ESTIMATION OF BIDIRECTIONAL INFORMATION FLOW IN THE HUMAN BRAIN FROM EVOKED POTENTIALS BY USE OF DIPOLE TRACING METHOD

Noriyuki Take[1,2], Yukio Kosugi[1], Toshimitsu Musha[2]
[1]Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, Yokohama, Japan
[2]Brain Functions Laboratory, Inc., Kawasaki, Japan

Abstract- **It is important to know the information flow between active regions in the brain for the elucidation of the information processing mechanism and for the disease detection in the human brain. In this paper, at first, we estimate dipoles (via 3-layered concentric spherical model, 2-dipole estimation) from evoked potentials. Secondary, using derived 2 dipole locations and moments as loci and quantities of brain activities, we analyze the information flow between the two time-series of the 1st and the 2nd dipole moments by use of the time-series analysis method based on the directed transinformation. We obtain bidirectional information flows between the neuronal activities localized in 3D space of the brain with respect to somatosensory evoked potentials measured with 21 electrodes arranged according to the international 10-20 standard by electrical stimulations on the median nerve of the right hand.**
***Keywords* - Dipole Tracing Method, Directed Transinformation, 3D-display, Information Flow, Evoked Potentials**

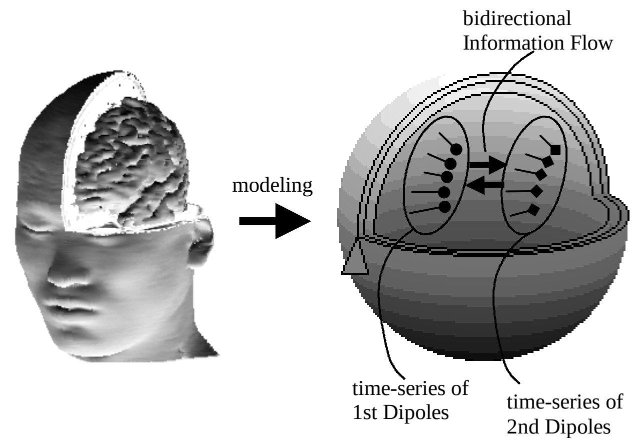

Fig. 1. Information flow between two time-series of 1st and 2nd dipoles by assuming 2 dipoles in 3-layered concentric spherical model

I. INTRODUCTION

Recently, an information flow between the scalp potentials measured by multiple electrodes is reported [1]. However, it was not possible to reveal the three-dimensional information flow within the brain, because this method is based on the assumption that the intra-cranial activities might be indirectly estimated by the information flow between the two-dimensional specified points on the scalp. Therefore, it was not sufficient for the elucidation of the information processing mechanism and the detection of disease in which the deeply seated neuronal activities are involved.

In the present study, we make dipole localization (via 3-layered concentric spherical model, 2-dipole estimation) of evoked potentials (EPs) measured with multiple electrodes to quantitatively estimate neuronal activities in the brain. Then, we analyze the bidirectional information flows between equivalent dipoles representing neuronal activities in the specified locations of the brain as schematically shown in Fig. 1. Our new method requires high time-resolution data such as EP, and will give a 3D information flow estimate almost automatically, with small number of pre-set parameters adequately adjusted.

II. METHODOLOGY

A flow chart of the analysis method is shown in Fig. 2. First, two equivalent dipoles are estimated from given EPs [2][3][4], and then an information flow is analyzed between the two dipoles from correlation analysis of time variations of dipole moments [5]. In the dipole estimation, we developed a method to align the time-series of the 1st and the 2nd dipoles because in the two-dipole estimation at each time, locations of the two dipoles can be exchanged, if we do not pay attention for keeping the consistency in each series.

A. Dipole Estimation

The 2-dipole estimation in the 3-layered concentric spherical model [2][3] is carried out for all samples in a time range of EPs by setting the 3-layered structure, and all electrode positions on the 3rd layer of the sphere. The simplex method [4] is used to solve the inverse problem. The estimation is carried out six times for every sample from

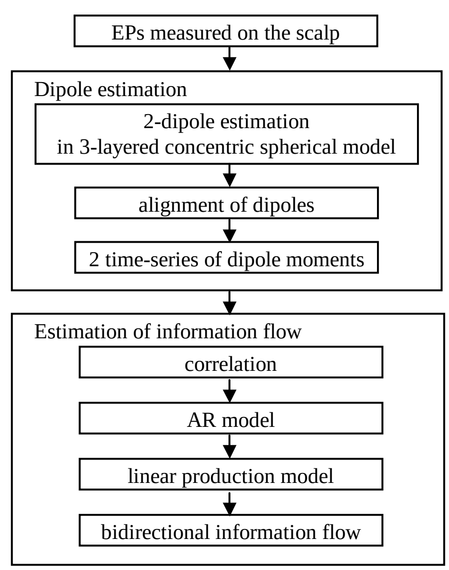

Fig. 2. Flow chart to obtain the information flow from EPs

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25 Oct 2001	N/A	-

Title and Subtitle Estimation of Bidrectional Information Flow in The Human Brain From Evoked Potentials by Use of Dipole Tracing Method	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Interdisciplinary Graduate School of Science and Engineering Tokyo Institute of Technology Yokohama, Japan	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes Papers from 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom.	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 4	

each initial simplex position randomly chosen, and a result giving the best estimation accuracy is chosen from the six estimated ones. The dipolarity (%) shows the estimation accuracy as,

$$Dipolarity = \sqrt{1 - \frac{\left\| \vec{p}_{meas} - \vec{p}_{cal} \right\|^2}{\left\| \vec{p}_{meas} \right\|^2}} \times 100 \qquad (1)$$

where, P_{meas} and P_{cal} are the measured and the calculated scalp potentials based on the two-dipole model respectively, both expressed in n-dimensional column vectors composed of EPs on the n electrodes. The dipolarity ranges from 0 to 100 % and shows that the estimated dipoles are sufficiently accurate as the value approaches to 100.

As the result of the estimation, two time-series of the 1st and the 2nd dipoles are obtained. However, they become a mixed state from a time-series point of view, because the order of the estimated 1st and 2nd dipoles at each sample is indefinite. Therefore, we developed a method to align them. An explanatory drawing is shown in Fig. 3. D1, D2 show the 1st and the 2nd dipole locations respectively at a sample time. M1 and M2 show the mean locations of the 1st and the 2nd dipoles respectively, averaged for several samples preceding to D1 and D2, with sufficiently high dipolarity. Thus, we define a criterion for the evaluation of "Proximity" as,

$$P = \frac{r1}{r1 + r2} \qquad (2)$$

where, r1 and r2 show the distance between D1 and M1, D1 and M2 respectively (or between D2 and M1, D2 and M2). Here we suppose, P1 and P2 as the criterion for D1, D2 respectively. We perform the dipole alignment according to the following rule:

If P1 > P2; Exchange D1 and D2.
If P1 ≤ P2; No change. (3)

The alignment is carried out by the above exchange rule from the beginning to the end of the time-series with respect to the 1st and the 2nd dipoles for all samples.

After the alignment, magnitude of the 1st and the 2nd dipole moments is calculated through all samples of the time-series. It is possible to regard the time-series of the magnitude of the 1st and the 2nd dipole moments derived through our method as being the time-series of the brain activities approximated by the two equivalent dipoles.

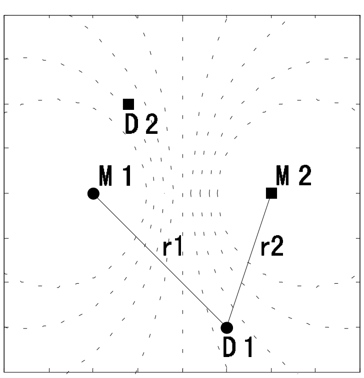

Fig. 3. Explanatory drawing for the alignment of dipoles

B. Information Flow

Beforehand, each mean value of the derived time-series of the magnitude of the 1st and the 2nd dipole moments is set to zero respectively. Since then, by use of the time-series analysis method based on the directed transinformation [5], the analysis is carried out between these two time-series of the moments with each mean is zero.

First, the correlation function of the two time-series is calculated. Next, the signal representation by two-dimensional AR model (autoregressive model) is carried out after the selection of the AR model order by FPE (final prediction error criterion). Then, the linear production model is constructed from the derived AR coefficients. When the two time-series of the moments, X and Y, are shown as,

$$X = X_{k-N} \ldots X_{k-1} X_k X_{k+1} \ldots X_{k+M} = X^N X_k X^M$$
$$Y = Y_{k-N} \ldots Y_{k-1} Y_k Y_{k+1} \ldots Y_{k+M} = Y^N Y_k Y^M \quad , \qquad (4)$$

the directed transinformation from X_k to Y_{k+m} is given by

$$I(X_k \to Y_{k+m} \mid X^N Y^N Y_k) = \frac{1}{2} \log_2 \left\{ 1 + \frac{a^2_{YX\,k+m,k}}{\sum_{i=0}^{m-1} \left(a^2_{YX\,k+m,k+m-i} + a^2_{YY\,k+m,k+m-i} \right)} \right\} \qquad (5)$$

and the directed transinformation from Y_k to X_{k+m} is given by

$$I(Y_k \to X_{k+m} \mid X^N Y^N X_k) = \frac{1}{2} \log_2 \left\{ 1 + \frac{a^2_{XY\,k+m,k}}{\sum_{i=0}^{m-1} \left(a^2_{XY\,k+m,k+m-i} + a^2_{XX\,k+m,k+m-i} \right)} \right\} \qquad (6)$$

where a_{XX}, a_{XY}, a_{YX} and a_{YY} are the linear filter coefficients (the impulse response coefficients) in the linear production

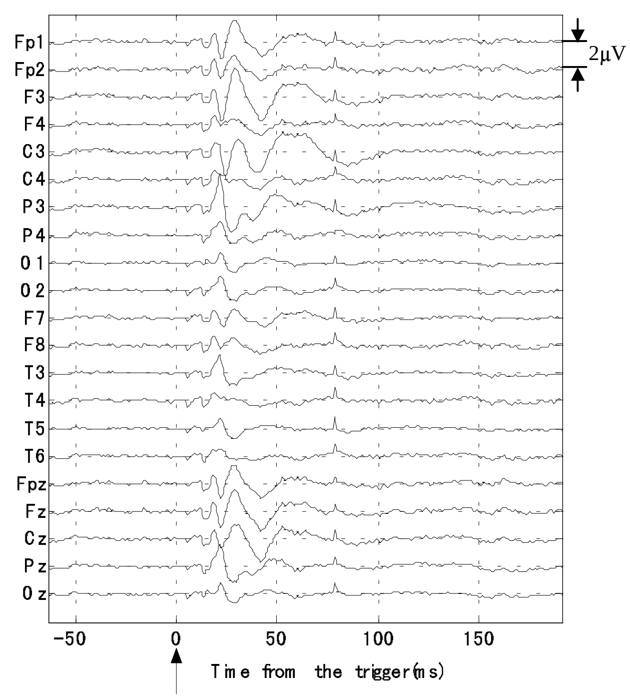

Fig. 4. Result of SEPs for input of the analysis
(21 electrodes of the international 10-20 standard,
2kHz sampling rate, averaged for 500 times, positive up display)

TABLE I
PARAMETERS USED FOR THE ANALYSIS

Name			Value (unit)		
analysis time range of SEPs			5– 105 (ms)		
radii for 1st, 2nd and 3rd layer			65, 71, 75 (mm)		
conductivities for 1st, 2nd and 3rd layer			0.33, 0.0042, 0.33 (S/m)		
number of sample to average for alignment			3		
threshold of dipolarity for alignment			95 (%)		
AR model order			30		
21 electrode positions					
name	θ (deg)	φ (deg)	name	θ (deg)	φ (deg)
Fp1	64.75	18.03	F7	64.44	54.02
Fp2	64.75	-18.03	F8	64.44	-54.02
F3	39.52	45.00	T3	65.51	90.00
F4	39.52	-45.00	T4	65.51	-90.00
C3	36.16	90.00	T5	64.44	125.98
C4	36.16	-90.00	T6	64.44	-125.98
P3	39.52	135.00	Fpz	65.51	0.00
P4	39.52	-135.00	Fz	36.16	0.00
O1	64.75	161.97	Cz	0.00	0.00
O2	64.75	-161.97	Pz	36.16	180.00
			Oz	65.51	180.00

model. In (5) and (6), I(*→*) shows the mutual information, and the direction is regulated automatically because k point of time is earlier time-related than k+m point of time. The directed transinformation is corresponding to the expanded one of Marko's information [6] in order to obtain the mutual information between k and k+m point of time for finite time-series. Therefore, we obtain the bidirectional information flows by which both directed transinformation are calculated for all delays of m. Since this method is steady-state analysis expressed by AR model (stationary model), the information flow is same for any point of time k.

III. RESULTS

We analyzed somatosensory evoked potentials (SEPs) evoked by the electrical stimulation on the median nerve of the right hand, as shown in Fig. 4. The parameters used for the analysis are shown in TABLE I. θ is the angle from the positive side of Z axis to XY plane, and φ is the one from

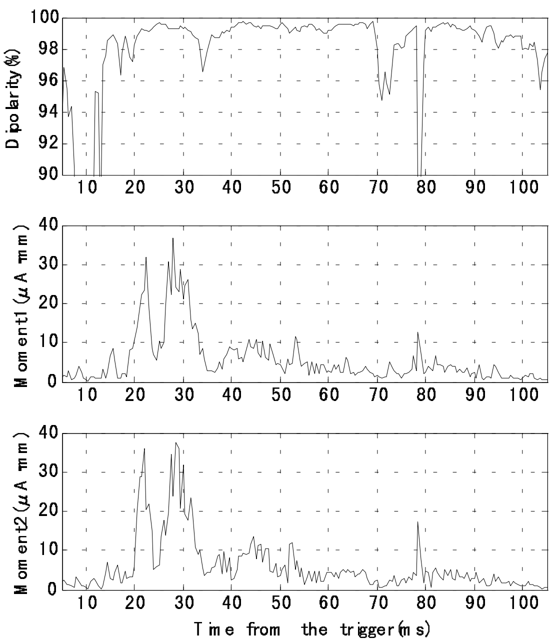

Fig. 5. Result of the dipole moments before the alignment

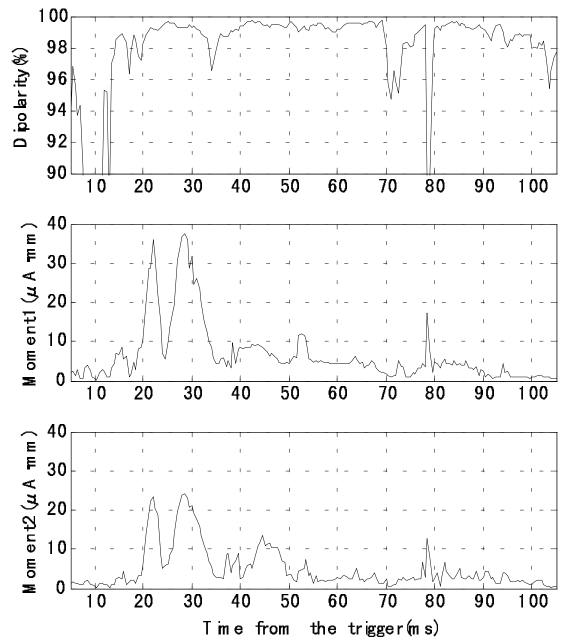

Fig. 7. Result of the dipole moments after the alignment

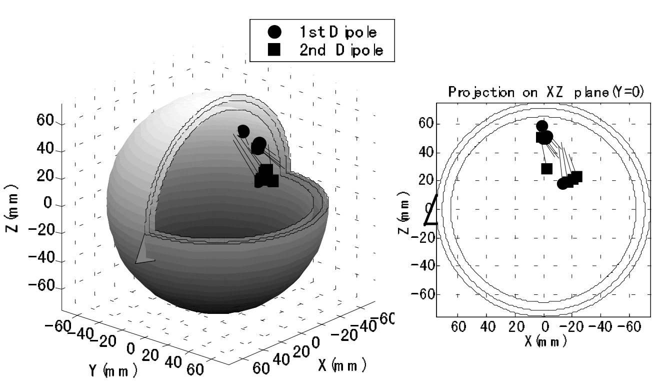

Fig. 6. Result of the dipole locations before the alignment, shown from 20.5 to 22.5 ms, length of the moment is 1 mm per 1 μA · mm.

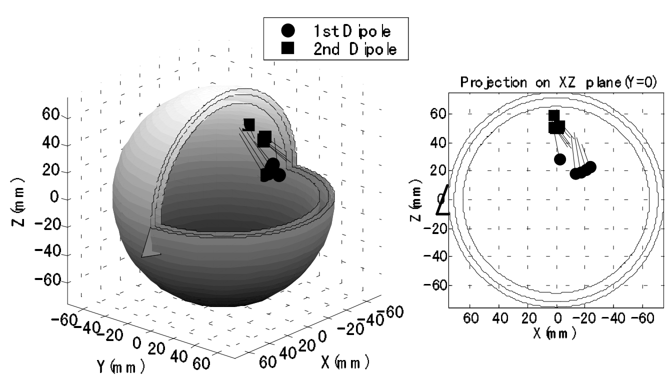

Fig. 8. Result of the dipole locations after the alignment, shown from 20.5 to 22.5 ms, length of the moment is 1 mm per 1 μA · mm.

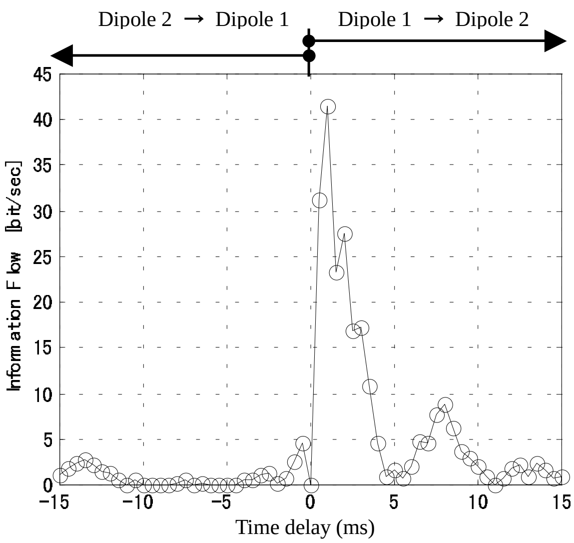

Fig. 9. Result of the information flow

the positive side of X axis to the positive side of Y axis. The AR model order is selected as 30 where FPE takes a minimal.

The results of the dipole estimation before the alignment are shown in Figs. 5 and 6, and the ones after the alignment are shown in Figs. 7 and 8 respectively. The result of the bidirectional information flows is shown in Fig. 9. The positive side of the abscissa is the directed transinformation from the time-series of the 1st dipoles to that of the 2nd dipoles, derived by (5). The negative side of the abscissa is the directed transinformation from the time-series of the 2nd dipoles to that of the 1st dipoles, derived by (6). The horizontal scale is a time expression of the delay of m in (5) and (6).

IV. Discussion

In comparing Fig. 5 and Fig. 7, the irregularity of Moment1 (time-series of the 1st dipole moments) and Moment2 (time-series of the 2nd dipole moments) in Fig. 5 was eliminated in Fig. 7. And with Figs. 6 and 8, the mixed state of the dipole locations in Fig. 6 was solved in Fig. 8. These results proved the effectiveness of the alignment procedure we proposed.

The result of the information flow in Fig. 9 shows that the information mainly flows from the time-series of the 1st dipoles to that of the 2nd dipoles. According to the neurophysiological knowledge of SEPs by the electrical stimulation on the median nerve of the hand, it is considered that the transmission route of the neuronal activities goes through the thalamus at about 15 ms latency, and reaches the somatic sensory area at about 20 ms latency. From Fig. 8, it is possible to consider that the time-series of the 1st dipoles reflects the neuronal activities of the thalamus, and the time-series of the 2nd dipoles reflects that of the somatic sensory area. Therefore, The result that the information mainly flows from the 1st dipoles to the 2nd ones, agrees with the knowledge that the neuronal activities move from the thalamus to the somatic sensory area. In addition, the result indicates that there might be a slight information flow from the 2nd dipoles to the 1st ones around the latency of 11 to 15 ms (from –11 to –15 ms in Fig. 9). This indicates that there might be a feedback from the somatic sensory area to the thalamus.

V. Conclusion

We proposed an analysis method to reveal the three-dimensional bidirectional information flows within the brain, and applied it for actual experimental data of SEPs. In the method, the causal relation between the two time-series of the 1st and the 2nd dipoles is revealed, and its intensity is obtained as a time-series of information quantity (bit/sec). We confirmed that there are the bidirectional information flows between them, and mainly the time-series of the 1st dipoles is a cause and that of the 2nd dipoles is a result, in case of the SEPs. And it agreed with the neurophysiological knowledge. Thus, our method can be applied for the elucidation of the information processing mechanism and the disease detection in the brain, when the original data has a high time-resolution.

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