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Multi-source localization in MEG using simulated annealing: Model order determination and parameter accuracy

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Introduction

Empirical neuromagnetic studies have reported that multiple brain regions are active at single instants in time as well as across time intervals of interest [1]. Determining the number of active regions, however, required a systematic search across increasing model orders using a reduced chi-square measure of goodness-of-fit and multiple starting points within each model order assumed [2]. Such a time-intensive strategy was necessary since initial source modeling assumptions for a given instantaneous or spatio-temporal data set are not available *a priori* and the minimization algorithms typically used rely on either a gradient-based search or simplex, both of which are reported to be sensitive to the initial starting points [2,3]. Simulated annealing was recently proposed for noiseless biomagnetic data [4,5] as an effective global minimizer. It does not require multiple starting points and with an appropriate cooling schedule, should converge to the global minimum. A modified cost function was also proposed to effectively deal with an unknown number of dipoles for noiseless, multi-source biomagnetic data [5].

Numerical simulation studies were conducted using simulated annealing as described in [6] to examine: 1) effects of a systematic increase in model order using both reduced chi-square [2] as a cost function as well as a modified cost function as proposed in [5]; and 2) effects of overmodeling on parameter estimation accuracy. Effects of different choices of weighting factors are also discussed. Simulated annealing was also applied to visually evoked neuromagnetic data and the effectiveness of both cost functions in determining the number of active regions was demonstrated.

Method

Instantaneous neuromagnetic field distributions were generated by 2- and 3-dipole configurations embedded in a spherical conductor. Field values were calculated at 135 measuring points distributed over a portion of a spherical surface ($R=11.3$ cm) as recorded by first-order gradiometers. Normally distributed noise of zero mean and a standard deviation of 20 fT was added. Simulated annealing was implemented as in [6]. The center of a spherical conductor was selected as the starting point in all cases. An iterative random search for dipole locations over the entire head volume was permitted. In order to approach the global minimum, the following annealing schedule was found as adequate: $T_{n+1} = (1-\epsilon)T_n$, where ϵ was 0.05 for noisy and 0.15 for noiseless cases examined, and T_{n+1} and T_n are the temperature parameters for two consequent states. Best-fitting parameter estimates were obtained by minimizing: 1) chi-square (χ^2) as a cost function for every model order assumed [2]

$$\chi^2 = \sum_{i=1}^N \left(\frac{B_i - \hat{B}_i(a_j)}{\sigma_i} \right)^2 \quad (1)$$

and 2) a modified cost function (MCF) as proposed by [5]

$$\text{MCF} \equiv \chi^2 + w \sum_{p=1}^P |\hat{B}_p|^{1/2} \quad (2)$$

where B_i are noisy simulated field values at every sensor location $i=1, \dots, N$, $\hat{B}_i(a_j)$ are field values for an assumed model described by parameters a_j ; σ_i are standard deviations of gaussian noise added assumed to be equal for every sensor; and $\hat{B}_p$ are field values generated by $p = 1, \dots, P$ dipoles assumed in the model, typically greater than the actual or expected number of sources; w is a weighting factor. The second term in Eq.(2) is referred to as E_w . A range of weighting factors, used in the second term of the modified cost function, was examined.

Results

Both cost functions permitted the identification of the actual number of sources for 2- and 3-dipole configurations under noiseless and noisy conditions. While χ^2 required a search across model orders, a modified cost function allowed the proper identification of the actual number of sources when a model order greater than the actual number was assumed. However, different choices of weighting factors were necessary in order to assure: 1) adequate cost function values (at least for χ^2 for which the probability distribution is known) were obtained; and 2) the moments of extra dipoles added were close to zero. Table I. represents actual source parameters (panel A) and best-fitting parameter estimates (panels B and C) for noisy 2-dipole data for both cost function values when the model orders assumed were 3 and 4 (both of which represented overmodeling). In cases where adequate weighting factors

Table I: Noisy 2-Dipole Data (SD = 20 fT)

A. Actual Source Parameters

Dipole:	ρ (cm)	ν ($^\circ$)	ϕ ($^\circ$)	P (nAm)	ψ ($^\circ$)
1	8.0	70.0	165.0	8.0	0
2	8.0	70.0	195.0	8.0	0

B1. Model order = 3; $w = 0.025$

Dipole:	ρ (cm)	ν ($^\circ$)	ϕ ($^\circ$)	P (nAm)	ψ ($^\circ$)	χ^2	$\chi^2 + E_w$
1	8.043	70.966	165.586	7.854	2.145	117.490	166.209
2	7.884	70.701	195.958	8.584	-0.814		
3	9.999	33.458	178.669	0.204	0.714		

B2. Model order = 3; $w = 0.01$

1	8.002	70.344	165.987	8.129	0.902	132.176	309.098
2	7.958	70.044	196.196	8.116	-0.147		
3	0.008	143.205	309.478	0.115	311.746		

B3. Model order = 3; $w = 0.02$

1	8.040	70.517	165.994	7.891	0.523	133.753	484.928
2	7.957	70.512	196.046	8.087	-0.039		
3	0.000	174.128	107.094	0.061	219.199		

B4. Model order = 3; $w = 0.03$

1	6.416	67.896	180.000	19.998	0.000	397.362	729.431
2	0.009	95.623	223.362	0.000	333.031		
3	0.000	28.366	310.637	1.371	21.174		

C1. Model order = 4, $w = 0.10$

1	8.052	71.079	165.657	7.837	-2.095	131.266	307.815
2	7.894	71.264	195.789	8.551	2.815		
3	0.000	137.978	169.243	0.155	152.699		
4	0.000	138.887	223.289	0.6475	308.489		

C2. Model order = 4, $w = 0.02$

1	8.099	71.462	165.729	7.548	-3.374	134.262	483.349
2	7.887	71.508	195.585	8.516	4.240		
3	0.721	116.628	212.920	0.000	79.465		
4	1.356	117.025	116.144	0.000	167.918		

were selected, accurate parameter estimation of the actual sources was possible and the addition of extra dipoles resulted only in minor effects on parameter estimation accuracy. The moments of the extra dipoles were very close to zero (panels B2, B3, C1, C2) and their estimated locations were close to the center of the spherical conductor. However, selecting too large of a weighting factor (panel B4), strongly affected parameter estimates of all sources and resulted in too improbable χ^2 values indicating inadequacy of the model assumed. In this case, it was assumed that the particular choice of the weighting factor was inadequate, since overmodeling itself always lead to adequate χ^2 values when an optimal solution is reached. The optimal weighting factors for 3-dipole noisy data (not shown) were different than for the 2-dipole case (Table I.) (e.g., $w = 0.075$ for an assumed model order of 4 and $w = 0.065$ for an assumed model order of 5, respectively). While Haneishi and colleagues [5] suggested a weighing factor of about 0.5 for noiseless data, we found empirically that the ratio of 2:3 between first and second term in Eq.(2), resulted in an adequate choice of weighting factors for noisy simulated conditions.

Table II. shows best-fitting parameter estimates and cost-function values when different multi-dipole models were applied to visual neuromagnetic data evoked by a small Target stimulus placed 4° below the horizontal meridian and 3° to the right of the vertical meridian [8]. A 2-dipole model was identified in this case as an adequate model for an instantaneous field distribution at an early latency of 110 ms poststimulus by both cost functions. The identified brain regions were in agreement with solutions obtained by spatio-temporal modeling of the early evoked activity from 80-120 ms. Reduced chi-square values, rather than χ^2 , are presented in panel A.

Table II. Visually evoked neuromagnetic data (SD = 25.44 fT)

A. Reduced chi-square - Increasing model order

Dipole:	x (cm)	y (cm)	z (cm)	P (nAm)	ψ ($^\circ$)	χ_r^2	Q
1	-4.93	1.23	7.03	6.37	173.93	1.479	0.007
1	-6.56	0.55	5.03	5.22	220.97	0.967	0.550
2	-4.39	3.09	5.23	8.48	115.52		
1	-7.20	0.02	4.96	2.97	219.32	0.867	0.749
2	-4.91	2.44	5.57	7.18	140.05		
3	-7.55	4.86	4.02	0.20	17.71		

B. Modified cost function - Overmodeling: Model order = 4; $w = 0.046$

Dipole:	x (cm)	y (cm)	z (cm)	P (nAm)	ψ ($^\circ$)	χ^2	$\chi^2 + E_w$
1	-6.74	0.72	5.11	3.89	216.54	54.36	88.03
2	-4.68	3.60	5.16	5.21	117.99		
3	-7.59	-4.26	8.33	0.08	54.51		
4	0.00	0.00	4.01	0.02	298.93		

Discussion

Both cost functions allowed for the identification of the actual number of sources in simulated cases (Table I) and the same adequate model order in empirical data (Table II). Best-fitting source parameters were either accurate estimates of the actual source parameters or represented physiologically plausible solutions which were similar to those obtained previously using other methods [7]. While χ^2 required a systematic increase in model order as demonstrated earlier [1], the use of a modified cost function allowed for more efficient model order determination

while preserving the accuracy of parameter estimation. In essence, if one applies a model order which represents overmodeling, the correct number of dipoles can still be obtained since the "extra dipoles" would either have close to zero moments and they would be placed near the center of the head. Consequently, these "extra dipoles" are easy to identify. However, while a systematic search over different model orders might be avoided by using a modified cost function as proposed by [5], consideration of different weighting factors was necessary since both previous [5] and present simulations indicate that optimal values should be found empirically. Therefore, a search over model orders or over a range of weighting factors seems unavoidable. Since we found the optimal choice of the weighting factor to be related to the actual source configuration, which is unknown in empirical cases, it turns out that a search over model orders is likely to be more efficient. Previous simulations [5], as well as the present results, demonstrate the promise of simulated annealing as an efficient minimization approach for neuromagnetic applications. We are currently implementing simulated annealing for spatio-temporal analysis of neuromagnetic data [8] with χ^2 as a cost function of choice.

References:

- [1] Aine, C.J., Supek, S., and George, J.S. Temporal dynamics of visual-evoked neuromagnetic sources: Effects of stimulus parameters and selective attention, *Intern. J. Neuroscience*, 1995, 80: 79-104.
- [2] Supek, S., and Aine, C.J. Simulation studies of multiple dipole neuromagnetic source localization: Model order and limits of source resolution, *IEEE Trans. Biomed. Eng.*, 1993, BME-40: 529-540.
- [3] Press, W.H., Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P. *Numerical Recipes in C*, Cambridge University Press, 1992
- [4] Sekihara, K., Haneishi, H., and Ohya, N. Details of simulated annealing algorithm to estimate parameters of multiple current dipoles using biomagnetic data, *IEEE Trans. Med. Eng.*, 1992, BME-11: 293-299
- [5] Haneishi, H., Ohya, N., Sekihara, K., and Honda, T. Multiple current dipole estimation using simulated annealing, *IEEE Trans. Med. Eng.*, 1994, BME-41: 1004-1009
- [6] Corana, A., Marchesi, M., Martini, C., and Ridella, S., Minimizing multimodal functions of continuous variables with the "simulated annealing" algorithm, *ACM Trans. Mathem. Software*, 1987, 13: 262-280
- [7] Aine, C.J., Supek, S., George, J.S., Ranken, D., Lewine, J., Sanders, J., Best, E., Tiee, W., Flynn, E.R., and Wood, C.C. Retinotopic organization of human visual cortex: Departures from the classical model (in press, *Cerebral Cortex*, 1996)
- [8] Huang, M., Supek, S., and Aine, C., Application of simulated annealing for multi-source spatio-temporal localization in MEG: Simulation and empirical study, 2nd International Conference on Functional Mapping of the Human Brain, June 17-21, 1996.

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