. They have the origin mainly inside the human body and are coupled with some elastic and cellular forces. Our results can be applicable if it is assumed: i) influences from physiological resources and relaxation processes of RMI will be neglected and ii) the area of retained PFM will not be larger than 1 cm^2. This situation can be considered similar to that one in the lung tissue, where the contaminants are situated mostly in small local areas on the respiratory organs. As magnetopneumography is usually performed by object's movement under a pick-up system with the speed approximately 5 cm s^{-1}, the crucial noise is concentrated in the range below the 1/f corner frequency. We used a more complicated method for obtaining the minimum measurable concentration c_L because it was difficult to carry out the sets of samples with the accurate concentration of PFM which are close to c_L. On the contrary, the samples with the concentration 1 mg cm^{-2} of PFM can be reliably prepared. On that account this method is applicable for standard laboratory conditions when it is needful to test a SQUID system for specific biomagnetic measurements.

Acknowledgement

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