Causality analysis of ANS activities by multidimensional directed coherence on body temperatures variations

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I. INTRODUCTION

Several studies have indicated the significance of a tympanum temperature (TT) as a physiological index. The TT has been regarded as a substitute for the temperature of the brain, especially hypothalamus, which has been known as the control center of the autonomic nervous systems (ANS). Since a very little has reported that a forehead temperature (FHT) has had a strong correlation with the TT, which has been indicated that the FHT could be possible index as a substitute for the TT. Meanwhile, a nasal skin temperature (NST) has been known as a physiological index strongly related for ANS activity. A declining NST has been the sign of the activation of the sympathetic nervous system (SNS), which has been a part of ANS. And the FHT has been considered as a 'reference' for the core body temperature, which has been stable and has had less relation with ANS activity in NST studies. Thus, there has been a inconsistency in interpretation of the FHT in physiological aspect, and this has been considered as one of the unsolved problem on noise in biological systems. The relationship between the temperatures have to be clarified, however, those has never been analyzed from the view of the biological system. The objective of present study is to analyze the causal relationship between body temperatures as an ANS activity index. The multidimensional directed coherence (MDC) has been know as an quantitative index of causal relationship between periodical signals[1,2]. In this paper, MDC has been calculated between body temperatures time series measured in psychophysiological experiment.

II. EXPERIMENTAL

Experiment was conducted for six 22- to 23-years-old healthy subjects (three males and three females). Subject sat on chair in front of desk while the experiment. Experiment was constructed with six 90-seconds experimental periods for a task and six 60-seconds experimental periods for a rest. Six experimental periods for a task were T1, T2, T3, T4, T5 and T6, and R1, R2, R3, R4, R5 and R6 those for a rest assigned in chlonological order. Each experimental period for a rest was aligned after the period for a task, respectively. Thus, each task came in every 150 seconds. In the period for a task, the subject was instructed to perform a mental arithmetic task (MAT) as fast as possible in order evoking an acute stress. The MAT was an addition of two double-digit numbers without carrying, which presented every 5 seconds by PC installed in front of the subject. The subject had to type the answer to the PC with numerical keyboard on the desk. In the period for a rest, the subject was instructed to sit with closing the eyes. Physiological data time series were measured through the experimental periods at a sampling frequency of 0.5 Hz, which were right FHT ($\mathrm{FHT_R}$), left FHT ($\mathrm{FHT_L}$), NST, right TT ($\mathrm{TT_R}$), left TT ($\mathrm{TT_L}$) and mean blood pressure (MBP). The data were subjected to MDC analysis after resampling process at a sampling frequency of 4 Hz with a linear interpolation.

III. MULTIDIMENSIONAL DIRECTED COHERENCE ANALYSIS

The causal interrelations between an arbitrary number of time series signal are calculated as follows. A model of linear system for generating multi-channel sequences is described as multidimensional autoregressive model (MAR model) such that

$$\mathbf{x}_n = \sum_{m=1}^{M} \alpha_m \mathbf{x}_{n-m} + \boldsymbol{\beta}\mathbf{w}_n \tag{1}$$

The order M is optimized by Akaike's Information Criterion (AIC). a_{ij}^m is the autoregressive coefficients, the input sequence w_i is the signal source that is white noise satisfying (2) of the output time sequence $x_i(n)$, and β is a weighting factor.

$$\mu = \frac{1}{N}\sum_{n=1}^{N} w_i(n), \sigma = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(w_i(n)-\mu)^2} \tag{2}$$

where μ is the average of $w_i(n)$ and σ is the standard deviation. Fourier transform of (1) is given as

$$\mathbf{X}(f) = \mathbf{A}(f)\boldsymbol{\beta}\mathbf{W} \tag{3}$$

Here respectively $\mathbf{X}_i(f)$ and $\mathbf{W}_i(f)$ are Fourier transformation of $x_i(n)$ and $w_i(n)$, I is identity matrix, and Δt is a sampling interval.

The power spectrum $P_{x_i}(f)$ and the cross spectrum $P_{x_i x_j}(f)$ are defined using $\mathbf{X}(f)$ as follows:

$$\begin{bmatrix} P_{x_1}(f) & \cdots & P_{x_1 x_k}(f) \\ & \ddots & \\ P_{x_k x_1}(f) & \cdots & P_{x_k}(f) \end{bmatrix} = E[\mathbf{X}(f)\cdot\mathbf{X}^t(f)]$$
$$= \mathbf{A}(f)\cdot\boldsymbol{\beta}\cdot\boldsymbol{\beta}^*\cdot\overline{\mathbf{A}}(f)^* \tag{4}$$

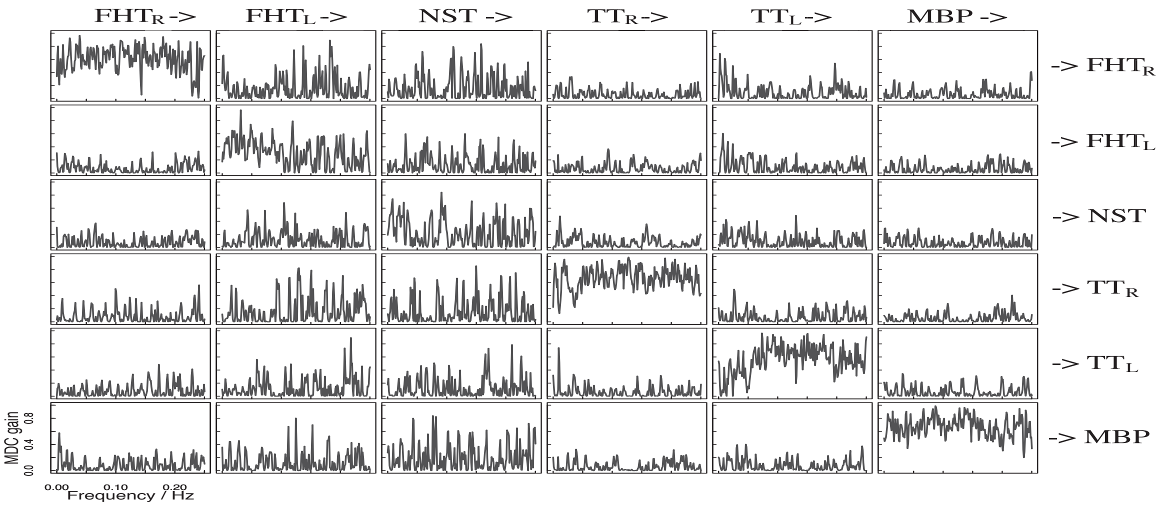

FIG. 1. The examples of the MDC gain of signals. (Subject F)

where E is an ensamble mean, $*$ is transposed matrix, and an overline is the complex conjugate. The power spectrum $P_{w_i}(f)$ of the signal source $w_i(n)$ satisfies $P_{w_i}(f) = 1$. MDC of an output sequence x_i from a signal source W_{x_i} is defined as

$$\gamma_{x_i x_j}(f) = \frac{P_{x_i W_{x_j}}(f)}{\sqrt{P_{x_i}(f) \cdot P_{W_{x_j}}(f)}} = \frac{b_{x_i x_j} A_{x_i x_j}(f)}{\sqrt{P_{x_j}(f)}} \qquad (j = 1, 2, \cdots, k) \tag{5}$$

These directed coherence also signify a composition ratio between P_{x_i} and $P_{W_{x_i}}$. A generation source of $x_i(n)$ is $w_i(n)$, therefore, the power spectrum $P_{x_i}(f)$ must be generated from any of $P_{Wx_i}(f)$. Considering the composition ratio, the gain transformed from $W_{x_i}(f)$ of P_{x_j} is represented

$$G_{x_i \to x_j}(f) = \frac{\left|b_{x_i x_j} A_{x_i x_j}(f) P_{W_{x_i}}(f)\right|^2}{P_{x_j}(f)} = \frac{\left|b_{x_i x_j} A_{x_i x_j}(f)\right|^2}{P_{x_j}(f)} \tag{6}$$

A correlation between the directed coherence and the power composition ratio is given as follows by (5) and (6)

$$G_{x_i x_j}(f) = \frac{\left|b_{x_i x_j} A_{x_i x_j}(f)\right|^2}{P_{x_i}(f)} = \left|\gamma_{x_i x_j}(f)\right|^2 \tag{7}$$

IV. RESULTS AND DISCUSSION

Fig.1 shows total combinations of the MDC gains of the physiological signals. Horizontal axis represents frequency of the signal, and MDC gain is on vertical axis. Hereinafter, MDC gain of A on B is referred to as $G_{\mathrm{A} \to \mathrm{B}}$. The MDC gains aligned on the diagonal lines from upper-left to lower-right in the figure indicate a 'signal source' referred to as G_{A}, which represents MDC gain of A on itself. Higher gain in the signal source indicate that the signal flows more to itself, lower gain indicates less, as well. Frequency bands around 0.01 Hz and 0.20 Hz are focused. It is assumed that 150-seconds task-rest period make the signals have 0.01 Hz frequent responses, and 5-seconds repeated MAT questionnaire periodically reflects on the signals as 0.20 Hz fluctuations as well. $G_{\mathrm{TT_L}}$ shows low gain in a frequency band of 0.01 Hz in the figure, which indicates $\mathrm{TT_L}$ is the source and has an impact on other signals in the band. Corresponding to the low gain in $G_{\mathrm{TT_L}}$, $G_{\mathrm{TT_L} \to \mathrm{FHT_R}}$ and $G_{\mathrm{TT_L} \to \mathrm{FHT_L}}$ have high gains in the band around 0.01Hz, while $G_{\mathrm{FHT_L} \to \mathrm{FHT_R}}$ has high. Those clarifies that thermal signal flows from left tympanum to forehead. Regarding $G_{\mathrm{FHT_R}}$ as a source, $G_{\mathrm{FHT_R}}$ has slight low gain in the band around 0.01 Hz, and $G_{\mathrm{FHT_R} \to \mathrm{MBP}}$ has high gain in the band, while G_{MBP} has high gain in the band. $G_{\mathrm{MBP} \to \mathrm{NST}}$ shows a small impact MBP on NST, while $\mathrm{TT_L}$ recurrently has the impact from MBP. It is assumed that the thermal signal generated in left tympanum flows to blood pressure and nasal region by way of forehead region from the view point of biological system.

[1] Bjorn Schelter et al., Journal of Neuroscience Methods, **152**(1), 210-219 (2005)

[2] Luiz A. Baccala et al., Biological Cybernetics, **84**(6), 463-474 (2001)