Application of source localization algorithms in magnetoencephalography: test on a new generation of magnetometers

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Abstract - Magnetoencephalography (MEG) is a non-invasive neuroimaging technique for measuring the activity in the brain. In the vicinity of the head it measures the magnetic field produced by the electric currents in neurons. From the measured magnetic field, using various computational techniques, we determine the location of the source of the electric currents of nerve cells [3]. The main goal of this method is to determine the location of the source of the measured magnetic field as accurately as possible. The measured magnetic fields are very weak, order of few pT, therefore the measurements must be carried out within a magnetically shielded room, this is also one of the major drawbacks. The temporal resolution of this method is around 1 ms, on the other hand, the spatial resolution is in best conditions around 2 – 3 mm [4].

Another drawback of the standard MEG method is the use of the SQUID gradiometers [5]. Although they are very accurate, they require a cooling with liquid helium, which is why they need to be placed in a bulky Dewar vessel. This is the reason why the gradiometers are not in the optimal position next to the head. Another consequence of this is that the patient must not move his head during the measurement, which is very uncomfortable. We can solve this problem with the use of a new generation of magnetometers, optically-pumped magnetometers (OPM). These sensors operate at a room temperature, therefore they don’t need a cryogenic cooling and can be placed directly to the head.

The use of these new OPMs in a neuroimaging technique such as MEG is a quite new concept, which is why it still needs a lot of improvements. In a recent study A. Borna with colleagues compared the results between the use of OPMs and SQUIDs [6]. In the experiment they used an auditory and a somatosensory evoked response. The results they got, look very promising for the future use of the OPM sensors in MEG. Another very important study was made by E. Boto et al, where they made a study of a simulation where they compared two cases [7]. In the first case, the magnetometers were located like in SQUID systems and in the second case, the OPMs were close to the head (approx. 4mm). They found out that by placing the sensor closer to the head, greatly improves the signal to noise ratio (SNR).

In our work, we present some standard methods [4] used in magnetoencephalography and also test and compare the performance of the existing MEG systems based on the SQUID gradiometers with a new system based on OPM magnetometers. First, we present methods for processing the MRI scans, pre-processing the MEG data and then solving the inverse problem. Next, we show the results as measurements of the magnetic field and the solutions of the inverse problem as locations of dipoles on
MRI scans. Lastly, we evaluate and compare the results obtained for both measurement devices.

II. METHODS

To make measurement with the MEG system and to determine the regions of increased activity, we have to do quite a few things. The SQUID device is a standard device with fixed number and locations of fixed sensors. On the contrary, the OPM measuring system has no unitary sensor holder with standard locations of the sensors. Therefore we first make a custom sensor holder with a 3D printer. For this, we obtain an MRI scan of the subjects head, and then process it with various techniques. Next, we start with the experiment for an auditory evoked response. The magnetic field was measured first with the SQUID and then with the OPM system. All the collected data must then be filtered and averaged. For the times, when we measured the greatest response, we solved the inverse problem using the least square fitting of a current dipole, which is a well known method in MEG. This work introduces the methodology and the results of one subject only, as the study is still ongoing.

A. Processing of the MRI scans

The processing of MRI scans is of great importance. Without it we couldn’t build the custom sensor holders for the OPMs or determine which brain region produces the measured magnetic field around the head. In this paper we extracted the geometry of the head out of the MRI scans. For this task we created a script in the programming language Python. In this script we first import all the MRI data, which are saved either in NIfTI or DICOM file format. Then we manipulate this data so that we get a 3D matrix of values for each measured pixel. Each measured pixel has also its own \( x \), \( y \) and \( z \) position. On the 3D matrix we then apply a Canny edge detector, which is an algorithm for detecting a wide range of edges in images [8]. The result of this algorithm is a new matrix with values 1, when a specific pixel is an edge or 0 otherwise. From this matrix we then extract only the outer pixels with values different from 0, we store their \( x \), \( y \) and \( z \) positions in a new array. To create the model for 3D printing we have to first triangulate these points. For the triangulation we use the Poisson surface reconstruction method [9]. With this triangles we can then create a model for sensor holder using computer programs like OpenSCAD [10]. An example of a sensor holder for the OPM system is shown on the bottom part of Fig. 2. Similar helmets have been made by other research groups [11]. On the left side in Fig. 1 we show the image of all triangles generated with this method, which form a reconstructed head.

Our next goal was to extract only the brain area and individual layers of the brain out of the anatomical MRI. We achieved that with the use of the program called Freesurfer [12], [13]. An example of this results is presented on the right side in Fig. 1. These results will be important in our future work, where we will try to improve the accuracy of localized sources.

B. Obtaining the MEG data

The acquisition of MEG data is a very complex task. All our MEG measurements were performed inside a magnetically shielded room with a SQUID system. In addition to that, we performed some first test measurements with a system of OPM sensors. The SQUID system consists out of 128-channel SQUID sensors produced by the company Yokogawa. The sensors holder for this system is shown on the top part of Fig. 2. The whole system is cooled with a liquid helium. Each channel is a gradiometer composed of two parallel sensors separated by a 5 cm distance along the sensing direction, which is approximately perpendicular to the head surface. The OPM system consists out of 15 two-axis magnetometers, which can measure two space components. The sensors are produced by the company

![Figure 1. Reconstruction of the MRI scans. On the left side is a model of head composed of triangles, which were obtained as a result of extraction of the outer edges from the MRI scans. On the right side is the volume of the brain, obtained from the entire MRI scan of the head. Yellow lines represent the edges of individual layers of the cortex.](image1)

![Figure 2. Sensor holders for two different measurement systems. On the bottom part is the sensor holder for the system of OPM magnetometers, and on the upper part for the SQUID system [15].](image2)
QuSpin Inc. and does not need a cooling system [14]. Since we have a limited number of these sensors, we have placed them only on the right side of the head, where we expect the greatest response, as shown on the bottom of Fig. 2. In our experiment we measured auditory evoked fields for a 1 kHz tone of duration 500ms, which were performed for over 500 stimulations. To acquire meaningful results, we need to follow quite a few steps. Results from the measurements gives us so called “Raw data”, from which we have to extract many artifacts and noise. Then we average responses for individual stimulations. These steps can be performed with various computer tools like MNE [16], Brainstorm [17] and FieldTrip [18]. In our case, we used the latter.

C. Solving the inverse problem

As a result of all the steps in previous chapter, we obtained the averaged time series of the magnetic field $B$ for all channels. Fig. 3 displays so called butterfly plot, where all channels are plotted. The external auditory stimulation was at $t=0$. We can clearly observe that the maximum response is at time around $t=100$ ms after the stimulation. The upper part of Fig. 4 shows an example of the measured values ($B$) at a specific time. Since the sensors of the SQUID system are distributed on a helmet shaped surface, see Fig. 2, we showed the magnetic fields as projection on a flat plane. We calculate the new locations in the projection as: $\Delta x = r_i \cos(\arctan(\phi))$ and $\Delta y = r_i \sin(\arctan(\phi))$, where $r_{ij}$ represents the euclidean distance between $i$-th and the highest lying channel with index $j = 118$. The angle is defined as $\phi = y_j - y_i / (x_j - x_i)$.

Next step is localization of source at the time when the sensors measured the biggest response. There are several ways to localize increased activity within the brain, when measuring with the MEG method. Most of them assume, that the net currents can be approximated as a current dipole, which give rise to a magnetic field. At this point we have to introduce a forward model. In our work we have used a model which calculates a magnetic field ($B$) outside a spherically symmetric volume conductor. If we want to use this model, we have to approximate the head with a best fitted sphere. In our case we fitted a sphere on the upper part of reconstructed head, that we presented earlier.

We calculated the magnetic field $\vec{B}$ in the sensor positioned $\vec{r}$ outside the sphere due to the current dipole with strength and orientation $\vec{p}$ and position $\vec{r}_{\text{p}}$ inside the sphere using the following equation derived by Sarvas [19]:

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi r^2} \left[ F(\vec{p} \times \vec{r}_{\text{p}}) - (\vec{p} \times \vec{r}_{\text{p}}) \cdot \nabla F \right], \quad (1)$$

where $F = |\vec{a}|^2 + |\vec{a} \times \vec{r}|$, $\vec{a} = \vec{r} - \vec{r}_{\text{p}}$, and

$$\nabla F = \frac{F}{|\vec{a}|} + |\vec{a}| \vec{a} + \left( \frac{\vec{a}^2}{|\vec{a}|} + |\vec{a}| \right) \vec{r}. \quad (2)$$

Note that the equation (1) is defined only for points outside the conducting sphere model.

The inverse problem, which represents finding the source for all the measurements of $B$ at one specific time, is solved with performing a nonlinear least squares curve fitting using Levenberg–Marquardt algorithm [20]. In other words, this method searches for the optimal values of $\vec{r}_{\text{p}}$ and $\vec{p}$, where the difference between the measured values of $B$ and the values calculated with the model (1) is the smallest. This method also needs a starting approximations for the searched variables. These approximations should be wisely picked, otherwise, the algorithm can find a local minimum instead of a global minimum.

III. RESULTS AND DISCUSSION

A. SQUID system

As observed in Fig. 3 we can expect the biggest response after around 100 ms after stimulation. First we plotted a color map of values of the magnetic field ($B$) at time of greatest response after the subject received an auditory stimulation, for all 128 channels in the SQUID system in the upper part of Fig 4. From this picture we can observe two dipole-like field patterns, one on the left part and another on the right part of the SQUID system. For these values of magnetic field ($B$) we solved the inverse problem. As a result we obtained the locations and direction of two current dipoles. Next, we calculated the magnetic field for the same locations as the squid channels using the forward model (1). These fields are represented on the bottom of Fig. 4. Relative error (RE) defined as a root mean square (RMS) of difference between measured and calculated data divided by the RMS of measured data was 0.33 and corresponding correlation coefficient (CC) 0.94.

When comparing these two results presented on Fig. 4, we can clearly see that the values in both maps are very similar. Locations of the maxima and minima coincide. The center of the maximal measured field of the first

![Figure 3. A so called “butterfly plot” for the averaged time series obtained with the SQUID system. Each curve, marked with the same color represents a time series of measured signal for a specific channel. At $t=0$ the measured subject/patient received a auditory stimulation, at around $t=100$ ms, we measure the maximum response (N100).](image-url)
The dipole is at around $\Delta x = -120 \text{ mm}$ and $\Delta y = -80 \text{ mm}$ and the minimum at around $\Delta x = -170 \text{ mm}$ and $\Delta y = 20 \text{ mm}$. On the fitted result the maximum and minimum are slightly shifted to the location at around $\Delta x = -120 \text{ mm}$ and $\Delta y = -70 \text{ mm}$ and the minimum at around $\Delta x = -190 \text{ mm}$ and $\Delta y = 0 \text{ mm}$. For the second dipole, this shift is not so noticeable. The maximum is at around $\Delta x = 180 \text{ mm}$ and $\Delta y = 50 \text{ mm}$ and the minimum at $\Delta x = 150 \text{ mm}$ and $\Delta y = -50 \text{ mm}$.

The locations of the fitted dipoles ($\vec{r}_0$) obtained by solving the inverse problem for the values of the magnetic field ($\vec{B}$) are shown on Fig. 5. Locations are presented on different viewing angles of the MRI scan. On these graphs the dipole is displayed with a red dot. On the left side of Fig. 5 projections of the first dipole are shown, on the right side projections of the second dipole are shown. The upper two graphs represent a sagittal viewing plane, the middle two an axial viewing plane and the lower two a coronal viewing plane. These results coincide with expectations, the calculated locations are near the center of the auditory cortex [21].

B. OPM magnetometers

Next, we measured the response of the auditory stimulation with the system of 15 OPM magnetometers. The results of these measurements are presented on the upper two graphs in Fig. 6. The left graph represents the radial component of the magnetic field and the right graph the tangential component. For these values of ($\vec{B}$) we solved the inverse problem as presented in previous chapter. As a result we obtained a location ($\vec{r}_0$) and the dipole direction ($\vec{p}$) for one dipole. Next, we calculated the magnetic field for the same locations and orientations as the OPM magnetometers using the forward model (1). These fields are represented on the bottom of Fig. 6.

On the graph of the measured radial component, we can observe a minima of ($\vec{B}$) on the middle and a maxima on the right side and on the graph of measured tangential component a minima of ($\vec{B}$) on the right side and a maxima on the left side. If we compare the measured and fitted values we can see that these values do not completely overlap. Consequently, $RE=0.37$, $CC=0.90$ for
radial, and RE=0.70, CC=0.79 for tangential components are worse than in the case of SQUID system, see Fig. 4. The locations of the fitted dipole ($\vec{r}_p$) obtained by solving the inverse problem for the values of the magnetic field ($B$) are shown on Fig. 7. The location of the fitted dipole are also close to the auditory cortex as in the case of SQUID system, see Fig. 5. These measurements with the OPM system are the first test results. This system still needs a lot of optimization, but the current results look very promising.

IV. CONCLUSION

In our work we were dealing with the basis of the neuroimaging technique called magnetoencephalography (MEG). We addressed the major advantages and drawbacks when measuring with the classic SQUID system. We then presented a new alternative system consisting of optically-pumped magnetometers (OPMs). For both systems we described how the measurements are made. An important role in the interpretation of MEG results is also the processing of MRI scans. We showed how we extracted from the MRI scan the outer surface of the head and individual layers of the cortex. These surfaces were also triangulated into a mesh, which will be very useful in our future work, when we will use realistically shaped head volume conductor model and apply the boundary element method (BEM) for calculating the magnetic field and the source localization [22]. To determine the locations of active regions inside the cortex, we solved the inverse problem using the dipole source model in the spherical volume conductor model [4,19]. Main results for the SQUID and the OPM measuring system were presented with color maps for measured and fitted values of the magnetic field. We also showed the locations of the fitted current dipoles on the MRI scans. We realized that with the SQUID system, the locations of the active regions coincide with our expectations. Despite the fact that the measured and calculated fields of the OPM system doesn’t completely overlap, the location of the fitted current dipole is still in the region of the brain close to the auditory cortex. In order to confirm these conclusions, these methods will be in the future tested on a larger population. This system still needs improvements, particularly the number of channels was much lower compared to the SQUID system. This will also be a motivation for our further work. Since we are limited by the number of OPM magnetometers, we will explore how they need to be distributed to get as much information as possible.

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REFERENCES


