Recursive minimum-leakage (REML) spatial filter for MCG source imaging

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Abstract. This paper proposes a novel spatial filter imaging derived based on the constrained optimization in which the beam response is forced to be delta function with the filter gain equal to the sensor-array gain. The spatial resolution of the proposed filter is significantly higher than that of non-adaptive spatial filters, while it is free from the limitations of adaptive spatial filters. Results of applying the proposed filter to MCG source imaging are presented to demonstrate the method's capability of providing high-spatial resolution and small location bias.

Keywords: : spatial filter imaging, minimum-norm method, sLORETA, MCG source imaging

1. Introduction

Spatial-filter source imaging has gained a great interest in the field of bioelectromagnetism. There are two types of spatial filters: adaptive and non-adaptive spatial filters[Sekihara and Nagarajan,2008]. Adaptive spatial filters generally provide high spatial resolution and small location bias[Sekihara et al., 2005]. The adaptive spatial filters, however, require large number of time samples to obtain an accurate estimate of the covariance matrix. They give erroneous results when highly correlated sources exist. Although non-adaptive spatial filters do not have these problems, they generally have much lower spatial resolution and larger location bias. This paper proposes a novel spatial filter that provides the spatial resolution higher than that of non-adaptive spatial filters but is free from the limitations of the adaptive spatial filters. In this paper, the proposed spatial filter is derived based on the beam response optimization. The results of applying the proposed filter to MCG source imaging are also presented..

2. Spatial filter formulation based on beam-response optimization

The spatial filter estimates the source intensity $s(\boldsymbol{r},t)$ from sensor-array outputs $\boldsymbol{b}(t)$ using

$$\hat{s}(\boldsymbol{r},t) = \boldsymbol{w}^T(\boldsymbol{r})\boldsymbol{b}(t)\,. \tag{1}$$

where $\boldsymbol{w}(\boldsymbol{r})$ is the weight vector of the spatial filter. Defining the sensor leadfield vector as $\boldsymbol{l}(\boldsymbol{r})$, the beam response, $\boldsymbol{w}^T(\boldsymbol{r})\boldsymbol{l}(\boldsymbol{r}')$, expresses the sensitivity of the spatial filter pointing at $\boldsymbol{r}$ to a source located at $\boldsymbol{r}'$. We then wish to derive a spatial filter that only passes the signal from a source at the pointing location and suppresses the leakage from other locations. Such a spatial filter may be derived by imposing a delta-function-like property on the beam response. That is, the weight vector is obtained using

$$\boldsymbol{w}(\boldsymbol{r}) = \arg\min_{\boldsymbol{w}(\boldsymbol{r})} \int \left[\boldsymbol{w}^T(\boldsymbol{r})\boldsymbol{l}(\boldsymbol{r}') - \delta(\boldsymbol{r}-\boldsymbol{r}')\right]^2 d^3r'\,. \tag{2}$$

The resultant weight is expressed as

$$\boldsymbol{w}(\boldsymbol{r}) = \boldsymbol{G}^{-1}\boldsymbol{l}(\boldsymbol{r}) \tag{3}$$

where $\boldsymbol{G}$ is called the gram matrix, which is obtained as $\boldsymbol{G} = \int \boldsymbol{l}(\boldsymbol{r})\boldsymbol{l}^T(\boldsymbol{r})d^3r$. The spatial filter using Eq. (2) is the well-known minimum-norm filter[Hamalainen and Ilmoniemi, 1984].

Variants of the minimum-norm filter can be obtained by adding various constraints to the optimization in Eq. (2) [Greenblatt et al.,2005]. One example is the standadized low-resolution electromagnetic tomography (sLORETA) filter [Pascual-Marqui, 2002; Sekihara and Nagarajan, 2008]. Its weight vector is derived from

$$\boldsymbol{w}(\boldsymbol{r}) = \underset{\boldsymbol{w}(\boldsymbol{r})}{\arg\min} \int \left[\boldsymbol{w}^T(\boldsymbol{r})\boldsymbol{l}(\boldsymbol{r}') - \delta(\boldsymbol{r} - \boldsymbol{r}') \right]^2 d^3r' \ \text{ subject to } \int \left[\boldsymbol{w}^T(\boldsymbol{r})\boldsymbol{l}(\boldsymbol{r}') \right]^2 d^3r' = 1 \tag{4}$$

In the above optimization, the second term makes the total amount of leakage to be unity. The resultant weight is expressed as

$$\boldsymbol{w}(\boldsymbol{r}) = \boldsymbol{G}^{-1}\boldsymbol{l}(\boldsymbol{r}) \left[\boldsymbol{l}^T(\boldsymbol{r})\boldsymbol{G}^{-1}\boldsymbol{l}(\boldsymbol{r}) \right]^{-1/2} \tag{5}$$

3. Proposed spatial filter

We propose a spatial filter derived from the following optimization:

$$\boldsymbol{w}(\boldsymbol{r}) = \underset{\boldsymbol{w}(\boldsymbol{r})}{\arg\min} \int \left[\boldsymbol{w}^T(\boldsymbol{r})\boldsymbol{l}(\boldsymbol{r}') - \delta(\boldsymbol{r} - \boldsymbol{r}') \right]^2 s^2(\boldsymbol{r}', t) d^3r' \ \text{ subject to } \boldsymbol{w}^T(\boldsymbol{r})\boldsymbol{l}(\boldsymbol{r}) = \|\boldsymbol{l}(\boldsymbol{r})\| \tag{6}$$

where $s^2(\boldsymbol{r}, t)$ is the source power at $\boldsymbol{r}$. The idea behind the above optimization is that we wish to impose a delta-function-like property on the beam response only over a region where sources exist, instead of imposing that property over the entire space. We also add the constraint that forces the filter gain at the pointing location to be equal to the sensor-array gain. Therefore, the resultant spatial filter blocks leakage signal from sources located other than the filter-pointing location, and passes the signal from the pointing location with a gain equal to the sensor-array gain. The filter weight results in

$$\boldsymbol{w}(\boldsymbol{r}) = \bar{\boldsymbol{G}}^{-1}\tilde{\boldsymbol{l}}(\boldsymbol{r}) \left[\tilde{\boldsymbol{l}}^T(\boldsymbol{r})\bar{\boldsymbol{G}}^{-1}\tilde{\boldsymbol{l}}(\boldsymbol{r}) \right]^{-1} \tag{7}$$

where $\tilde{\boldsymbol{l}}(\boldsymbol{r}) = \boldsymbol{l}(\boldsymbol{r}) / \|\boldsymbol{l}(\boldsymbol{r})\|$ and $\bar{\boldsymbol{G}} = \int s^2(\boldsymbol{r}, t)\tilde{\boldsymbol{l}}(\boldsymbol{r})\tilde{\boldsymbol{l}}^T(\boldsymbol{r}) d^3r$. Since the source power $s^2(\boldsymbol{r}, t)$ is unknown, we use the estimated source power $\hat{s}^2(\boldsymbol{r}, t)$ when computing $\bar{\boldsymbol{G}}$, i.e., we use

$$\bar{\boldsymbol{G}} = \int \hat{s}^2(\boldsymbol{r}, t)\tilde{\boldsymbol{l}}(\boldsymbol{r})\tilde{\boldsymbol{l}}^T(\boldsymbol{r}) d^3r \tag{8}$$

The proposed weight is derived in a recursive manner. That is, by setting an initial $\hat{s}^2(\boldsymbol{r}, t)$ to have a uniform value, the weight $\boldsymbol{w}(\boldsymbol{r})$ is derived using Eqs. (7) and (8). The estimated source intensity $\hat{s}(\boldsymbol{r}, t)$ is obtained using Eq. (1). This $\hat{s}(\boldsymbol{r}, t)$ is then used in Eq. (8), and we update $\boldsymbol{w}(\boldsymbol{r})$ and $\hat{s}(\boldsymbol{r}, t)$. These procedures are repeated until some stopping criterion is satisfied. We call this spatial filter recursive minimum-leakage (REML) spatial filter.

4. Experiments

A healthy volunteer participated in the experiments. A biomagnetometer equipped with 64 coaxial gradiometers (Hitachi High-Technologies) [Tsukada et al., 1998] was used for measuring subject's MCG signal. The measured signal was bandpass filtered with a band with between 0.1—100 Hz, and averaged across thirty heart cycles. The averaged MCG recordings are shown in the left panel of Fig. 1. We applied the proposed spatial filter to the MCG data at 60 ms, which is indicated by a vertical broken line in Fig. 1. The reconstruction region and the coordinate system relative to the sensor array are depicted in the right panel of Fig.1. The reconstruction results obtained using sLORETA are shown in Fig. 2(a), and the results using the proposed filter are shown in Fig. 2(b). These figures show that the results from the proposed spatial filter has spatial resolution much higher than that of the sLORETA filter. Since the right heart atrium is considered to be electro-physiologically active at this time point, the location obtained from the peak maximum of the proposed REML spatial-filter image is more plausible than the location obtained from the sLORETA filter. These results demonstrate that the proposed spatial filter has high spatial resolution and small location bias.

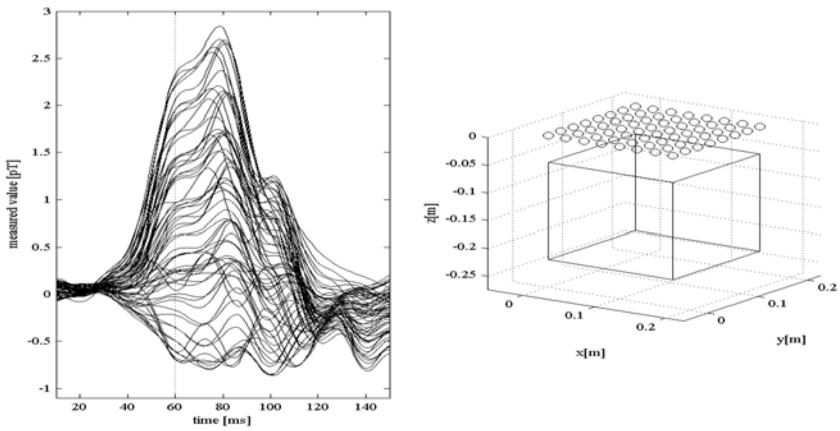

Figure 1. *Measured MCG waveforms obtained by averaged across thirty heart cycles(left panel), and MCG sensor array and reconstruction region(right panel).*

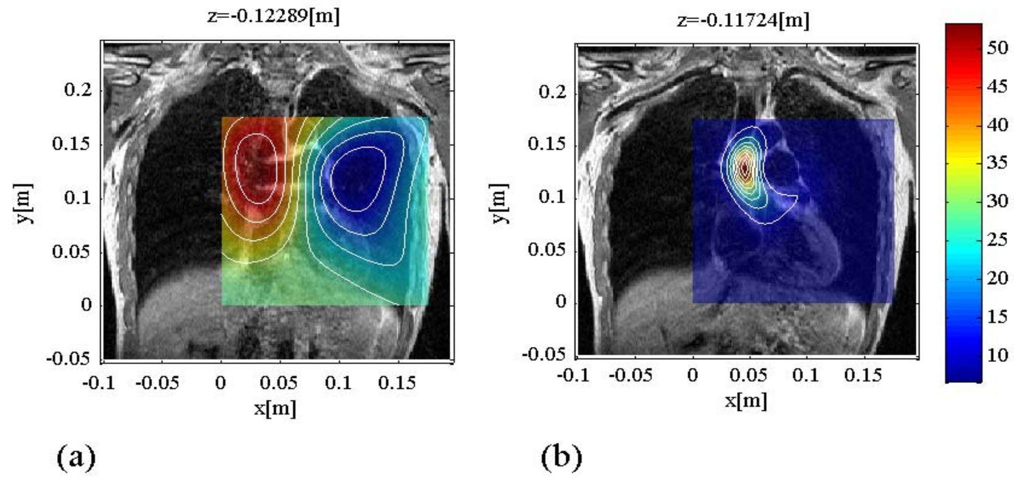

Figure 2. *Source reconstruction results overlayed onto the sobject's MRI. (a) sLORETA filter used, and (b) the proposed REML spatial filter used.*

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