

# Biomagnetic signal measurement and network connection based on OPM-MEG

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Optically pumped magnetometer (OPM-MEG) is a new method for detecting biomagnetic signals. Connectivity analysis describes the information flow and causal relationship of biomagnetic signals during a specific task or state. In this paper, a mathematical model of biomagnetic signals was constructed and a Bayesian network construction method was proposed. The results verified by actual data that the average estimation error of the MVAR model coefficients of the constructed Bayesian method was reduced by 89.2% compared with the traditional maximum correlation entropy filtering method. In summary, the ability of OPM-MEG to detect biomagnetic signals was verified and it can characterize the functional connectivity of the brain.

**Index Terms**—Biomagnetic signal, OPM-MEG, MVAR, Bayes connectivity

## I. INTRODUCTION

OPM-MEG is a new non-invasive measurement method for detecting biomagnetic signals[1]. Traditional superconducting quantum interference devices (SQUID-MEG) require liquid helium cooling, and the equipment is bulky and expensive, which is not conducive to the popularization of the equipment. In recent years, based on the emergence of OPM-MEG, sensors can be arranged near the scalp, and specific target brain areas can be measured flexibly and conveniently, and key neuroimaging features can be reliably characterized. The actual OPM-MEG measurement system is shown in Fig 1.

Biomagnetic signals can capture the spatiotemporal dynamic characteristics of neural activity in the brain through brain functional imaging equipment. Brain network connectivity research analyzes the functional and information transmission relationships between brain regions to understand the working mechanism of the brain from a holistic system perspective. Biomagnetic signal measurement provides accurate and rich brain activity data for brain network research, and brain network analysis further explores the intrinsic connections and functional significance of these data. The MVAR model is a common method for constructing brain functional connectivity networks, and the model coefficients can be obtained through Bayesian estimation.

Bayesian methods can further infer the connection relationship and directionality between neural signals. This method can combine prior knowledge of the data, quantify uncertainty, and optimize the network structure. However, the Bayesian network connectivity of OPM-MEG in biomagnetic signals has not been verified.

This paper constructs a mathematical model of biomagnetic signals and proposes a Bayesian network construction method. Actual data are applied to the Bayesian network and compared with the traditional maximum correlation entropy method. This paper aims to verify the effectiveness of OPM-MEG in measuring biomagnetic signal network connectivity.

## II. METHODS

### A. Electromagnetic signal model

The current generated by neural activity near the cell is the original current, which causes the change of the charge density  $\rho$  in space. According to Maxwell's first equation, the charge generates an electric field, which in turn drives the generation of volume current, which flows passively in the medium. When the current density at the  $r'$  source position is represented by  $J(r')$ , it can be expressed as the sum of the original current  $J^p(r')$  and the volume current  $J^v(r')$ , that is

$$J(r') = J^p(r') + J^v(r') = J^p(r') + \sigma(r')E(r') \quad (1)$$

Where  $\sigma(r')$  and  $E(r')$  are the conductivity and electric field at that location, respectively. The above formula can be interpreted at the microscopic and macroscopic scales: When  $\sigma(r')$  is described at the cell scale,  $J^p(r')$  is the transmembrane current; when described at a more macroscopic scale,  $J^p(r')$  represents the overall current effect of the local tissue. Generally,  $\sigma(r')$  takes the macroscopic conductivity, and the location of the brain source activity at this time is to find the origin of the macroscopic source current.

In neuroelectromagnetism, equivalent current dipoles are often used to approximate local primary currents. The primary current  $J^p(r')$  gathered at position  $p_Q$  can be described as:

$$J^p(r') = Q\delta(r' - p_Q) \quad (2)$$

where  $Q$  is the dipole moment of the equivalent current dipole and  $\delta(r)$  is the Dirac function. It can be expressed as  $q\mathbf{o}_Q$ , where  $q$  is the amplitude of the current dipole and  $\mathbf{o}_Q$  is the direction of the dipole.

The transmission relationship between the source activity and the magnetic field measured by the sensor is described by the forward solution. Since the frequency band of interest in brain magnetoencephalography is below 1 kHz (usually below 100 Hz), the time derivatives of the electric and magnetic fields can be ignored, that is,  $\partial B/\partial t$  and  $\partial E/\partial t$  are approximately zero. Under this quasi-static approximation, Maxwell's equations are transformed into:

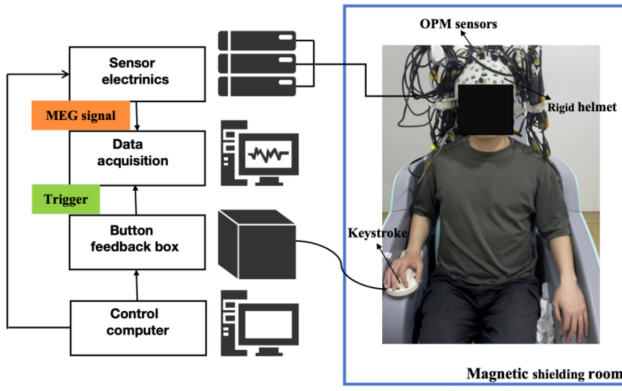


Fig. 1. OPM-MEG system and experimental scenario.

$$\begin{cases} \nabla \cdot \mathbf{E} = \rho / \epsilon_0, \\ \nabla \times \mathbf{E} = 0, \\ \nabla \cdot \mathbf{B} = 0, \\ \nabla \times \mathbf{B} = \mu_0 \mathbf{J}. \end{cases} \quad (3)$$

where  $\epsilon_0$  and  $\mu_0$  are the dielectric constant and magnetic permeability of free space, respectively. In equation (4), the curl of the electric field  $\mathbf{E}$  is 0. According to this identity  $\nabla \times (\nabla a) = 0$ , the electric field  $\mathbf{E}$  can be expressed as the gradient of a scalar potential, that is  $\mathbf{E} = -\nabla \varphi$ . At this time, the total current in equation (1) can be expressed as

$$\mathbf{J}(\mathbf{r}') = \mathbf{J}^p(\mathbf{r}') - \sigma(\mathbf{r}') \nabla' \varphi(\mathbf{r}') \quad (4)$$

where  $\nabla'$  represents the gradient of  $\mathbf{r}'$ .

The direct problem of brain magnetism field  $\mathbf{B}$  is to solve the magnetic field outside the brain  $V_{brain}$  given the original current distribution  $\mathbf{J}^p(\mathbf{r}')$ . The solution of the magnetic under the quasi-static approximation of Maxwell's equations can be obtained by the Biot-Savart law.

$$\begin{aligned} \mathbf{B}(\mathbf{r}) &= \frac{\mu_0}{4\pi} \int \frac{\mathbf{J}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV_{brain} \\ &= \frac{\mu_0}{4\pi} \int \frac{\mathbf{J}^p(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV_{brain} \\ &\quad - \frac{\mu_0}{4\pi} \int \frac{\sigma(\mathbf{r}') \nabla' \varphi(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV_{brain} \end{aligned} \quad (5)$$

Where  $\mathbf{r}$  is the measured position of the magnetic field,  $\mathbf{r}'$  is the source position, and  $|\mathbf{r} - \mathbf{r}'|$  represents the modulus of  $\mathbf{r} - \mathbf{r}'$ . The first term after the second equation in the above formula is the contribution of the original current  $\mathbf{J}^p(\mathbf{r}')$  to the magnetic field, and the second term is the magnetic field component  $\mathbf{J}^v(\mathbf{r}')$  contributed by the volume current.

### B. Bayes connectivity

The brain magnetic field values  $B$  measured by multiple sensors can be represented by a set of time series. Assuming that the vector is a joint stationary time series of N-dimensional MEG data:

$$\mathbf{x}(k) = [x_1(k), \dots, x_N(k)], 1 \leq k \leq n \quad (6)$$

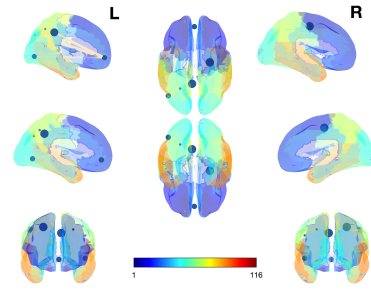


Fig. 2. Brain network connection.

Assuming that the order is  $q$  (the number of data channels is  $q$ ), the multiple autoregressive model can be expressed in the following form:

$$\begin{bmatrix} x_1(n) \\ \vdots \\ x_N(n) \end{bmatrix} = \sum_{r=1}^q A_r \begin{bmatrix} x_1(n-T) \\ \vdots \\ x_N(n-T) \end{bmatrix} + \begin{bmatrix} w_1(n) \\ \vdots \\ w_N(n) \end{bmatrix} \quad (7)$$

$A_r \in R^{N \times N}$ , Where  $q$  represents the maximum value of the model delay observation, and  $A_r$  represents the coefficient matrix when the delay is  $T$ , in the following form:

$$A_r = \begin{bmatrix} a_{11}(T) & a_{12}(T) & \dots & a_{1N}(T) \\ a_{21}(T) & a_{22}(T) & \dots & a_{2N}(T) \\ \vdots & \vdots & \ddots & \vdots \\ a_{N1}(T) & a_{N2}(T) & \dots & a_{NN}(T) \end{bmatrix} \quad (8)$$

$a_{ij}(T), i, j \in \{1, 2, \dots, N\}$  represents the linear impact of  $x_j(n-T)$  on  $x_i(n)$ , where non-zero coefficient values indicate the influence of time series  $j$  on time series  $i$ .  $\mathbf{w} = [w_1(n), w_2(n), \dots, w_N(n)]^T$  represents the multivariate Gaussian noise with zero-mean covariance matrix. To describe the relationship between two probabilities using Bayes' formula, the form is as follows:

$$P(A | B) = \frac{P(B | A) * P(A)}{P(B)} \quad (9)$$

Hence, the posterior probability  $f(\beta_k | x, y)$  is proportional to  $f(y | x, \beta_k) * f(\beta_k)$ , from which the expression for maximum posterior probability can be derived:

$$\arg \max_{\beta_k} f(y | x, \beta_k) * f(\beta_k) \quad (10)$$

## III. RESULTS AND DISCUSSION

This paper constructs a mathematical model of biomagnetic signals and proposes a Bayesian network construction method (See Fig 2 for the network). The results verify that the average estimation error of the MVAR model coefficients constructed by the Bayesian method is 89.2% lower than that of the traditional least squares method through actual data. The feasibility and effectiveness of OPM-MEG in measuring the connectivity of the biomagnetic signal network are evaluated. The results provide new evidence for the ability of OPM-MEG to measure biomagnetic signals.

## REFERENCES

- [1] S. Baillet, "Magnetoencephalography for brain electrophysiology and imaging," *Nature Neuroscience*, vol. 20, no. 3, pp. 327–339, 2017.