QUANTITATIVE ANALYSIS OF POWDERED FERROMAGNETIC MATERIALS CONTENT IN MAGNETOPNEUMOGRAPHY

Boháková Fatima, Šimáček Ivan

Institute of Measurement Science, Slovak Academy of Sciences, Bratislava, Slovakia

Abstract − Possibilities for quantifying the ferromagnetic particle contamination in human lungs with help of a rf SQUID system were studied. A tool for the analysis of the quantification of the measured data was developed. Conditions for the calculation of the particle concentration in human lungs from the measured remanent magnetic induction were established. The theoretical calculations were verified by measuring on physical lung models. The illustration of the method and a rough estimation of the concentration were carried out on an arc welder, with evidently contaminated lungs. The work also contains a discussion on problems associated with measuring the remanent magnetic induction in living organisms.

Keywords: biomagnetism, ferromagnetic particles, SQUID magnetopneumography

1. INTRODUCTION

The unique facilities of SQUID magnetopneumography in non-invasive diagnostic method of some lung diseases are known [1, 2]. The method consist of exposing the chest to a uniform DC magnetic field and subsequently measuring remanent magnetic induction of the powdered ferromagnetic particles (PFP) in the lungs by scanning the subject's chest by a stationary probe. The detection of trace amounts of magnetic substances in the lung was first reported by Cohen, subsequently studied by Kaliliomaki [3] and other authors. Magnetopneumography usually yields correct results based on statistical comparison measurements of group of subjects with lung dust retention and controls [4, 5]. Clinical practice of the occupational medicine faces the problem of quantifying the concentration of PMP in the lungs. The problems arise when an exact information about the PFP quantity in the living tissues is requested. Various methods have been tried to cope with this problem. In the forward solution the measured field is compared to that calculated from an ellipsoidal or a more elaborated model of lung [6, 7].

The aim of this study was to determine the total axial component of the remanent magnetic induction B_r in the space of the proximal coil of the aerial system of the SQUID measuring system from magnetized, fixed and spherically shaped PFP which were uniformly located in defined different large objects. Hence, the calculation of the relationship of the total magnetic induction originating from the magnetized PFP as a function of their mass concentration in different large sphere or ellipsoid models was performed. Using the SQUID magnetometric system with a second-order gradiometer, the computation was completed by measuring of selected models created with the defined concentration of PFP in the vax.

2. THEORY AND METHODS

2.1. General

To estimate the quantity and the spatial distribution of ferromagnetic particles in the lung it is necessary to consider many mutually dependent factors in the living organism, which complicate the interpretation of magnetometric data and make adequate corrections for them. The complexity of the problem of the quantification of PMP in magnetopneumography is schematically depicted on Fig. 1. The necessary operations leading to precise quantification can be summarised in the following points. There is a need:

a) to estimate the composition of the contaminating dust by analysing the samples of filtrates gain from the working environment of the person,

b) to define the physical parameters of dust particles, which affect long-time the ventilation process,

c) to determine the specific remanent magnetic moment m_{rs} ($Am^2 kg^{-1}$) of the ferro- or ferrimagnetic compounds of the contaminating fumes, which depends on the intensity of the applied magnetic field H_m, the size and shape of the particle; then the remanent magnetic moment of one particle m_p can be calculated,

d) to determine the position (frontal-rear thorax distance) and the volume (vital capacity) of the lung,

e) to obtain data about the: size, shape and position of the organs against the detector, the technical parameters of magnetometric system and the intensity and timing of the magnetisation process,

f) to measure the value of B_r of the magnetised organ,

g) to determine the value of the PFP concentration in human organs with the help of the model calculation and the measured value of m_p and B_r.

h) to correct this value of B_r with a system of correction factors which reflects the influence of physiological processes in the living tissue [2, 8].

In this paper we will follow the influence of the volume and shape of the organs on the value of remanent magnetization.
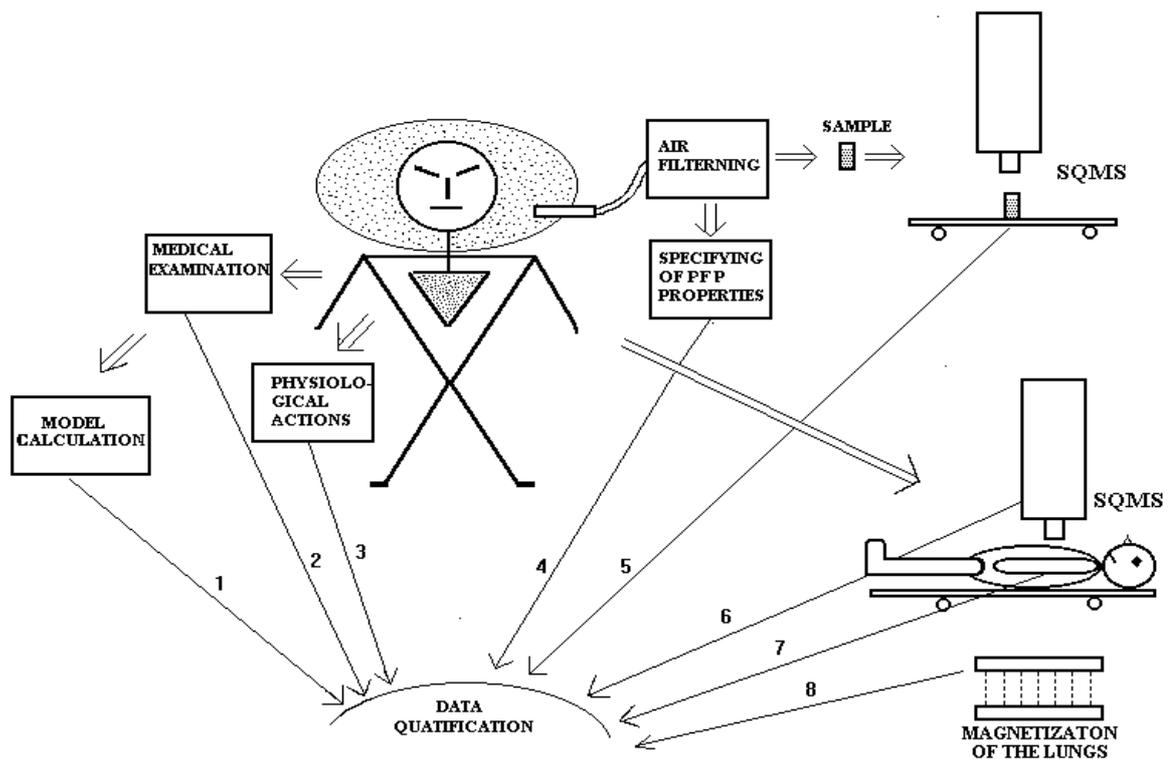
Fig.1. Functional block diagram of quantification of ferromagnetic contaminants in the lungs using SQMS (SQUID magnetometric system). Crucial data: 1. factor A_{max} (see (4)), 2. vital capacity V_c, frontal-rear thorax distance, X-ray picture, 3. relaxation curves of retained PFP, viscoelasticity of the particle environment, evaluation of the lung clearance mechanisms, lung ventilatory movements, mucus flow etc., 4. compound of the inspired dust, mechanical properties of the PFP in the inspired dust and their remanent magnetic moments m_r, 5. remanent magnetic induction of the measured sample, 6. technical parameters of the SQMS: sensitivity, aerial construction, 7. measured course of remanent magnetic induction B_r, 8. magnetization process of the thorax: strength of the field H_m, timing of the magnetization process t.

2.2. Theory

First, it is necessary to introduce a simple mathematical model of one lung lobe with the spherical and ellipsoidal shape. In our model we assume that the magnetized spherically shaped ferromagnetic particles are fixed in these defined objects with various volumes and totally deposit them.

The model treats every single PFP as a singular magnetic dipole with a constant m_p. It assumes that during the magnetization process the particle's magnetic moments turn to the direction of the external magnetic field. We consider a system of low concentration, contactless and non-interacting PFP uniformly distributed in the objects. At first approximation we assume that the dipolar field contribution of all the magnetic dipoles in the sample is concentrated into one single point in the middle of the detection coil's plane S. Each magnetic dipole can be found at the distance ν from the centre of the detection coil. The used model and its position relative to the coil of the antenna system are described by Fig. 2.

We began with the calculation of the portion B_r from one magnetic dipole above his axis in the centre point S of the first pick-up at ν from the dipole. By assumption that the vector of the magnetic moment of this particle has only
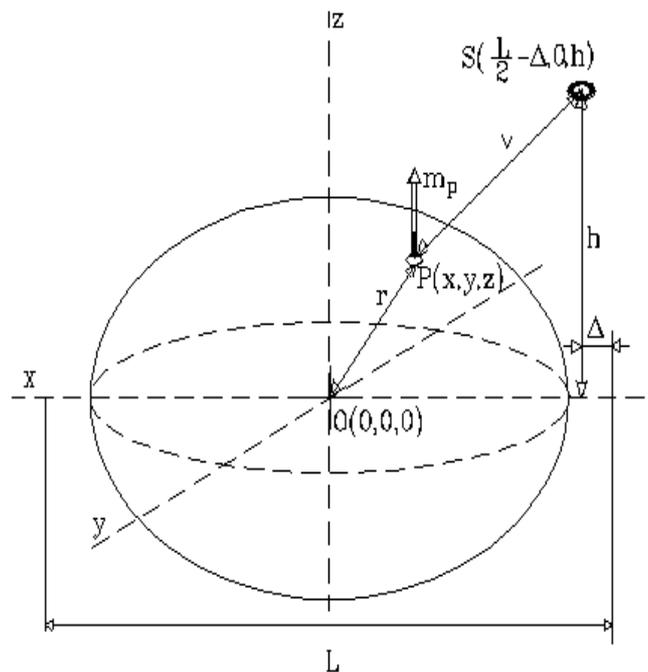

Fig. 2. The position of the SQUID magnetometer against the sample resp. single magnetic dipole

z-component $\vec{m}(0,0,m_p)$, the vertical component B_{rz} of this field is given by the following expression:

$$B_{rz}(\Delta) = \frac{\mu_o}{4\pi} m_p \frac{\{2(h-z)^2 - (\frac{L}{2}-x-\Delta)^2 - y^2\}}{\{(\frac{L}{2}-x-\Delta)^2 + y^2 + (h-z)^2\}^{\frac{5}{2}}} \quad (1)$$

where L is the distance along which the DC magnetised sample is moved, Δ is the shift of the SQUID against the beginning of L, μ_o is the permeability of the free space, h is the vertical distance between the centre of the pick-up coil S and the central point O of the sample.

Dividing the sample into small cubes and integrating the contributions of $B_{rz}(\Delta)$ over the volume V_0 of the sample, we get the total magnetic induction B_{rzt} in the z direction:

$$B_{rzt}(\Delta) = n_{vp} \int_{V_o} B_{rz}(\Delta) dV \quad (2)$$

where n_{vp} is the concentration of PFP in the object.

To estimate the concentration of PFP in the entire object, we examine the object in the optimal place relative to the detection coil, normal to its centre, by the maximum value of $B_{rzt}(\Delta)$: $B_{max} = B_{rzt}(L/2)$.

Based on the measured value of B_{max}, knowing the magnetic moment m_p, the volume V_o and the shape of the biological object, it is possible to estimate n_{vp} in it by the following formula:

$$n_{vp} = \frac{B_{max}}{A_{max} m_p} \quad (3)$$

where

$$A_{max} = \frac{\mu_o}{4\pi} \iiint_{V_o} \frac{\{2(h-z)^2 - x^2 - y^2\}}{\{x^2 + y^2 + (h-z)^2\}^{\frac{5}{2}}} dx dy dz \quad (4)$$

The measured voltage on the output of the magnetometer equipped with a second-order gradiometer can be expressed as:

$$U = W(B_{max}(h) - 2B_{max}(h+b) + B_{max}(h+2b)) \quad (5)$$

where W is a converting constant of the magnetometer, b is the base of the gradiometer and $B_{max}(h+i\,b)$, i = 0, 1, 2 is the remanent magnetic induction in the centre of the i-th coil of the gradiometric system.

To obtain n_{vp} the value of the remanent magnetic induction in the nearest (first) coil $B_{max}(h)$ is required. With the help of the calculated values of A_{max} at certain distances, the fields induced at the second and third coils of the gradiometric system can be expressed as:

$$B_{max}(h+b) = B_{max}(h) \frac{A_{max}(h+b)}{A_{max}(h)} \quad (6)$$

$$B_{max}(h+2b) = B_{max}(h) \frac{A_{max}(h+2b)}{A_{max}(h)} \quad (7)$$

Substituting (6) and (7) to (5), we obtain the expression for the value of the magnetic field in the nearest coil of a second order gradiometer:

$$B_{max}(h) = \frac{U}{W(1 - 2\frac{A_{max}(h+b)}{A_{max}(h)} + \frac{A_{max}(h+2b)}{A_{max}(h)})} \quad (8)$$

With the help of (4) it is possible to calculate the value of n_{vp}.

2.3. Materials and methods

The data to determine m_p were obtained by measuring the samples of powdered Co particles, which were homogeneously dispersed in six epoxy samples of mean volume $V_a = (0.3 \pm 0.012)$ cm^3. The mass concentrations ρ of the particles in the sample were 1, 5 and 10 mg cm^{-3}. The magnetic characteristics of the mentioned samples were measured using the compensation method [9]. The magnitude of m_r of the samples was determined from the magnetisation curve at the point $H_m = 0$. From this value and from the entire mass of the powder, the m_{rs} was calculated. The particle size of the Co powder was examined by a polarisation microscope. The volume of the particles was calculated, using the determined mean value of particle diameter d_a. The value of m_p was calculated using ρ and the particle volume V_p.

Finally, (4) have been verified by measuring $B_{rzt}(\Delta)$ using two lung phantoms. Powdered Co with $\rho = 1$ mg cm^{-3} (27 320 particles in 1 cm^3) was uniformly mixed in wax and modelled to ellipsoidal and spherical shape with a volume of 370 cm^3. For measuring, a one-channel rf SQUID magnetometer, equipped with a second order gradiometer with detection coils of diameter 2,6 cm, baseline 4,5 cm, having input energy sensitivity 8 x 10^{-28} J/Hz [10] was used. All the samples were magnetised in DC magnetic field of intensity $H_m = 1,6$ x 10^4 A m^{-1}. A special moving mechanism, situated below the gradiometer, enabled the transport of the magnetic material samples in the horizontal direction, at a constant speed of 5 cm s^{-1} on the path of 30 cm. The position of the sample and the voltage output of the SQMS were being simultaneously recorded by a computer.

The method was tested on the thorax of an arc welder suffering from pneumoconiosis. The contribution of the magnetic field of the earth and of the endogenous ion currents to B_r was measured before magnetising the lung. These values were later subtracted from B_r by mean to avoid the influences of these phenomena by the calculation.

The lungs were magnetised in $H_m = 3,5$ kA m^{-1} during 30 s. The subject was laid down and successively moved 40 cm long in three longitudinal directions (one was along the sternum, and two were at the distance of 8 cm on both sides of the sternum, at about the nipples). Each of the measurements were repeated three times under the same conditions, while the subject exhaled the air from his lung and hold his breath. The complete measurement lasted for four and a half minutes. The duration of the measurement was controlled by a time-relay arrangement.

Dust was extracted from the breathing zone of the welder and chemical analysis has shown that the proportion

of contaminating PFP in the dust is Ni : Fe = 71% : 29%, while the mean diameter of the particles was estimated to be $d_{Fe} = 25$ μm and $d_{Ni} = 10$ μm. Remanent magnetic moment of the dust was estimated using the same method as before.

Human lungs were simulated as two ellipsoids with proportion of semiaxes $a : b : c$ = 6,5 cm : 4 cm : 4 cm localised at a distance of 2,5 cm from the centre point of the sternum [6].

3. RESULTS

The calculations of the integral A_{max} for spherical and ellipsoidal objects with V_o 125, 250, 500 1000, 2000 and 3000 cm^3 were done using the Simpson's method adapted to three dimensions. Fig. 3 and 4 present the calculated values of A_{max}.

Fig. 5 presents the behaviour of a part of the magnetization characteristic of powdered Co with particle diameter $d_{Co} = 20$ μm and $\rho = 10$ mg cm^{-3}. The determined m_{rs} of the Co samples was 0,26 Am^2 kg^{-1}, of a single particle of weight $w_p = 3,66 \times 10^{-11}$ kg it was $m_p = 0,95 \times 10^{-11}$ Am^2.

Fig. 6 illustrates the measured dependence of U on L for a lung model of ellipsoidal shape with $V_o = 370$ cm^3, magnetised by the field $H_m = 1,6 \times 10^4$ A m^{-1} for 30 s. The calculated values of nvp of Co particles for both models are summarised in Table 1. The mean values of the calculated n_{vp} are (27405 ± 1244) cm^{-3} for the sphere, and (27165 ± 764) cm^{-3} for the ellipsoid.

To illustrate the method and the difficulties connected with determining of the concentration in living tissues a rough calculation was done with the data obtained from human lung measurements, in which an important factor the relaxation of B_r, was neglected. The estimated values of magnetic moments and weight for one Ni and one Fe particle were $m_{Ni} = 0,346 \times 10^{-12}$ A m^2, $m_{Fe} = 23,77 \times 10^{-12}$ Am^2 and $w_{Ni} = 0,981 \times 10^{-12}$ kg, $w_{Fe} = 141,49 \times 10^{-12}$ kg. As for the proportion of the Ni to Fe in the filter, we created a fictive particle with the magnetic moment of $7,14 \times 10^{-12}$ Am^2. The measured values of U are illustrated in Fig. 7. The calculation was done with the average value of U measured closely above the sternum. The calculated values of A_{max} and $B_{max}(h)$ in the first coil are $0,118 \times 10^{-7}$ TA^{-1}m and $394,8 \times 10^{-11}$ T. The calculated n_{vp} is 23430 cm^{-3}, which corresponds to the mass concentration $\rho = 0,977$ mg cm^{-3}.

4. DISCUSSION

It is clear that the quantitative evaluation of the dispersed PFP in magnetopneumography is a very complicated problem. One needs to consider many factors concerning the magnetic behaviour of small particles in living tissues, the highly inhomogeneous structure of the thorax, and contributions from physiological processes (heart activity, blood flow, volume changes, etc.), that occur during the cardiac and respiratory cycles. In this paper we analyse the difficulties associated with the determination of the volume and shape of the contaminated area and their influence on the quantification of PFP in the lungs. We have examined the difference of the factor A_{max} between the
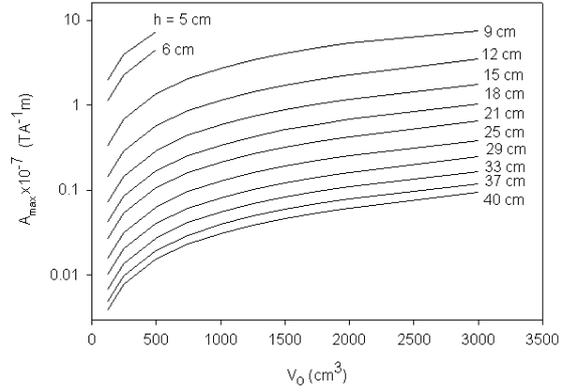

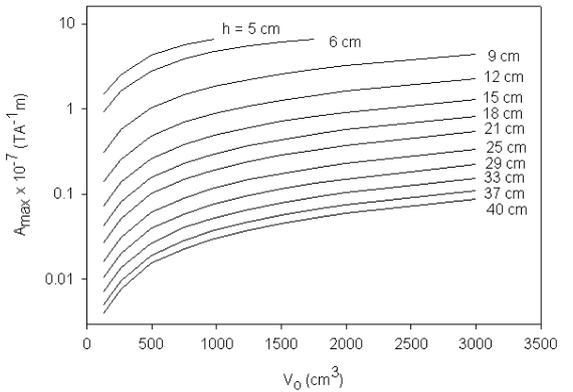Fig. 3. The calculated values of factor A_{max} for spherical models of volume V_o for different distances h

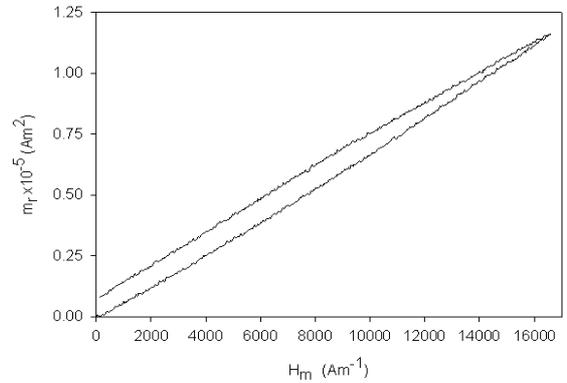Fig. 4. The calculated values of factor A_{max} for ellipsoidal models of volume V_o for different distances h

Fig. 5. Remanent magnetic moment m_r of a cylindrical sample of powdered Co particles mixed in epoxy of volume 0,28 cm^3

sphere and ellipsoid, that can be approximately thought of as models of the lung lobe. From (4) it is clear that the factor A_{max} reflects the dependence of B_{max} on the position of the contaminating magnetic dipoles in the lung lobes with volume V_o. The estimation of the PFM amounts in the lungs was shown to depend strongly on the distance ν. Therefore, it is important to estimate the position of the lungs relative the pick-up coil. The approximate volume and position of the lung lobes can be determined by measuring the vital capacity of lungs, the front-rear diameter of the thorax, and
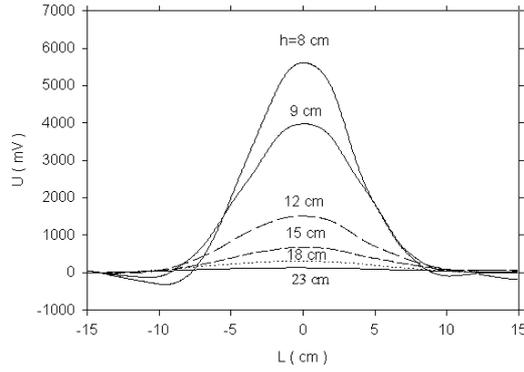
Fig. 6. Output value of U versus L from an ellipsoidal sample of volume of 370 cm^3 for different values of h
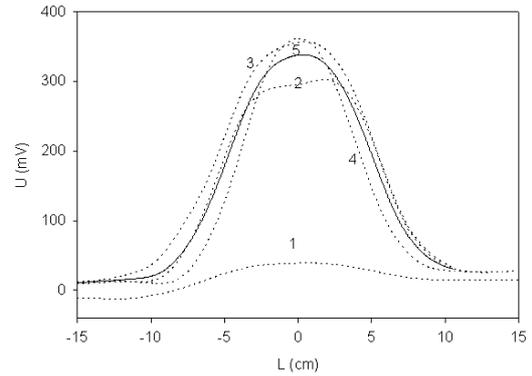

Fig. 7. The dependence of U versus L measured above the sternum at the distance of 16 cm: 1) before the magnetization; 2) 4 min 3) 4 min 32 s, 4) 5 min 2 s after the magnetization, 5) the mean value of U

TABLE 1. The calculated values of $B_{max}(h)$ and n_{vp} for the spherical and ellipsoidal lung models of volume of 370 cm^3

	h / cm	8	9	12	15	18	23
SPHERE	$B_{max}(h) / nT$	34,67	25,85	11,39	5,84	3,52	1,49
	n_{vp} / cm^{-3}	25 900	26 940	28 130	28 100	29 360	26 000
ELLIPSOID	$B_{max}(h) / nT$	28,03	19,66	9,6	5,1	3,06	1,54
	n_{vp} / cm^{-3}	28 100	25 680	27 200	27 000	27 220	27 790

by examining using X-rays.

Given that the majority of adults have frontal rear thorax distance in the interval (24 ÷ 40) cm and that B_r was recorded approximately 1 cm above the skin surface, the value of h was chosen in the range of (12 ÷ 25) cm. Knowing that the vital capacity of adult lungs varies in the range (3500 ÷ 6000) cm^3 and that the residual volume of the lungs is (700 ÷ 1200) cm^3, the volume V_o of one of the examined lung lobes falls into the interval (500 ÷ 3000) cm^3. From the presented curves of the factor A_{max}, one can come to the conclusion that the difference of the factors A_{max} for the sphere and ellipsoid do not exceed 35 % at distance h=12 cm and 22% at h = 25 cm for V_o = 3000 cm^3. For the smallest lung model the differences were 14,5 % and 3,3 %.

The calculated values of n_{vp} on the lung models (Table 1) are in good agreement with the estimated values. However, it should be noted that we are working with objects under several simplified assumptions. We considered PFP with low concentration, which are fixed, do not exert forces on each other, and do not agglomerate. In reality such an ideal lung model does not exist. The magnitude and behaviour of the B_r depend on the amount of the ferromagnetic material. Moreover, there are many factors and mechanisms which are need to be taken into account when analysing the results. An essential factor in the precise quantifying of the lung contamination by PFP is the time decay of the amplitude of the remanent magnetization due to random progressive rotations of PFP, that is, the relaxation process. There are also many physiological factors, such as respiratory motion, cardiovascular pulsation, motion of the chest muscles, diaphragm, cilliary beating, the elasticity of the lung tissue, which in the lungs randomise the magnetic orientation of PFP and reduce the B_r. Other factors are the agglomeration tendency due to the inhomogenity of the lung tissue, the shape of the particle, its size, and the viscosity of the nonmagnetic fluid suspension. That is why the actual final value of B_r is influenced by the time interval between the end of the magnetization of the sample and the beginning of the measurement. This relaxation drop of the B_r should be accepted by the evaluation of the content of the PFP.

Fig. 7 presents the value of U of the magnetised human thorax measured vertically above the chest at three different time instants. From this picture it is not possible to distinguish between the relaxation and the change of the lung volume caused by the breathing. Additional measurements are required to approve both processes. Since the volume V_o varies during the breathing cycle, it is necessary to agree on the breathing pattern with the tested subject during the measurements. During the estimation of the particle concentration we neglected the relaxation process. The result, ρ = 0.977 mg cm^{-3} is acceptable, but several additional corrections and measurements are necessary to provide in the future.

5. CONCLUSION

We have developed an analysis tool for the quantification of ferromagnetic data in human lungs. The values of calculated A_{max} represents a starting point for the quantification of the lung contamination in the case of uniformly scattered and non-interacting PFP. The method was examined on physical lung models and on an arc welder with evident contamination of the lung. The results treated above show that the method can be utilised in magnetopneumography and in other fields of science, where in organic and inorganic structures with defined borders the concentration of ferro- and ferrimagnetic contaminants have to be determined.

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Authors:

1. Fatima Boháková, MSc, Institute of measurement science of SAS, Dúbravská cesta 9, 842 19 Bratislava,
   Tel:+421-7-5477 3269, fax: +421-2-5477 5943, e-mail: umerfati@savba.sk
2. Ing. Ivan Šimáček, CSc, Institute of measurement science of SAS, Dúbravská cesta 9, 842 19 Bratislava,
   Tel:+421-7-5477 3269, fax: +421-2-5477 5943, e-mail: umersima@savba.sk