Identification of scalp blood flow in NIRS data based on Granger causality

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***Abstract*— NIRS (Near infra-red spectroscopy) is a spectroscopic device to assess the dynamic changes in the hemoglobin concentration evoked by brain activity non-invasively. It has been said that NIRS data reflects brain activities of cortical surface. Recently, it is reported that NIRS data reflects not only cortex blood flow but also the scalp blood flow. To discuss about this matter, we applied Granger causality for the NIRS data to detect the relationship between scalp and cortex blood flows in motor execution. Five healthy subjects took part in the experiment. We measured scalp blood flow and conventional NIRS data simultaneously using a high density probe holder. As a result, in four of five subjects, we detected the Granger causality strongly from the scalp blood flow data to the conventional NIRS data. This method can be useful to quantify the scalp blood flow component included in the conventional NIRS data.**

I. Introduction

NIRS (Near infra-red spectroscopy) is a spectroscopic method to assess dynamic changes in the hemoglobin concentration evoked by brain activity. There are many advantages in measuring brain activity with NIRS. For example, NIRS data can be obtained easily compared to the other brain functional measurement devices. Measurement with NIRS needs neither shield rooms nor strong magnetic fields. Therefore, measurement can be done for in/out patients. Since the obtained data is robust to the motion artifacts, from the view point of neural circuit reconstruction, NIRS is widely used in neuro-rehabilitation after stroke [1]. Although there are not established analysis methods, many studies related to NIRS have been reported due to the convenience.

It has been said that NIRS data reflects the brain activities of the cortical surface. In recent study it is reported that NIRS data reflects not only cortex blood flow but also the scalp blood flow [2]. To discuss about the relationship between the scalp blood flow and the cortex flow, there are several studies reported from the various points of view, for example, independent component analysis (ICA) and diffusion optical tomography (DOT) [3], the discrimination of autonomic nervous system using multimodal measurements [4]. However, causality from the scalp blood flow to the conventional NIRS data has not been discussed yet. In this report, we measured simultaneously both NIRS conventional data and the scalp blood flow data with newly marketed high density probe holder. Moreover, we adopted Granger causality to the obtained data for detecting the relationship between the scalp blood flow and the cortex blood flow.

Granger causality is one of the useful methods to detect the relationships between time series [5]. Recently, many studies have been reported about the effective connectivity between the region of interest (ROI) based on Granger causality [6][7]. In this paper, we apply Granger causality for the NIRS data to detect the relationship between the scalp blood flow and conventional NIRS data in motor execution task.

II. NIRS (Near infra-red spectroscopy)

A. Principles of NIRS

NIRS refers near infra-red spectroscopy. With different wavelengths of near infra-red light, absorption of the light can be measured. Near infra-red light starts from light sources , going through hair, scalp, skull, dura mater, arachnoid mater, pia mater, cortex, reflecting and scattering again and again , goes back to the surface and reaches to the detector. The intensity ratio decreases less than micro order. The passage of near infra-red light is shown in Fig. 1.

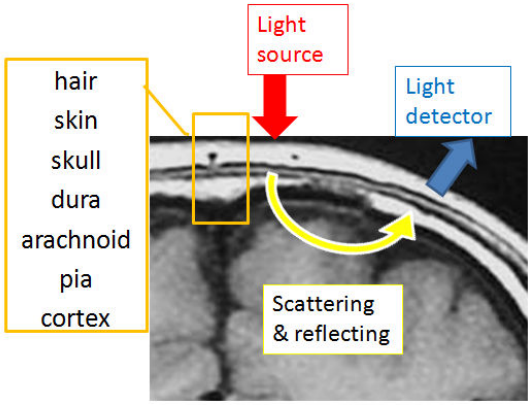

Fig. 1. Light paths from a light source to the detector. Near infra-red light is brought from the light sources, reaching the surface of the cortex. Passing through the cortex, reflecting and scattering again and again, finally, light goes out of the scalp.

Due to the scattering and reflecting in the brain, distance of the light path is unclear. The baseline of hemoglobin concentration is also unknown, so we can calculate the

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relative changes of hemoglobin concentration using modified Lambert Beer's Law.

Traditionally it has been said that NIRS data reflects hemoglobin concentration changes in the cortex surface only. On the other hand, recently, it is reported that NIRS data also contains hemoglobin concentration changes in the scalp blood flow. To discuss about the relationships between scalp blood flow and cortex flow, there are several studies reported from the various points of view, for example, ICA and DOT, discrimination of autonomic nervous system using multimodal measurements. However, causality between two regions has not been reported yet.

NIRS has many advantages. Measurement is non-invasive, small, portable device. Neither shielding nor magnetic fields is necessary, so subjects can be infants and in/outpatients. In recent studies, multi-modality is reported, for example, NIRS with fMRI, EEG or MEG. Many kinds of analysis have been done with NIRS data. However, standard analysis is not well established. In this study, we used a high density probe holder to measure the scalp blood flow and conventional NIRS data simultaneously. Then we applied Granger causality for the obtained NIRS data to detect the influence affected by the scalp blood flow.

B. Scalp blood flow and the conventional NIRS data

In this section, we show the relationship between the scalp blood flow and the conventional NIRS data. Near infra-red light is transmissive in the human tissue. Relationship between the light paths and the depths of them are shown in Fig.2.

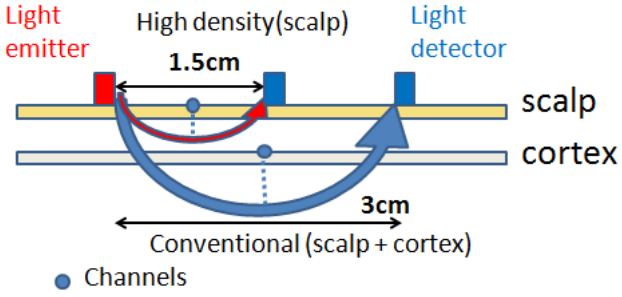

Fig. 2. Comparison of light paths (conventional and scalp).

C. High Density Probe Holders

To solve the problem which lies in the influence from the scalp blood flow to the conventional NIRS data, we used newly developed high density holder. To solve this problem, we used the newly marketed high density probe holder (Shimadzu Corporation, Kyoto, Japan).

As for conventional probe holder, the distance between adjacent probes is 3cm. On the other hand, as for high density holder, the minimum distance between adjacent probes is 1.5cm. Therefore, with a conventional probe holder, we can measure both the cortex blood flow and the scalp blood flows. In the following text, such data is called conventional NIRS data. On the contrary, with a high density probe holder, we can measure the scalp blood flow data. Conventional probe holder and newly marketed high density probe holder are shown in Figs 3 and 4, respectively.

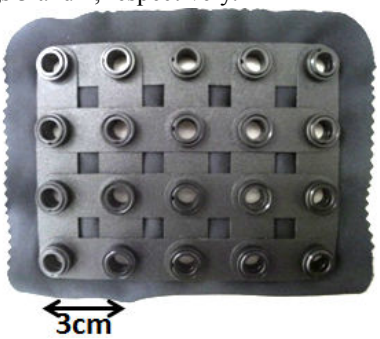

Fig. 3. Conventional probe holder.

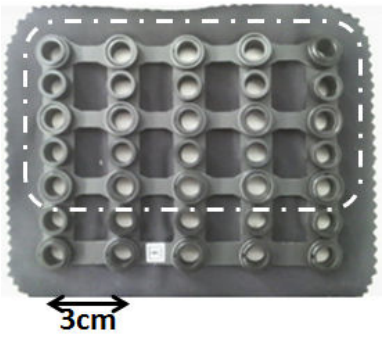

Fig. 4. High density probe holder. In this study, we used part of the high density probe (5 rows by 5 columns, surrounded by the dotted line)

D. Placement of the channels

It is clear that, in NIRS experiments, measuring points in scalp layer and cortex layer are different from the projection of the probe positions. We define the measuring points as the channels. We used 5 rows by 5 columns of high density probe holder on the subject's left hemisphere. The center of high density probe holder corresponded to C3 in international 10-20 method. Placement of all the channels is shown in Figs 5 and 6.

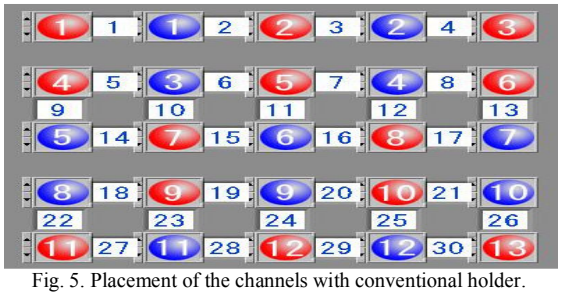

Fig. 5. Placement of the channels with conventional holder.

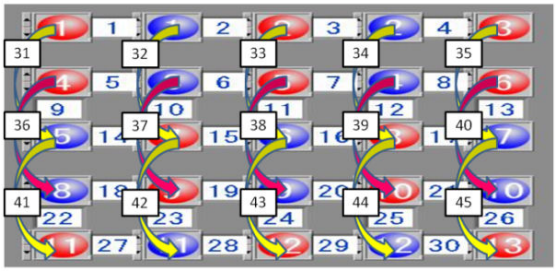

Fig. 6. Placement of the channels with high density holder.

III. GRANGER CAUSALITY

For analyzing the NIRS time series, we adapted Granger causality. Granger causality is one of the useful methods to investigate the causality between time series using F-test [5]. Granger causality is also used to detect the effective connectivity between brain regions in various measurements, such as fMRI, MEG and EEG.

Let X,Y be two time series. Two types of fitting with autoregressive model (order p) can be defined by the formula (1), (2).

$$X(t) = \sum_{i=1}^{p} \alpha_i X(t-i) + \mu + \varepsilon_x(t) \cdots (1)$$

where

$$\varepsilon_x(t) \sim N(0, {\sigma_x}^2)$$

$$X(t) = \sum_{i=1}^{p} \{\alpha_i X(t-i) + \beta_i Y(t-i)\} + \mu + \varepsilon_{yx}(t) \cdots (2)$$

where

$$\varepsilon_{yx}(t) \sim N(0, {\sigma_{yx}}^2)$$

In this study, model order P is defined as the value that gives the minimum value of BIC (Bayesian information criterion).

If the value F is defined as follows.

$$F = \frac{(RSS1 - RSS2)/P}{RSS2/(T-2P-1)}$$

where

$$RSS1 = \sum_{t=1}^{T} \varepsilon_x^2, \quad RSS2 = \sum_{t=1}^{T} \varepsilon_{yx}^2$$

and T is iteration of time series, Granger causality is evaluated by F-test. If F is significant large, Granger causality exists from Y to X.

Based on Granger causality, the probability of Granger causality (PGC) is defined, which reflects the influence of the one time series to the other [6]. Under the Null hypothesis, PGC = 0 means that there is a strong oriented influence between two time series, while PGC = 1 means that there is no significant oriented influence between them. In this paper, we applied the probability of Granger causality to detect the causality from scalp blood flow to the conventional NIRS data.

IV. SUBJECTS AND METHODS

Five healthy volunteers participated in the experiment. All of them have no neurological disorder and are judged as right-handed with EHI (Edinburgh Handedness Inventory). Measurements were done in the quiet and lighted room appropriate for examinations. We adapted the block design, which consists of pre-task (20 seconds), task (20 seconds) and post-task (20 seconds). Each session contains five repetitions of the blocks. The experimental design is shown in Fig. 7.

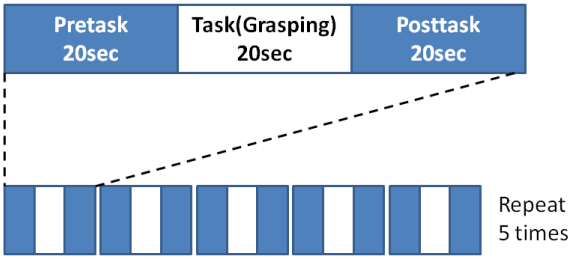

Fig. 7. Scheme of experimental design. Block design consists of pretask (20sec), task (20sec) and posttask (20sec).

The visual stimuli were presented on the PC monitor at the distance of 70cm ahead of the subjects. With pacing visual stimuli (1Hz), subjects are asked to execute grasping during task periods. On the other hand, during the pre-task and post-task periods, subjects are asked to look at the stimulus. Measurements were done with Foire-3000 (Shimadzu Corporation, Kyoto, Japan), functional near infra-red spectroscopy system, with wavelengths at 780nm, 805nm and 830nm. We used the software Presentation 16.3 (Neurobehavioral systems) for making and presenting the visual stimuli, and MATLAB2013 (MathWorks) for analyzing the NIRS data. Each experiment was performed according to the tenets of the Declaration of Helsinki and under the approval of the Ethics Committee of the Tokyo Denki University. Written informed consent was obtained from all the subjects after the explanation of the nature and possible consequences of the study.

V. RESULTS

Concentration changes in oxygenated hemoglobin (oxyHb) were analyzed. Channels around C3 (corresponding to the channel #38 in Fig. 6) were selected to detect the causality from the scalp blood to C3. We calculated the Granger causality probability from the scalp blood flow to conventional NIRS data. The channels with which we used the data for calculation are shown in Fig.8.

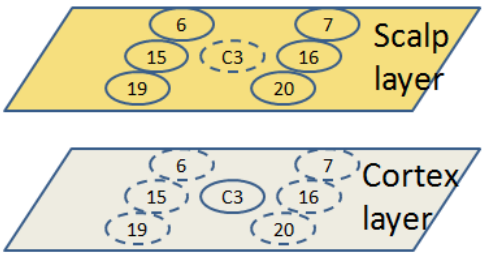

Fig. 8. Location of the channels selected for the calculation of Granger causality probability.

As shown in the Fig. 8, the projections of channels in the scalp layer are not coincided with those in cortex layer. Therefore we calculate Granger causality probability from (1)each scalp channels around C3(#6, #7, #15, #16, #19 and #20), (2)mean of channels adjacent to C3(#15 and #16), (3)average among the six channels around C3, to the conventional NIRS data in C3.The results of calculation are

shown in TABLE 1.

TABLE 1
Granger causality probability (GCP) from scalp layer (# of channel) to cortex layer (C3)

# of channel	sub1	sub2	sub3	sub4	sub5
6	0.019	0.486	0.001	0.014	0.544
7	0.234	0.740	0.060	0.834	0.797
15	*	0.002	0.099	0.949	0.332
16	*	0.170	0.016	0.018	0.148
19	*	0.968	0.159	0.110	0.326
20	*	0.635	0.907	0.032	0.319
A	*	0.001	0.031	0.497	0.096
B	*	0.087	0.001	0.444	0.242

A indicates the mean of #15 and #16
B indicates the average among six channels
* indicates that GCP is less than 0.001.

The results of Granger causality probability in TABLE 1 are shown as the line graphs in Figure 9.

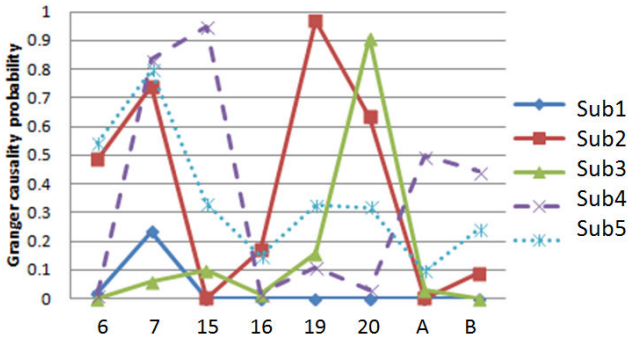

Fig. 9. Granger causality probability shown in TABLE 1. A, B in horizontal axis refer the mean of two channels(#15,#16), six channels(#6, #7, #15, #16, #19, #20), respectively

Fig. 9 shows that, in four of five subjects, we detected the Granger causality strongly from the scalp blood flow data to the conventional NIRS data. The values of Granger causality probability varied widely, however, at channel 16, Granger causality probability showed smaller values in all subjects. Therefore, we detected Granger causality strongly from #16 to C3. We also detected strong causality from A(the mean of #15 and #16) in four of five subjects. On the contrary, there are less causality from B(the average among six channels) to the C3.

VI. DISCUSSION

Since we placed the center of high density probe holder (5 rows by 5 columns) to C3, GCPs are expected to be sufficiently small from channels #15 and #16. Our result shows that, in all subjects, GCPs from #16 to C3 are sufficiently small and that, in four of five subjects, GCPs from #15 to C3 are sufficiently small. Inasmuch as GCP from #15 to C3 in subject 4 is more than 0.9, there seems to be little causality. However, this may result from individual difference in such as positioning of the probe, pericephalic size or vessel anomaly because GCPs from #16, #19 and #20 to C3 are sufficiently small. More subjects are needed to compensate the variability of individual difference, including the difference of activation of the cortex, the positioning of C3 and the anomaly of blood vessels.

VII. CONCLUSION

To detect the relationship between the scalp blood flow and the conventional NIRS data, we used a newly marketed high density probe holder, and adapted the Granger causality for the NIRS data. As a result, in four of five subjects, we found the strong Granger causality from the scalp blood flow to the conventional NIRS data. The methods in this paper can be helpful to validate the contribution of the scalp blood flow to the conventional NIRS data.

REFERENCES

[1] Miyai et al, Longitudinal optical imaging study for locomotor recovery after stroke, Stroke 34:2866-2870,2003

[2] Kohno et al, Removal of the skin blood flow artifact in functional near-infra-red spectroscopic imaging data through independent component analysis, Journal of Biomedical optics 12,062111,2007

[3] T.Shimokawa et al, Hierarchical Bayesian estimation improves depth accuracy and spatial resolution of diffuse optical tomography, Optic Express 20(18): 20427-20446

[4] Yamada et al, Use of the wavelength differential method to eliminate baseline drift in the assessment of cerevral function using NIRS, Transactions of Japanese Society for Medical and Biological Engineering (in Japanese with English Abstract)

[5] C.W.J.Granger, “Investigating Causal Relations by Econometric Models and Cross-Spectral Methods,”Econometrica 37, 414-& (1969).

[6] Im, CHANG-HWAN et al., Estimation of directional coupling between cortical areas using Near-Infrared Spectroscopy (NIRS), Optics Express, Vol. 18 Issue 6, pp.5730-5739 (2010).

[7] Chen et al, Evaluation of the effective connectivity of supplementary motor areas during motor imagery using Granger causality mapping ,NeuroImage Vol.47, pp.1844-1853,2009