Estimation of activation site using cephalic sensitive distribution in brain function measurement with near-infrared light

Toshiyuki Tanaka¹, Daisuke Shimizu²

¹Prof. of Faculty of Science and Technology, Keio University (E-mail : tanaka@appi.keio.ac.jp)
²School of Science and Technology, Keio University

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Abstract

Recently, technology of brain activity measurement has developed, and many researchers have tried to elucidate the human brain function. In those technology, Near Infrared Spectroscopy (NIRS) enables us to measure brain activity safely and easily. That is the reason that NIRS is expected to apply variable study field. Since the spatial resolution of NIRS is not sufficient for further measurement of brain function, which is the disadvantage of NIRS and prevent development of applied research. In some previous researches, the spatial resolution improvement of NIRS have been performed by the minimum norm method and so on. The approaches can three-dimensionally estimate activation site in brain. However, the activation site estimated by the minimum norm method widely spreads, and it is difficult to perform the activity estimation in deep area. Therefore, the purpose of our study is to improve the measurement of activation site in deep position in brain by the modified minimum norm method. In this study, an experimental model based on the head structure is used, and the sensitivity distribution in the model is calculated by Monte Carlo simulation. We focus on the sensitivity distribution, and voxels in the model are classified by some levels depending on intensity of the sensitivity distribution. By comparing estimation value in each level, inactive voxels were determined and estimated active position was able to be narrowed down. As a result, estimation of brain activity in local position is improved compared with the conventional minimum norm method especially in estimation of small active position.

1. Introduction

In recent years, the study of higher brain function measuring device has been actively carried out. The human experiments have been attracted attention, since a functional brain imaging has been non-invasively performed [1,2]. Functional near infrared spectroscopy (fNIRS) is used for brain function imaging in this study. The fNIRS is expected to measure non-invasively brain activity and applications in various fields. fNIRS measures a blood hemoglobin concentration change according to hemoglobin absorption characteristics, and estimate brain activity. However, the method of mapping the observation data in 2D has different results according to the relative position of channel and activation position. Therefore, it is a problem that a rough position of activation can be measured.

For such problems, the previous studies try 3D estimation of brain activity position using the minimum norm method[3]. In the method, brain activity is estimated in 3D by spatial sensitivity distribution, using the light propagation equations or Monte Carlo method to experimental object model. This makes it possible to improve the spatial resolution by limited data of fNIRS. This is an ill-posed problem that obtains the 3D position from small number of data. The researchers often use the minimum norm method that the regularization term is the square norm. Brain function is limited function by site, and it has been shown in a number of experiments using a fMRI and so on that the hemodynamic response is localized. On the other hand, the activation site in brain is estimated wider than the real regions by the minimum norm method, and the region is influenced by the near-surface activation site. The minimum norm method in previous study is not suitable for estimation of brain activity in deep position.

In this study, we show the improvement method for estimation accuracy of brain activity in the deep position and local activation site estimation. The estimation accuracy of our proposed method is compared with the previous method, by numerical experiment using cephalic model. Our method uses the Monte Carlo method [4] for light propagation, and estimates based on the minimum norm method. We propose the method that narrow down the activation region by reducing the inactive region from estimation results of
2. Method

2.1 Derivation of observatory data for simulation

In this study, we obtain the activation site in brain by simulation. First, we make the fNIRS data for simulation. Conceptual diagram of light propagation from source to detector in fNIRS is shown in Fig. 1. The light intensity in source, detector and medium can be computed by simulation with Monte Carlo method. The absorbance change in a small region is characterized below, using Rytov approximation.

\[ \Phi(r_s, r_d) = \Phi_0(r_s, r_d) \exp\left\{ - \Phi_{\text{pert}}(r_s, r_d) \right\} \]  (1)

In the above equation, \( \Phi_0(r_s, r_d) \) is an obtained light intensity in optical characteristic value of cephalic region, and \( \Phi_{\text{pert}}(r_s, r_d) \) is perturbation term when an absorbance change occurs in some region as shown in the following.

\[ \Phi_{\text{pert}}(r_s, r_d) = \frac{1}{\Phi_0(r_s, r_d)} \int \Phi_{\text{src}}(r_s, r) \delta \mu_a(r) \Phi_{\text{det}}(r, r_d) \, dr \]  (2)

The next equation is obtained from eq. (1) and (2).

\[ \ln \left( \frac{\Phi_0}{\Phi} \right) = \frac{1}{\Phi_0(r_s, r_d)} \int \Phi_{\text{src}}(r_s, r) \delta \mu_a(r) \Phi_{\text{det}}(r, r_d) \, dr \]  (3)

Fig. 1  Conceptual diagram of sensitivity matrix

When the observational results is set to be \( Y = \{ y_i | i = 1, ..., M \} \) and the absorption coefficient change \( \delta \mu_a \) is set to be \( X = \{ x_j | j = 1, ..., N \} \), the next relation is satisfied for \( X \) and \( Y \).

\[ Y = AX \]  (4)

Matrix \( A = \{ A_{ij} | i = 1, ... M, j = 1, ..., N \} \) is sensitive matrix, and shows a sensitive distribution in cephalic parts. Each component of sensitive matrix is computed by the following equation.

\[ A_{ij} = \frac{\Phi(r_{s,i}, r_j) \Phi(r_j, r_{d,i})}{\Phi(r_{s,i}, r_{d,i})} \]  (5)

In this study, each value in sensitive matrix is obtained by Monte Carlo method.

2.2 Estimation of activation site in brain

We estimate activation site in brain using Tikhonov regularization method that gives regularization function \( \Omega(X) \) to the inverse problem. In this solution, the estimation function \( f(X) \) is characterized below.

\[ f(X) = \frac{1}{2} || Y - AX ||^2 + \alpha \Omega(X) \]  (6)
In this approach, the square norm is selected as the regularization function $\Omega(X)$ as shown in the following.

$$\Omega(X) = \frac{1}{2} \| X \|^2$$  \hspace{1cm} (7)

Finally, the estimation values $\hat{X}$ are computed by the next equation as traditional method.

$$\hat{X} = (B^T B + \alpha I)^{-1} B^T Y$$  \hspace{1cm} (8)

In our proposed method, parameter $\alpha$ is set to be different value for each medium.

### 3. Results

In this study, we use the theoretical medium that has the optical characteristics as shown in Table 1, and the medium size is shown in Fig. 1.

| region          | thickness [mm] | Absorption coefficient $\mu_a$ [1/mm] | Scatter coefficient $\mu_s$ [1/mm] |
|-----------------|----------------|---------------------------------------|-----------------------------------|
| Skull           | 10             | 0.010                                 | 1.0                               |
| Cerebral cortex | 20             | 0.020                                 | 1.0                               |

![Experiment model](image)

The small activation site in model is given as shown in Fig. 3(a), and Fig. 3(b) is the result of the previous method and Fig. 3(c) is the result of our proposed method. The result of our method is closer to the original data.

![Original activation site](image)
4. Discussion

In the results of simulation, our proposed method has better accuracy of activation position estimation in deep position than one of the previous method. The activation site is estimated as that of an epidermal part in the previous method, and value of false positive becomes larger. The false positive is reduced by narrowing down with threshold in our method. However, the activation site in the deepest layer is not sufficiently estimated even by our method. Because the near infrared light cannot sufficiently travel to deep position, and sensor has a low sensitivity. In fact, it is difficult for our method to measure the activation site deeper than 2.5 cm.

5. Conclusion

In this study, we estimate three-dimensionally the activation site in brain from fNIRS data using the minimum norm method. A spatial sensitivity distribution in cephalic simulation model is computed using Monte Carlo method, and pseudo observatory data of fNIRS is obtained for simulation. The activation site in brain is estimated from simulated fNIRS data using spatial sensitivity distribution. Although the previous method has a defect that the activation site in deep position cannot be precisely estimated, our proposed method improves the defect.

Reference

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