MAGNETIC INDUCTION TOMOGRAPHY SPECTROSCOPY (MITS) OF LIVING TISSUES: AN EXPERIMENTAL EVALUATION

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Abstract: Magnetic induction tomography (MIT) is an imaging-method for reconstructing the complex conductivity distribution of biological tissue inside an object. Magnetic induction tomography spectroscopy (MITS) allows the reconstruction of the change of the complex conductivity distribution of biological tissue due to a change of the investigating frequency. In this paper single-frequency reconstruction of an agar-agar sphere as well as frequency-differential reconstructions obtained from a potato are shown and demonstrate the applicability of MITS in real objects.

Introduction

The production of cut-away views of a body is of major importance in medical imaging. One of the most recent among computer-imaging techniques is magnetic induction tomography (MIT), which is a non-invasive and contactless method for reconstructing the distribution of the passive electrical properties (*PEP*), i.e. the permeability μ, the permittivity ε and the complex conductivity κ inside an object under investigation. For our purpose we focus on the reconstruction of the complex conductivity $\kappa = \sigma + j\varepsilon_0\varepsilon$.

The measurement principle is based on determining a pertubation field (ΔB) of a primary magnetic field (B_0).The alternating field B_0 is coupled from an array of excitation coils to the object. Multifrequency operations can achieved by superposition of multiple sinusoidal signals. The corresponding voltages ΔV and V_0 induced in the receiver coils carry the information about the conductivity distribution.

For image reconstructions a complex 3D eddy current problem has to be solved and due to the ill-posedness of the inverse problem suitable regularization methods have to be applied (for details see [2] and [1]).

The reconstructions by MIT are often state-differential, but in relative immobile organs like the brain frequency-differential reconstructions are of paramount importance due to the fact, that they allow a quantitative spectroscopic characterization of the conductivity. The spectra contain specific information about patho- and physiological properties of the investigated tissue (e.g brain odema). In MIT single-step reconstructions of the absolute value of $\Delta\kappa$ are very difficult, nevertheless the reconstructions show a good performance in the localization of a pertubation object. This paper presents an experimental evaluation of the Graz MITS-System and illustrates reconstructions of single-frequency measurements as well as images and conductivity spectra obtained from multi-frequency measurements of living tissue.

Materials and Methods

Image reconstruction requires the solution of the inverse 3D eddy current problem and were done with a previously published regularized single-step Gauss-Newton-Algorithm [2]. With S beeing the sensitivity-matrix, R a regularization matrix (e.g. unit-matrix), λ a suitable regularization parameter and Δy the measured differential-data the problem can be expressed as:

$$\Delta\kappa = (S^T S + \lambda R)^{-1} S^T \Delta y \qquad (1)$$

Frequency-differential reconstruction aims at the calculation of a series of relative conductivity changes $(\Delta\sigma(\Delta f_1), \Delta\sigma(\Delta f_2, ...)$. According to [5] frequency-differential images can be generated after a suitable transformation of the data which compensates the frequency dependence of the sensitivity:

$$\Delta y(\Delta f)_i = \Delta y(f_{ref}) - \Delta y(f_i) * (\frac{f_{ref}}{f_i})^2 \qquad (2)$$

According to [5] this allows a generation of relative differential spectra $\Delta\sigma/\Delta\sigma_o$, where $\Delta\sigma_0$ is an arbitrary base difference, here: the difference between σ at 400kHz and σ at the reference frequency of 300kHz. The reconstructed spectra do not represent the absolute conductivity values, but preserve the shape of the spectra. In order to get a relative $\Delta\sigma$ between two test frequencies the mean value of all perturbed voxels was calculated.

For all reconstructions in this paper the regularization parameter λ was chosen by the Morozov criterion [3], whereby the noise level was about 10%.

The hardware of the Graz MITS-System [4] consists of 14 planar gradiometers, one reference coil, one excitation coil with 8 turns, one power amplifier, 15 low noise preamplifiers, one stepping motor unit and a personal computer for data aquisation and signal processing (see Figure 1).

A real challenge for every MITS-System is the separation of the primary signal V_0 from the desired signal ΔV caused by eddy currents in the pertubation because ΔV is by sveral orders of magnitude smaller than V_0. The use of planar gradiometers greatly improves the dynamical

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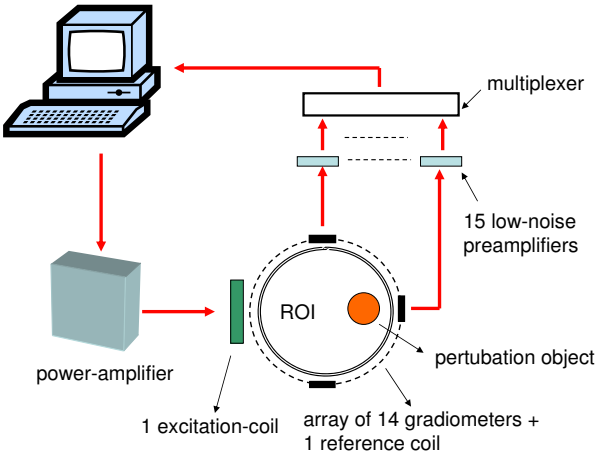

Figure 1: Schematic of the hardware of the MITS-System

range of the measurements [6]. The planar gradiometers are formed by pairs of vertically adjacent receiver coils and the resulting ΔV can be expressed by the following equation:

$$\Delta V_{Grad} = \Delta V = \Delta V_{uppercoil} - \Delta V_{lowercoil} \qquad (3)$$

The real and imaginary parts of ΔV were extracted by digital synchronous demodulation. In the range of physiolocical conductivities the imaginary part of ΔV reflects the real part of the complex conductivity κ. In order to obtain 16 different projections of the excitation field with a single excitation coil the sample was rotated by 22.5° in 16 consecutive steps.

The experimental arrangement is shown in figure 2. The rectangular receiver coils (edge lenght of 38.7 and 20mm) were placed with their centers on two paralell rings with a radius of 110mm. The solenoid excitation coil (diameter=95mm, hight=20mm and width=5mm) had a distance of 145mm and was placed with its center 3mm above the median transversal plane of the outer cylinder. The cylindrical conductor had a radius of 95mm and a height of 140mm for the first experiment and 130mm for the second experiment.

The first experiment is dedicated to the question, if diffusion between the pertubation and the background medium in a phantom can produce a relevant error during the time which is necessary for the spectroscopic experiment. Previous measurement data of non-diffusive objects (e.g. a metall sphere) showed constant behavior of the values at different time points. To this end, an agar-sphere with an initial conductivity of 1 S/m was immersed in a saline tank with 0.2 S/m. The total duration of the experiment was 150 minutes and measurements were carried out for 6 time points.The investigating frequency was 300kHz. Referring to figure 2 the pertubating sphere with a diameter of 42mm was placed at [x,y,z]=[65,0,35]. Regularization was done with the unit-matrix and the regularization parameter was $4.689 * 10^{-20}$. To inhibit sloshing of the medium during probe rotation glue was added in order to increase the viscosity of the fluid.

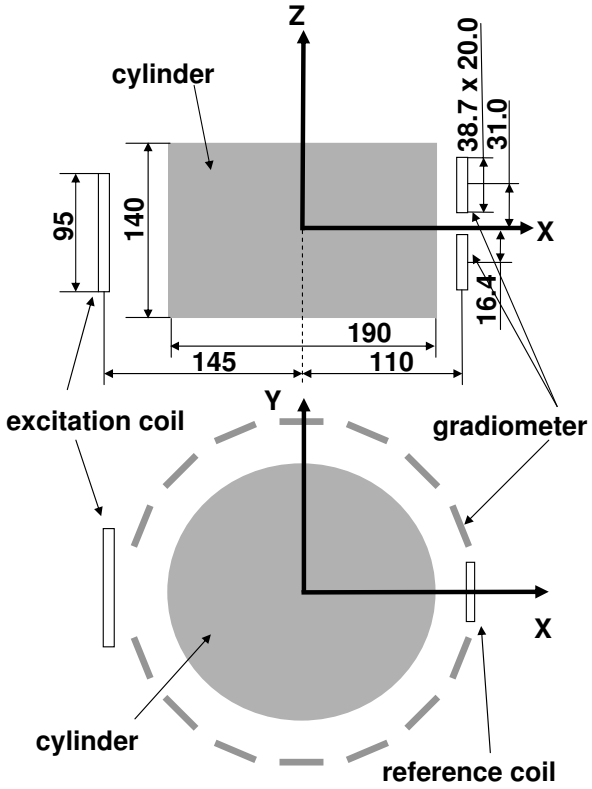

Figure 2: Geometry of the measurement setup (all dimensions in mm), top: front-view (sagital cross-section), bottom: top-view (transversal cross-section)

The second experiment was dedicated to the reconstruction of the frequency-dependency of κ of a biological object, in our case a potato. For validation the spectrum was compared with a reference spectrum obtained with an electrode based impedance spectrometer (Solartron SI1260) and a four needle probe (stainless stell) inserted into the tissue. The reference spectrum was acquired for different positions of the electrodes by calculating the average of the measured spectra. The immanent systematic phase error of the Solartron SI1260 was corrected by calibration with saline. Frequency-differential reconstructions were carried out for the measurement frequencies 100kHz, 200kHz, 300kHz, 400kHz, 450kHz and 500kHz and the relative spectra were calculated for a reference frequency of 300kHz. A cylindrical potato with radius=40mm and hight=40mm was positioned at [x,y,z]=[65,0,35] (coordinates see figure 2). The background medium (saline tank) had a conductivity of 0.23 S/m. The reconstruction was again performed using the unit-matrix and a regularization parameter of $\lambda = 5.5 * 10^{-16}$.

Results

Due to the non-iterative nature of the algorithm, the reconstructed values cannot be interpreted quantitatively. The step in (1) yields the correct search direction but the wrong step width due to the lack of a line search

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procedure. Based on this fact the colormaps were not quantified and only qualitative images are shown. The black/white dotted lines in the figures mark the original position of the pertubating object.

Figure 3 illustrates a reconstructed image of the diffusion experiment after a time of 120 minutes. The decreasing relative conductivity for 6 different time points (circles in the diagram) is shown in figure 4. The continuous line mark a fitted curve of first order.

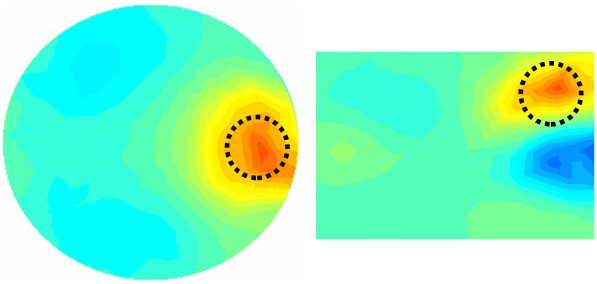

Figure 3: Selected reconstruction for the position of the sphere at [x,y,z]=[65,0,35] after 120 minutes. Left: transversal cross-section at z=35, right: sagittal cross-section at y=0

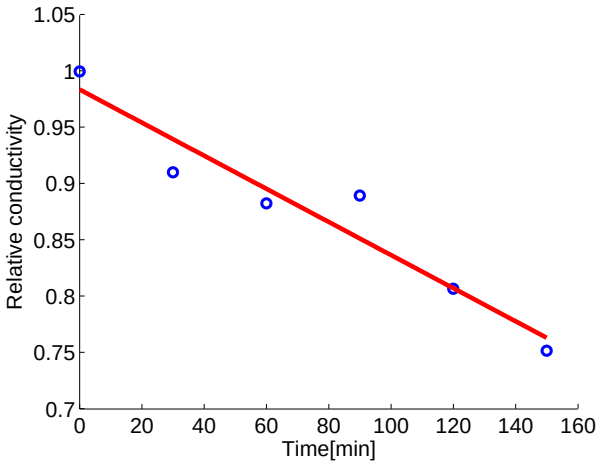

Figure 4: Decreasing relative conductivity of the agar-sphere caused by diffusion of the Na^+ and Cl^- ions into the tank medium

In figures 5,6 and 7 the results of the second experiment are shown. The absolut conductivity spectra which are necessary for the calculation of the relative reference spectrum are shown in figure 5. Figure 6 shows two reconstructed images and figure 7 compares the relative electrode based spectrum with the relative spectrum obtained by MITS.

Discussion

The images in figure 3 and 4 display the reconstruction results of the first experiment. Figure 3 shows an image of the agar-sphere after 120 minutes. The position of

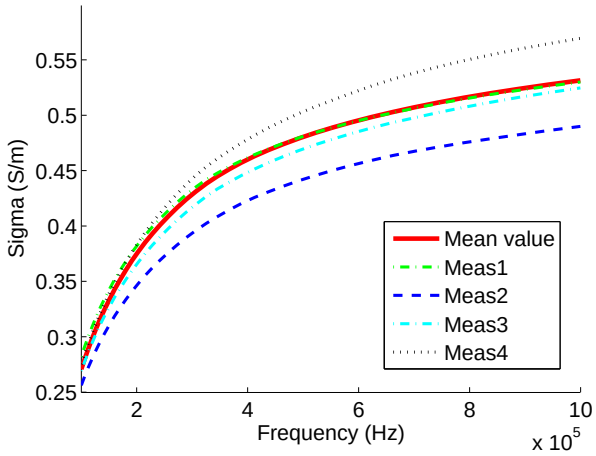

Figure 5: Absolute conductivity spectra for different positions of the measurement electrodes (dashed lines) and calculated mean of the reference- spectrum (continuous line)

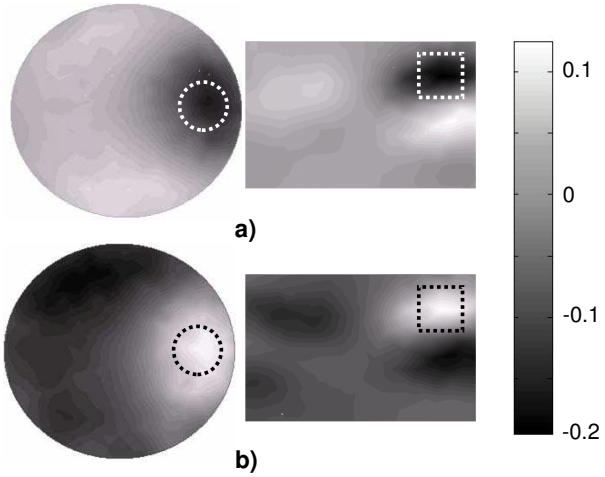

Figure 6: Selected reconstrutions of frequency-differential images: **a)** Frequency-differential reconstruction between 200kHz and 300kHz for the position of the potato at [x,y,z]=[65,0,35]. Left: transversal cross-section at z=35, right: sagittal cross-section at y=0 **b)**Frequency-differential reconstruction between 400kHz and 300kHz for the position of the potato at [x,y,z]=[65,0,35] Left: transversal cross-section at z=35, right: sagittal cross-section at y=0

the pertubation is correct, but a ghost with opposite sign is visible beneath the real object. With the positioning of the planar gradiometers described in the measurement setup (figure 2) this is a known fact as the used planar gradiometer arrangement cannot distinguish between an upper positive or lower negative object and vice versa.

Figure 4 demonstrates the feasibility of MIT reconstruction to track a diffusion process over time. It can be shown that a 150 minutes long diffusion process reduces the relative conductivity of an agar-sphere by 21%.

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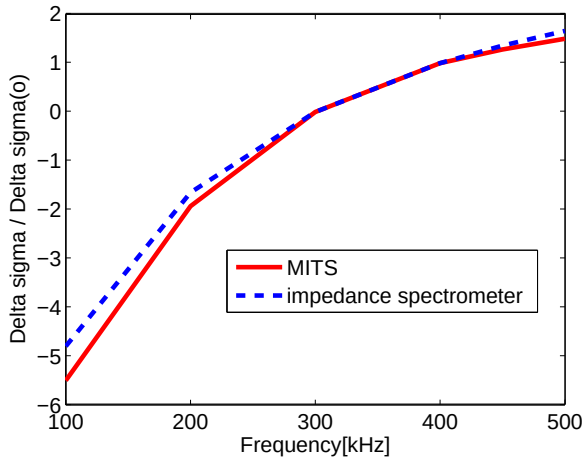

Figure 7: Comparison of the electrode based and MITS based relative conductivity spectrum

If we assume that due to the presence of cellular structures the diffusion of the ions of a potao is slower than the diffusion process out of an agar sphere, the curve in figure 4 represents the worst case. This is of importance for MITS as a multi-frequency measurement currently requires up to 10 minutes. The drop of the conductivity after 10 minutes is less than 2% and is therefore negligible for multi-frequency measurements.

The shown result in figure 5 illustrates 4 different absolute spectra for 4 different positions of the measuring electrodes (dashed lines). It should be kept in mind, that the shown reference spectrum can only be compared with the MITS-spectrum (figure 7) by calculating a relative reference spectrum ($\Delta\sigma_{Solartron}/\Delta\sigma_{Solartron,o}$). The spectra obtained from measurement 2 and measurement 4 differ at a frequency of 500kHz up to 12%.

Figure 6 shows frequency-differential reconstructions between 200kHz and 300kHz (figure 6a)) and reconstructions between 300kHz and 400kHz (figure 6b)) for a reference frequency of 300kHz. Both images were reconstructed with the same scaling. The reconstructed pertubation at 200kHz has a negative sign wherby the reconstructed object at 400kHz has a positive sign. The sign chance can be explained by looking at figure 7. All frequency-differential reconstructions above the referency frequency (300kHz) result in a positive sign and all reconstructions under the referenc frequency have a negative sign. Also the ghost appears in both images with the opposite sign beneath the detected object.

The comparison between the relative spectrum determined by the impedance spectrometer and the relative spectrum obtained from the MITS-reconstruction is depicted in figure 7. The reference frequency for the MITS-reconstructions was 300 kHz and $\Delta\sigma_0$ was calculated between 300kHz and 400kHz. Consequently the spectra coincidence exactly between these frequencies. Between reconstructed and true (impedance spectrometer) values is a maximum deviation of 14% which is fairly good for a one-step-reconstructor (1) considering a maximum conductivity change of 84% and a spread of 12% (at 500kHz) in the reference spectra (figure 5).

The waviness of the reconstructions is an artefact of the necessary regularization and might be prevented in future with edge-preserving regularization methods(e.g. Total Variation).

Conclusions

We have studied the feasibility of a magnetic induction tomography system. The reconstructed relative conductivity changes coincides with those obtained from an electrode based measurement with a maximum deviation of 14%. Hence, MITS with single step reconstruction allows a spectroscopic characterization of the 3D-conductivity distribution inside a biological sample.

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