MAGNETIC FIELD OF THE LUNGS – NEURAL NETWORK INVERSE MODELS

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Abstract: Magnetopneumography (MPG) is a diagnostic method that uses examination of remnant magnetic field for determination of amount and distribution of ferromagnetic dust respired into the lungs. The measurements are carried out by fluxgate gradiometer fixed on portal over a positioning bed. Experimental physical model and forward computer solver were built in order to provide data for training of neural network inverse model. Early results of our experiments are quite promising. Refinement of models, gradiometric configurations and inversion techniques is under research.

Introduction

Lungs of workers including mainly metal grinders and welders are usually contaminated by total amounts of at most several grams of ferromagnetic inorganic dust that is usually diffusively distributed according to airiness and elimination abilities of the organ. Localized deposits may accompany certain diseases. Such deposits can be detected via their remnant magnetic field after magnetization of the subject in an electromagnet. The method was devised in early 1970s by Cohen [5], it can provide early diagnosis of dust loads long before pathological changes appear on X-ray, because the magnetic measurement is more sensitive.

Nowadays the magnetic measurements gain in importance, moreover the methodology can be used in other measurements of weak magnetic fields.

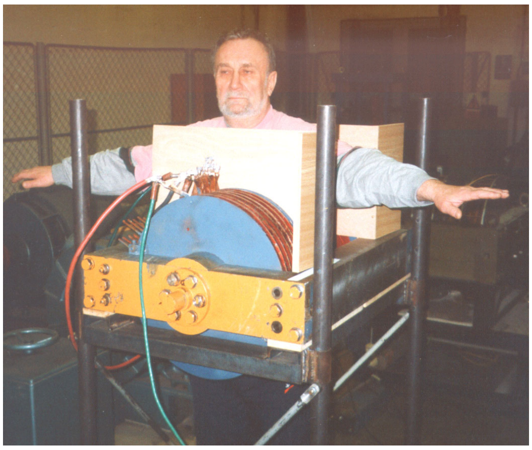

Figure 1: Magnetization of a subject in electromagnet

Utilization of SQUIDS is traditional in this branch, but we work with much more affordable fluxgates in unshielded room. To suppress distant fields' variations gradiometric configurations are necessary.

In our laboratory a lot of research was done on lung tissue samples, aerosols and also on some professional workers (Figure 1), our effort was then aimed to computer modeling and measurements using physical phantoms, finally inverse problem experiments were conducted. However reasonable reconstruction of spatial distribution of the dust in lungs was not achieved jet. We have implemented neural networks for this problem, though other possibilities were considered too.

Measurements

Our previous studies have shown, that the DC field necessary to reproducibly magnetize the lung volume for in-vivo measurements is 100 to 200 mT, much higher than field used for earlier measurements reported in the literature. Remnant fields after proper magnetization in big electromagnet reach up to hundreds of nT. Such fields can be effectively detected by fluxgates.

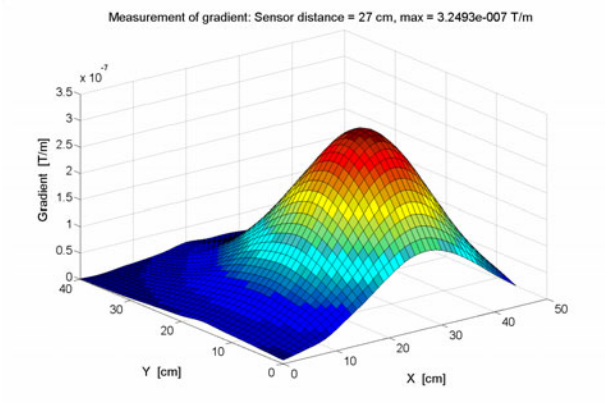

Figure 2: Example of measured field gradient – localized compact source

We use a set of sensors of our design in gradiometric arrangement to suppress signals from distant sources and to focus on the weak fields in plane over subject's chest. Present first-order fluxgate gradiometric system was proved to have sufficient sensitivity and spatial resolution to detect particles of grinding dusts and welding fumes [1], however we plan usage of higher order gradients to obtain even less noisy data. The

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sensors are driven by multi-channel magnetometer that realizes analogue feedback and processes the signals. Outputs are measured by digital multi-meters (Agilent 34401A), that are group-triggered via GPIB bus and the data are collected for processing by LabWindows program running on PC. Scanning is performed by movement of the patient or measured object – fibreglass phantom with cubes containing magnetite (Fe_3O_4) – or tissue specimens. An example of gradient map measured for a source in the phantom is in Figure 2.

Our phantom for in-vitro experiments consists of 475 cubes of 8 cm^3. Its shape respects physiological asymmetries and volume of standard human lungs [6]. The measurements of localized cubic sources composed of cubes containing magnetite were used for validation of forward computer solver. The cubes composing the source contained 80 mg of magnetite powder and all were magnetized in laboratory magnet. Their Ampere magnetic moment magnetic moment was relatively small (about 300.10^{-6} Am^2). We have also clear cubes and some containing 40 mg of Fe_3O_4.

Forward computer model is also discrete, designed just according to the phantom and the system layout and dimensions. The model performs summation of magnetic induction from each cube for every measuring node of the lattice over the phantom. The calculations are based on Biot-Savart law, but just a component in axis of probes' sensitivity is evaluated. Comparison of one measurement and a model of the same source is in cross-section in Figure 3. There is just slight shift because of inaccurate setting of the source position under gradiometer. We still work on refinement of the models and on more appropriate probe layout.

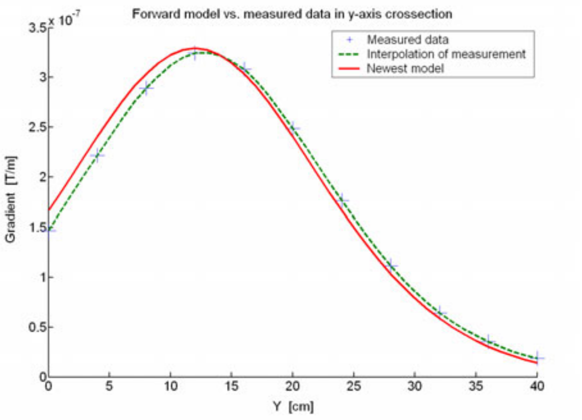

Figure 3: Comparison of measured data and computer model (along y-axis)

For future measurements a special positioning bed made of glass-reinforced polyester composite and other non-magnetic materials was designed and built. It allows positioning patient in plane and adjusting the distance from the sensor. Without any magnetic shielding these measurements can be performed in our city laboratory only during night, when the background gradient change during the measurement time can be kept below 3 nT/m. At magnetically silent location this variation is below 1 nT/m anytime. The probes are fixed to separate portal that has heavy basement on rubber layer to prevent carriage of vibrations that would affect the signals. We can scan the subjects in higher resolution and precision and add more probes and change the layout easily.

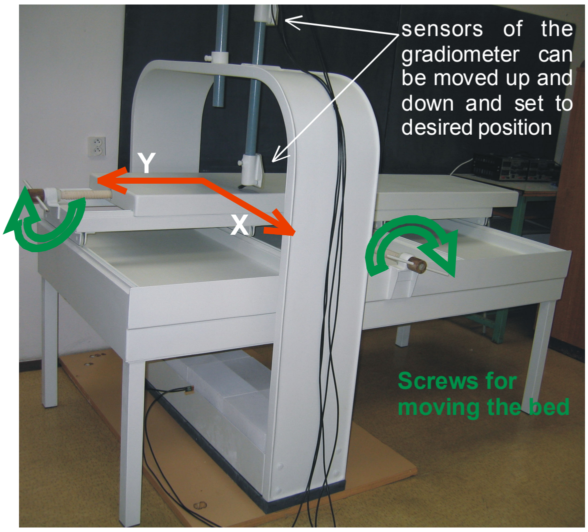

Figure 4: New bed for examination of subjects. Gradiometer fixed to the portal.

Inverse problem

The reconstruction (determination) of the amount and spatial distribution of ferromagnetic dust in the lungs is derived from computational inversion of performed surface gradiometric measurements. Since the magnetic inversion problem is generally non-unique [4], restrictions particularly on resolution (8 cm^3 cubes used) and on magnetic properties of our models were taken. Incorporation of a priori knowledge is also crucial for most applicable inversion techniques.

Although derivative optimization techniques were considered primarily, even Matlab program for automatic differentiation of the forward model was realized, neural networks (NNs) were chosen for early experiments with inversion due to their versatility and generalization abilities. Neural network simulates mapping of the measurements to sources, we have tried various configurations and network topologies to see which could be used in further experiments.

Data for training of the NNs were generated using the 3D solver simulating fields of deposits of optional layout. This forward model was set according to several real measurements (Figure 1.) using lung phantom – sources composed of cubes of defined magnetic properties – and to specific experiment layout. The model was then verified by further measurements. We achieved very good results with new higher precision forward solver (see Figure. 3). Datasets were composed of many thousands of couples of data describing compact localized cubic sources and corresponding magnetic field distributions.

To decrease number of variables and to achieve reasonable sizes of the networks for initial modeling, proper fitting function (e.g. generalized Gaussian, see formula (1) – good fit, minimum variables) was used, nevertheless that brought some errors. The optimization procedure of setting of the parameters during the fitting was performed by Nelder - Mead simplex method. For those localized homogenous cubic deposits MLP (multilayer perceptron) networks [3] with 6 inputs (describing the fields – amplitude, peak location and pseudo-variances), 6 outputs (describing the source dimensions and position) and with just single hidden layer gave the best results. The activation functions were logistic. Without fitting (all the nodes of the measuring lattice used) some interesting results were achieved by radial basis function (RBF) NNs.

$$F = A \cdot \exp\left(\frac{-0.5(x - c_x)^N}{s_x^N} \; \frac{-0.5(y - c_y)^N}{s_y^N} \right) \qquad (1)$$

For newest measurements, having different configuration of the experiment (some changes for utilization of the positioning bed) even four layer MLPNNs were tried, giving promising results - however the fitting anyway seems to be very problematic for real measurements as well as using GKPCA (Greedy kernel principal component analysis) [7] or splines, because a lot of information is lost.

NN forward models for iterative procedures were also implemented. These NNs could substitute the forward solver that is relatively slow. MLPNNs with single hidden layer had test errors up to 0.006. We have tried datasets with and also without fitting. Without fitting the data are unfortunately too bulky for processing even on high-end desktop PC. Reasonable compression or down-sampling could be helpful.

We have worked also on generally distributed phantom cubes but already just in volumes smaller than whole lung model. No fitting was used. These experiments were conducted to see how many "dipoles" can be determined out of 228 measuring points of the lattice (old device) at given distance. Simple linear networks showed the best performance. Other network types worked much worse. Already examined volumes contained 27 and 64 model cubes out of 475. Each cube could be either magnetic or not and their presence in correct position was to be computed out of the magnetic field distribution.

To simulate real cases, higher resolution on more than just one frontal surface should be used, as well as phantom cubes containing various amounts of dust (magnetite). As the data obtained from single surface measurement are not enough for determination of the general dust distribution our effort now must be aimed also back to the MPG measurement system in order to get more and less noisy independent data. We have got already the new scanning bed and can obtain more precise data at higher resolution. To the portal more probes can be fixed and the gradients can be measured in more planes at once. Advanced gradiometric configurations can also suppress noise.

Results

Positions and dimensions of localized deposits composed of cubes of defined magnetic properties were reconstructed by means of the MLP networks out of the measurements. The best performing network had 6 inputs (parameters of generalized Gaussian fitted to the data) 95 hidden neurons and 6 outputs (parameters of the deposit in the lungs). Logistic activation functions were used. Test error of this network was 0.047. The inverse model worked therefore quite well. The presented example is in Table 1. In the real data, however, noise and measurement errors are dominant and therefore the inversion is not satisfactory. The worst are determinations of dimensions and positions of the sources in z-axis, where noise and fitting errors play very important role.

Table 1: Comparison of modeled source (3D location and size) and corresponding estimation found by NN. Pure computer model and "real" physical phantom were evaluated.

Variables	Source [cm]	NN – model [cm]	NN – real [cm]
Center X	28	28,13	27,99
Center Y	12	11,95	11,97
Center Z	23	22,10	20,31
Size X	4	3,39	5,96
Size Y	8	8,68	8,01
Size Z	8	5,31	2,63

Four layers MLPNN for newest measurement setup had test error 0.042, again it used 6 inputs and 6 outputs 40 and 20 neurons in hidden layers, however no better results were achieved in inversion of real data obtained during measurements with the phantom.

Estimation errors of the general distributions of magnetic and non-magnetic cubes (dipoles) in 27 cubes' volume were below 1%. Inversion was realized by linear network with test error 0.0025.

Table 2: Sample of results for 27 cubes volume of the lung model. **Sxxx** indicate centers of cubes in 3D array in 2 cm resolution

Magnetic moments of cubes of original and predicted sources, [10^{-6}Am^2]					
S111	**S111 (p)**	**S135**	**S135 (p)**	**S335**	**S335 (p)**
480	480,0784	0	-1,5789	480	483,5993
480	479,8852	480	481,8678	480	476,3467
0	0,0144	0	-1,6118	0	2,9445
0	0,0706	480	480,3571	0	-0,7291
480	480,1683	0	-2,4670	0	5,3539

Table 2 depicts several examples showing the perfect function of the network. It is evident that even in case that the data were not binary (cubes with magnetic moment 480.10^{-6} or 0 Am^2) the network would have been able to distinguish between several discrete intermediate values or could have worked with almost continuous moments.

The problem is that for bigger volumes there is not enough information from the current measurements, therefore more complex scanning will be necessary. In case of 64 cubes volume the limited number of magnetic field data resulted in severe errors up to 50% in cases where clear cube was surrounded by magnetic ones.

Conclusions

Fluxgate gradiometric system and neural networks inversion model were used in our experimental system for magnetopneumography. Various experiments with models, in-vitro and in-vivo samples were conducted. Discrete computer forward model was developed and verified by several phantom measurements. Due to non-uniqueness of magnetic inverse problem many restrictions had to be taken, particularly on resolution and on magnetic properties of phantom elementary cubes. Neural network inverse models of various configurations were implemented to predict simple compact localized field sources. General distributions of cubes in coarse resolution were tried in small volumes; however, more information from the scans would be necessary for inversion in such cases.

For more precise in-vitro and especially for in-vivo measurements a new positioning bed was designed and prototype was made of glass-reinforced composite. More sensors in advanced gradiometric configurations are to be used to obtain more information about the measured objects and to satisfactorily suppress variations in background magnetic field. Models are to be improved and more a priori knowledge reducing unrealistic solutions incorporated. Some gradient optimization techniques could be tested as well as advanced filtering and fitting of the measured data in order to get better inversion results.

Acknowledgments

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