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An analysis of cerebral blood flow from middle cerebral arteries during cognitive tasks via functional transcranial Doppler recordings

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ABSTRACT

Functional transcranial Doppler (fTCD) is a useful medical imaging technique to monitor cerebral blood flow velocity (CBFV) in major cerebral arteries. In this paper, CBFV changes in the right and left middle cerebral arteries (MCA) caused by cognitive tasks, such as word generation tasks and mental rotation tasks, were examined using fTCD. CBFV recordings were collected from 20 healthy subjects (10 females, 10 males). We obtained both the raw CBFV signal and the envelope CBFV signal, which is the maximal velocity to gain more information about the changes and hemisphere lateralization in cognitive tasks compared to the resting state. Time, frequency, time–frequency, and information-theoretic features were calculated and compared. Sex effects were also taken into consideration. The results of our analysis demonstrated that the raw CBFV signal contained more descriptive information than the envelope signals. Furthermore, both types of cognitive tasks produced higher values in most signal features. Geometric tasks were more distinguished from the rest-state than verbal tasks and the lateralization was exhibited in right MCA during geometric tasks. Our results show that the raw CBFV signals provided valuable information when studying the effects of cognitive tasks and lateralization in the MCA.

1. Introduction

The transcranial Doppler sonography (TCD) was first introduced by Aaslid et al. (1982), who utilized the TCD to measure the blood flow velocity in large basal arteries. TCD is useful for investigating mental activities because of the closely coupled relationship between mental activities and cerebral metabolism (Paulson et al., 2009). The diameter of the large basal arteries, including middle cerebral, anterior cerebral, and posterior cerebral arteries, is assumed to be fixed, so changes in brain perfusion results in velocity changes (Huber and Handa, 1967). Due to the frequency dependence on ultrasonic wave attenuation, researchers use a relatively low ultrasonic frequency (2MHz) and the thinnest part of the skull (transtemporal window) for insonation (the exposure to ultrasound) (White and Venkatesh, 2006). Compared with other neuroimaging techniques, such as positron emission tomography and functional magnetic resonance imaging, TCD is known for its high temporal resolution, and its ability to continuously measure blood flow velocity in a variety of conditions (Duschek and Schandry, 2003).

Because MCAs supply much of the brain area involved in cognitive processing tasks, almost all of the studies investigating cognitive functions insonate MCAs (Ingvar and Risberg, 1965; Risberg and Ingvar, 1973; Lassen et al., 1978; Risberg, 1986). Bilateral insonation is often used to measure cerebral blood flow velocity (CBFV) (e.g., Deppe et al., 2000; Knecht et al., 1998a,b; Schmidt et al., 1999) but the reliability of detection of CBFV using bilateral insonation varies across different cognitive tasks (Knecht et al., 1998a). There is evidence showing that the CBFV during mental activities was more rapid than that during baseline periods (e.g. Droste et al., 1989b; Kelley et al., 1992). The effects of tasks on lateralization have been studied by previous researchers; for example, Markus and Boland (1992) showed a left-sided increase for right-handed participants in a word association task. Similar results were observed in other studies (e.g., Tiecks et al., 1998; Hartje et al., 1994). The results were more equivocal for tasks involving spatial processing (e.g., mentally rotating shapes). A greater increase in CBFV was observed in the right MCA (Klingelhöfer et al., 1994, 1997), but the result of R-MCA dominance within spatial processing was not verified (e.g., Hartje et al., 1994; Gur and Reivich, 1980). TCD studies also have shown that females have higher velocities than males at the same ages (e.g., Russo et al., 1986; Vriens et al., 1989).

Previous work (e.g., Duschek and Schandry, 2003; Matteis et al., 2009) has focused only on the envelope signals (i.e. peak

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velocities) and thus possibly lack the information only embodied in raw signals (Deppe et al., 2004). A recent study showed that the raw CBFV signals contain significantly different characteristics in the resting state (Sejdić et al., 2013). Therefore, we focused on raw and enveloped CBFV signals in the current study in order to understand the MCA blood flow change caused by language and spatial tasks, as well as the lateralization associated with these cognitive tasks. Furthermore, we used information-theoretic approaches and time–frequency techniques that have not been previously incorporated into the study of cognitive tasks effects on CBFV signals. We analyzed both the envelope and the raw CBFV signals with focus on information found in the higher frequency content of raw CBFV signals and the effects of cognitive tasks on the features extracted from the raw CBFV signals. Considering additional information sources and a comprehensive list of features can enable us to understand finer clinical differences.

2. Methodology

2.1. Subjects

Twenty healthy participants (10 females, 10 males; 21.5 ± 1.86 years old; 67.9 ± 14.2 kg; 174 ± 9.69 cm) participated in the experiment. Before each data collection session, participants signed consent forms that were approved by the University of Pittsburgh Institutional Review Board. Then, participants filled out basic information forms, screening questionnaires, and Edinburgh handedness tests (Oldfield, 1971). No participants were found to have a history of concussions, heart murmurs, strokes, migraines, or other neurological conditions or brain-related injuries. Among these twenty participants, 16 subjects were right-handed with a mean score of 64% (38–93%), 3 subjects were left-handed with a mean score of 80% (76–88%) and one was determined as ambidextrous.

2.2. Procedure

Participants were initially seated in front of a computer monitor. The investigator informed them about the importance and the goal of this study. In this experiment, we insonated MCAs by using a SONORA TCD system (CareFusion, San Diego, CA, USA). One 2 MHz transducer was stabilized to the left-side transtemporal window, and another 2 MHz transducer was stabilized to the right-side transtemporal window. The transtemporal window is located approximately above the zygomatic arch (Alexandrov et al., 2007). The TCD's depth was initialized to 50 mm to approximate the mid-point of the MCA segment depth (Monsein et al., 1995). A plastic headband was used to adjust and fix the positions of the two probes. The insonation angle was then optimized by manually rotating the incident angle and following the sound and velocity of insonation. Once the TCD transducers were aptly positioned and fixed, the nasal cannula was placed under the nose to detect the end-tidal CO_2 ($ETCO_2$) levels which might affect CBFV in the MCA (Markwalder et al., 1984). The $ETCO_2$ levels were measured using a Capnocheck Sleep Capnograph/Oximeter (Smiths Medical, Dublin, OH, USA). Fig. 1 depicts the experimental setup.

The experiment consisted of three parts. In the first part, the participants rested for 20 min which provided us with baseline information (Sejdić et al., 2013). The next two parts consisted of two 15-min periods involving cognitive tasks, with a 5-min break between each 15-min period. Each 15-min period consisted of five mental rotation tasks, five word generation tasks in random order and 45-s resting periods between each task. These tasks were presented as visuospatial stimuli on a computer screen because it is expected that a visual mode of presentation does not influence the expected significant CBFV changes of the linguistic tasks (Stroobant and Vingerhoets, 2000).

2.2.1. Mental rotation task

Pairs of images, randomly selected from a database of shapes constructed from 3D cubes (Peters and Battista, 2008) (see Fig. 2), were displayed for 9 s each during the 45-s activation periods of tasks. In each pair of images, the patterns were either identical or mirror symmetrical. Participants were asked to determine whether the image pairs were identical or symmetric by mentally rotating the patterns.

2.2.2. Word generation task

An arbitrarily chosen capital letter was displayed on the screen during the activation periods. During this period, we instructed the participants to use nonverbal modes of responding, i.e. to think of words starting with that letter. A nonverbal mode was used to avoid any artifacts from speech or changes in intrathoracic pressure (Diehl et al., 1990; Silvestrini et al., 1994).

2.2.3. Resting state

During the resting state, subjects were instructed to remain awake, relax and maintain a thought-free mental state.

3. Feature extraction

Here, we summarize a comprehensive set of features to be used in the analysis of recorded signals. The features were chosen in order to gain a detailed understanding of cerebral blood flow characteristics in time, frequency, and time–frequency domains. This is an essentially critical step if cerebral blood flow signals are to be

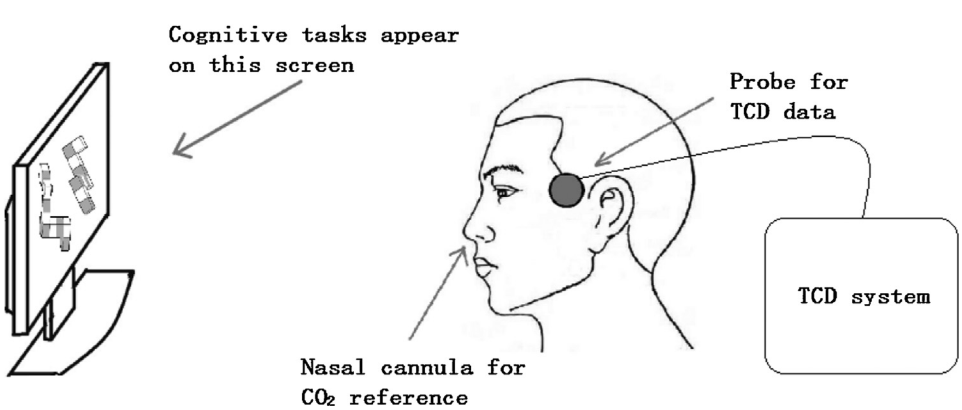

Fig. 1. Setup for the TCD experiment: a cognitive task is displayed on a screen, while TCD probes are placed on transtemporal windows and a nasal cannula is placed over the nose.