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Maps of cerebral hemoglobin concentration changes obtained by near-infrared spectroscopy. Characterization of phase shifts among locations.

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Abstract: We obtained maps of cerebral hemoglobin concentration changes by near-infrared spectroscopy during functional stimulation and physiological activity at rest. The correlation and phase shift between locations were characterized by phase portraits and the phase synchronization index.

OCIS codes: (170.5270) Photon density waves; (170.6510) Spectroscopy, tissue diagnostics

1. Introduction

Using the multi-channel near-infrared spectroscopy it is possible to obtain functional maps of human tissue, which depict changes in the optical parameters associated with brain or other physiological activity. The values of the measurement can be converted into values for O_2Hb and HHb concentration. The question is whether a relationship between the values of the different locations of the map can be found. Is it possible to see a pattern?

We applied two methods to demonstrate such patterns by using phase potraits and more quantitatively by the phase synchronization index.

2. Materials and methods

Instrument set-up

We used a frequency-domain near-infrared spectrometer (NIRS) (model-no.96208 Omnia ISS Champaign IL USA), which has two photomultiplier tubes as detectors and eight pairs of laser diodes, each pair having two wavelength (758nm, 830nm), as light sources. The light of the laser diodes was guided to the tissue by optical glass fibers. Five pairs of source fibers were arranged around each detector fiber, equidistant on a circle of radius 3cm. The detectors were arranged such, that two pairs of source fibers were equidistant to both detectors. The laser diodes were turned on in a sequence in order to be able to identify each location and wavelength at the detector side. Each sequence of eight pairs of laser diodes took 1/6 seconds, i.e. maps were sampled at a rate of 6 Hz.

Measurement protocol

The above described source-detector arrangement was placed on the subject's head above the motor cortex of the left hemisphere.

A baseline period of five minutes was collected. After that the subject was tapping his fingers of the right hand to the beat of a metronome. The subject had to tap for 25 seconds and was resting for 30 seconds. Thus one period of measurement took 55 seconds and was repeated 9 times.

This protocol was approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign.

Data analysis

The raw optical data was converted for oxy- and deoxy-hemoglobin concentrations by the DPF-method [1]. A $DPF_{758nm} = 6.32$ and $DPF_{830nm} = 5.64$ were assumed. The data was low-pass filtered to analyze the response to the finger tapping and high-pass filtered to analyze the pulsations due to the arterial blood-pressure changes. The data was detrended and each trace was normalized to the standard deviation of the fluctuations. The phase portraits were

generated by taking the signal of one location as a reference for all the other locations. The phase portrait consists of a scatterplot of the reference location (x-axis) versus the actual signal at the respective location (y-axis).

Recently a new time-domain method of data analysis was developed, which allows detection and quantification of phase synchronization between two signals [2]. The method is based on the generalization of the concept of phase. For an arbitrary real function of time the phase may be defined as the phase of the complex analytical continuation of the given function into the complex plane. The relative phase of two signals can be estimated as the difference of such generalized phases. Analyzing the statistical distribution of the phase difference, which is restricted to the interval from π to $-\pi$, one can estimate its sharpness and the average phase difference. The sharpness of the statistical distribution is quantified by the entropy-based phase synchronization index (PSI), which equals to zero for the absolutely flat distribution and to one for the delta function distribution. The perfect phase synchronized state corresponds to the PSI equal to one. Thus we used maps of PSI to describe the functional signals acquired on the human head in terms of phase synchronization with stimulation.

3. Subjects

Two healthy male volunteers (subject 1: 60 years and subject 2: 34 years) were included after written informed consent was obtained.

4. Results

The phase portraits proved to be very helpful in interpreting maps not only during finger tapping (Fig. 1.) but also in physiological state at rest, such as the arterial pulsation (Fig. 2.).

The PSI-method showed a similar distribution of correlation patterns as the phase portraits.

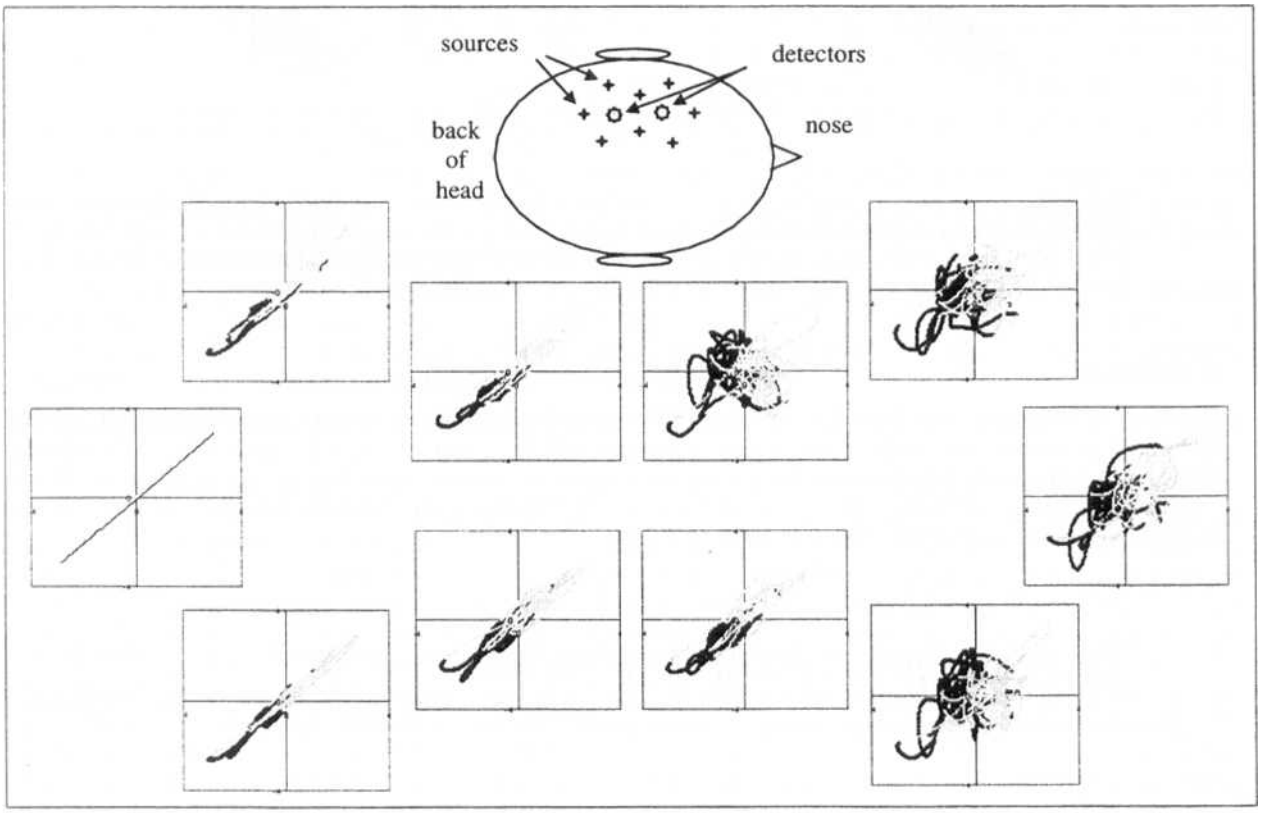

Fig. 1. Plot of map of phase portraits depicting the changes in O_2Hb during a finger tapping exercise of subject 1. The arrangement of the phase portrait figures represents the location of the 10 source-detector combinations (the two sources in the middle are used twice: once for each detector) on the head as shown in the diagram on top. The O_2Hb of the left-most figure was used as a reference for all x-axis values and therefore the figure represents a straight line. It can be seen clearly, that the phase portraits close to the reference are nearly straight lines and therefore in good correlation and almost in phase with the reference.

The broadening of the figures to an ellipse stands for a phase shift. Towards the right side four figures become round and more chaotic, which means that the correlation to the reference is lost. The gray part of the figure represents the O_2Hb level during finger tapping, and the black during rest. It can be seen in the figures, that there is a distinct polarity of the finger tapping and the rest periods especially for the left side with the good correlation. In the more chaotic figures it seems that the black part is more ellipsoid than in the gray part, which means, that the correlation to the reference is mainly lost for the effect of the stimulation.

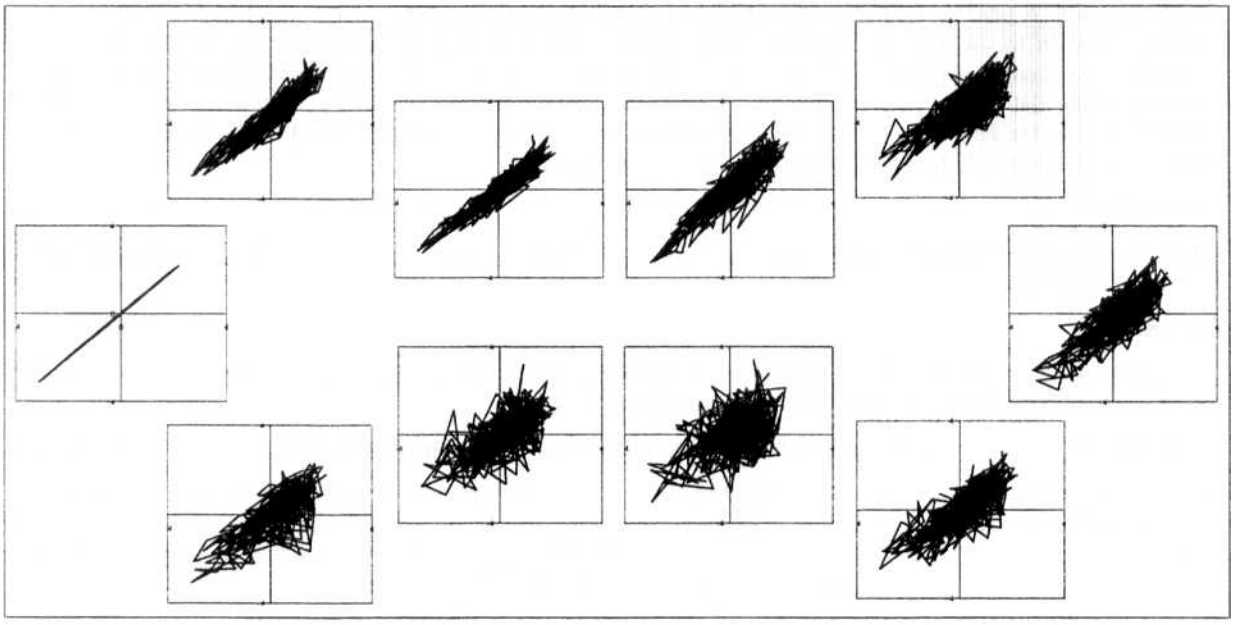

Fig. 2. Plot of the arterial pulsation at the same location as in Fig. 1, but on subject 2. Again the leftmost location was used as a reference for all the other locations. Clearly, there is a general pattern visible, as the ellipse becomes broader towards the right (nose) as well as for the lower locations. This broadening can be interpreted as an increase of the phase shift, i.e. delay, between the reference and the respective location.

5. Discussion

The focus of this paper is on the analysis of maps of the brain obtained by near-infrared spectroscopy. In this case it is difficult to interpret the common fast Fourier transforms (FFT), especially when the frequency of the observed signal, such as the heart rate, is not constant, or when the signal, such as the finger tapping, has a low frequency and contains only a couple of periods. Both phase portraits and the PSI do not have these disadvantages and are therefore appropriate tools to analyze the patterns of functional maps.

6. References

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