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The contribution of functional near-infrared spectroscopy (fNIRS) to the presurgical assessment of language function in children

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ABSTRACT

Before performing neurosurgery, an exhaustive presurgical assessment is required, usually including an investigation of language cerebral lateralization. Among the available procedures, the intracarotid amobarbital test (IAT) was formerly the most widely used. However, this procedure has many limitations: it is invasive and potentially traumatic, especially for children. To overcome these limitations, neuroimaging techniques such as functional magnetic resonance imaging (fMRI) have been used. Again, these methods are difficult to use with children, who must remain motionless during data acquisition. Functional near-infrared spectroscopy (fNIRS) is a noninvasive functional imaging technique that is easily applied to pediatric and cognitively limited patients. It has been used recently in epileptic children for presurgical assessment of expressive and receptive language brain lateralization. The aim of this review is to present the contribution of fNIRS to the presurgical assessment of language function in children with neurological diseases.

1. Introduction

In most individuals, functional integrity of the left cerebral hemisphere is required to produce and understand language. When the left hemisphere has been injured or exposed to chronic deleterious episodes, language function reorganization is likely to occur, especially when these events occur at a young age (Rasmussen & Milner, 1977). Language functions can then be taken over by the right hemisphere or both hemispheres. Accordingly, individuals with brain abnormalities show greater language dominance variety than healthy individuals (e.g., Berl et al., 2005). Children with neurological diseases such as refractory epilepsy, tumors, or cortical vascular malformations sometimes require neurosurgery. These procedures can result in neuropsychological deficits that are often specific to the resected area. For example, left frontal or temporal lobe resection may induce aphasia or word finding difficulties. The latter can then lead to learning difficulties as well as academic, social, and occupational problems (Dodrill & Clemmons, 1984; Helmstaedter, Gleissner, Zentner, & Elger, 1998; Mayeux, Brandt, Rosen, & Benson, 1980). Prevention of such deficits is therefore essential. To minimize the risk of postsurgical language deficits in individuals who undergo left frontal or temporal surgery, various presurgical techniques have been developed to assess language cerebral lateralization.

Until recently, the intracarotid amobarbital test (IAT) or Wada test (Rutten, Ramsey, Van Rijen, Alpherts, & Van Veelen, 2002; Wada & Rasmussen, 1960) was the most widely used procedure to explore language brain lateralization prior to neurosurgery. Sodium amytal is injected into one of the carotid arteries through a transfemoral catheter (Loring, Lee, & Meader, 1994; Smith, 2001) to produce a temporary anesthesia in the ipsilateral cerebral hemisphere, during which it is possible to assess language and memory functions of the contralateral hemisphere. Language task results then provide a relatively reliable indication of language cerebral lateralization (Branch, Milner, & Rasmussen, 1964; DeVos, Wyllie, Geckler, Kotagal, & Comair, 1995; Rouleau, Robidoux, Labrecque, & Denault, 1997; Trenerry & Loring, 1995). However, this procedure is invasive, and its validity cannot be verified by test–retest studies (Boas, 1999). Nor does the IAT provide precise spatial information on language localization (Gaillard, Bookheimer, Hertz-Pannier, & Blaxton, 1997), and it is constrained by the timing variability of the sodium amytal action (Bouwer, Jones-Gotman, & Gotman, 1993). Moreover, the patient's altered state of consciousness and behavioral and emotional reactions can obscure the results (Terennery and Loring). Finally, the technique is difficult to apply to young children (Williams & Rausch, 1992), a significant limitation considering that an early surgical intervention is often crucial (Engel, 1987), and in patients with mental retardation, or language and/or behavior prob-

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lems (Pelletier, Sauerwein, Lepore, St-Amour, & Lassonde, 2007), which are often found with neurological diseases (Jambaqué, Lassonde, & Dulac, 2001). Given these considerable limitations and the recent accessibility to safer alternative techniques, many centers worldwide have significantly reduced or halted their use of IAT in the last 15 years (Baxendale, Thompson, & Duncan, 2008).

As alternatives to IAT, minimally invasive techniques such as positron emission tomography (PET) (Hunter et al., 1999; Kaplan et al., 1999) and single photon emission computed tomography (SPECT) (Borbély et al., 2003) and recent noninvasive imaging techniques such as functional magnetic resonance imaging (fMRI) (Gaillard et al., 2004; Thiel et al., 1998) and magnetoencephalography (MEG) (Papanicolaou et al., 2004) have been used to investigate language dominance. However, as with IAT, these techniques are sometimes difficult to use in young children and patients with serious cognitive or behavioral problems. It is difficult if not impossible for young children to lie motionless in the scanner for a relatively long period of time. In addition, there is no way of verifying whether children are actually performing the mental task as instructed, as they must remain silent during data acquisition to avoid movement artefacts.

2. Functional near-infrared spectroscopy

Functional near-infrared spectroscopy (fNIRS) is a noninvasive functional imaging technique that is easily applied to pediatric and cognitively limited patients (e.g., Wilcox, Bortfeld, Woods, Wruck, & Boas, 2005). It allows measuring hemodynamic changes, which are used as an indicator of neural activity (Villringer, Plank, Hock, Schleinkofer, & Dirnagl, 1993). The different light absorption spectra of oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) within the near-infrared spectrum allow measuring concentration changes in these substances in living tissues, providing information on cerebral activation (Boas et al., 2001; Gratton & Fabiani, 2007). A typical cerebral activation is characterized by a small, short decrease in HbO and an increase in HbR, known as the initial dip, and regional oxygenation, probably due to underlying neuronal activity. This is followed by a large increase in HbO concentration accompanied by a decrease in HbR concentration in a given cerebral region, reflecting local arterial blood flow (Fig. 1a).

During fNIRS recording, near-infrared light of at least two wavelengths between 680 and 1000 nm is directed through optic fibers to the patient's head. The wavelengths and the number of wavelengths used vary depending on the fNIRS equipment. Increasing the number of wavelengths allows more accurate estimation of HbO and HbR concentration changes. HbO is preferentially absorbed by wavelengths closer to 680 nm and HbR by wavelengths closer to 1000 nm. Light travels through the scalp and the skull to a depth of a few centimeters in the cerebral tissue following a banana shaped trajectory (Fig. 2). Light detectors are placed on the scalp a few centimeters away from the source. The closer the detector to the source, the better the lateral spatial resolution, but the greater the distance between detector and source, the deeper the light can penetrate. The distance between source and detector is therefore set to obtain a good compromise between lateral and depth spatial resolution, typically at between 2 and 5 cm. The amount of detected light reflects the absorption of the two wavelengths in targeted cerebral areas. This allows using a modified Beer–Lambertz Law to quantify the relative HbO and HbR concentration changes (for a review see Minagawa-Kawai, Mori, Hebden, & Dupoux, 2008). For a brief description of a complete fNIRS recording session (from material preparation to data analyses), see Shalinsky, Kovelman, Berends, and Petitto (2009).

User-friendly data analysis software has only recently become available for fNIRS users. Formerly, each research team developed their own data analysis tools. This constituted a substantial obstacle for clinical fNIRS use. In the last decade, fNIRS equipment and data analysis tools have developed rapidly. Software that enable the analysis (e.g., normalization, filtering, averaging) and visualization of fNIRS data are now available, and some are publicly accessible on websites (e.g., HomER, Photon Migration Imaging Laboratory: http://www.nmr.mgh.harvard.edu/DOT/; and NIRS-SPM, Bio Imaging Signal Processing (BISP) laboratory: http://bisp.kaist.ac.kr/NIRS-SPM.html). Moreover, they are relatively easy to use. Recent technical advances have greatly contributed to the expanded use of fNIRS for clinical applications.

3. Advantages and limitations of fNIRS

Like other imaging techniques, fNIRS has many advantages over IAT. For instance, fNIRS is a noninvasive technique that can be administered to a patient repeatedly. As part of a presurgical language assessment, fNIRS not only investigates language brain lateralization, it also provides specific information on language localization. Importantly, unlike other imaging methods (Gratton & Fabiani, 2001a; Gratton & Fabiani, 2001b; Strangman, Boas, & Sutton, 2002; Villringer & Chance, 1997), fNIRS imposes no major restrictions on movement during recording, which makes it suitable for studies in mentally challenged individuals as well as young children, including infants (Wilcox, Bortfeld, Woods, Wruck, & Boas, 2008; Wilcox et al., 2005). In contrast to fMRI and MEG, both of which usually require covert articulation, the expressive language tasks used with fNIRS can involve overt articulation without the physical constraints that impede articulatory gestures. During data acquisition, the child is seated comfortably in a chair or on the parent's lap, allowing direct contact with the experimenter. Second, the equipment is portable, allowing bedside assessment (Hintz et al., 2001; Liebert et al., 2005), and is much less costly than fMRI or PET. Third, fNIRS offers better temporal resolution than fMRI, due to a much greater sampling rate (at least 10 Hz for fNIRS compared to 0.5 Hz for fMRI), so it can measure phenomena such as early-phase deoxygenation in the activated cortex, called the "initial dip." Another advantage of fNIRS is that it appears to be sensitive to bilateral speech patterns (Gallagher et al., 2007), which are less efficiently detected with fMRI. In fact, fMRI has correctly lateralized language functions in both hemispheres in most cases, but appears to be less efficient in detecting bi-hemispheric speech organization (Benke et al., 2006). Finally, fNIRS allows measuring independent HbO and HbR concentration changes, unlike changes in the fMRI BOLD signal, which are based mainly on local magnetic field variations induced by HbR changes. HbR changes are thought to be proportional to changes in oxygen consumption, which result from changes in cerebral blood flow (Raichle, 1998). Although several hemodynamic phenomena remain unclear, independent measures of HbO and HbR concentration changes can provide a better understanding of the physiology underlying language processing and cerebral reorganization patterns, which can be useful in presurgical assessment.

The main disadvantage of fNIRS is the shallow photon penetration (between 3 and 5 cm). This impedes reliable data recording of subcortical structure activation (e.g., in the thalamus), and may make it difficult to use in individuals with a dense skull and/or thick, dark hair. However, the limited penetration depth does not have a major impact on studies investigating cortical areas such as language areas.

4. fNIRS as an alternative technique for language investigation

fNIRS has been shown to allow functional brain lateralization and localization of responses to auditory speech stimuli in healthy