Medical Research and Innovations (MRI)

Review Article

ISSN: 2514-3700

A mini review of functional magnetic resonance imaging

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Abstract

fMRI, which captures images reflected the hemodynamic changes during the neural activity, shows great potential to uncover the neurophysiological relationship with the brain function and the neuropathological mechanism involved in brain lesions. In this article, an introduction of functional magnetic resonance imaging (fMRI) is presented on its imaging principle, instrumentation and methods, data analysis and current application.

Introduction

The major development in the study of brain function and lesions were made possible by the development of functional brain mapping techniques. The mechanism of functional brain mapping techniques is based on either electromagnetic activity or hemodynamic changes. Both electromagnetic and hemodynamic physiology signals are related to neural activity and neuro-vascular coupling.

Functional magnetic resonance imaging (fMRI) is one of the commonly used brain mapping techniques, which generates images that reflects which brain areas are activated (and how) during external stimuli or performance of different tasks. fMRI shows superiority over other brain mapping techniques: it is noninvasive and has excellent spatial resolution on the order of several millimeters, which makes it greatly developed over the past two decades to become the dominant technique in the study of brain science and lesion diagnosis [1].

The aim of this paper is to review the imaging principle, instrumentation, experiment design and data analysis of fMRI as well as its fundamental and clinical application.

The physics and physiological principle of fMRI

The physics of fMRI involves the interaction between the biological tissue and electromagnetic fields [1], while its physiological principle relies on the BOLD (blood oxygenation level dependent) effect.

Human brain needs a constant oxygen supply in order to maintain its functional and structural integrity. A special mechanism, which has to provide oxygen during both resting state and neural activity, is necessary to ensure the correct oxygenation level. The strict coupling existing between 'activation', local oxygen consumption and increased regional blood flow constitutes the basis of the so called BOLD effect [2,3].

When the participants undergo a MR scanning, the nuclei or protons in the brain region of interest aligns with the direction of magnetic field of the MR scanner. A radio-frequency (RF) sequence is then applied, causing the nuclei to alter their magnetization alignment. When the RF field is removed, the nuclei go back to their original state. By applying another gradient magnetic field that vary linearly over space, different nuclei to be spatially localized and specific slices to be imaged can be obtained [4]. A paramagnetic substance in the blood, known as deoxygenated hemoglobin (deoxy-Hb), can cause the nuclei to lose magnetization faster via the T_2^* decay [5,6], which is called transverse relaxation time. Thus, a pulse sequences sensitive to T_2^* show more MR signal where blood is highly oxygenated and less where it is not [7]. Usually the inhaled oxygen is more than the oxygen consumed in burning glucose, which causes a net decrease in deoxy-Hb in the brain region's blood vessels, as a result, its decrease leads to a less interference with the magnetization and an improved MR signal [8-10].

Data acquisition and data analysis

Generally, a fMRI image is obtained through four steps.

Experiment design

The determining factor whether a fMRI detecting is successful or not is how to design the experiment paradigms. According to the current literature reported, there are two kinds of stimuli paradigms. One is called blocked design, which implements the stimuli periodically, like, ABABAB..., A is the resting-state, B is the stimulus state, and AB is one cycle [11]. It measures average neural activity across a block of closely spaced, successive stimuli of the same type [12]. The other one is named event-related design, which records the neural activity on the condition of a single event, for example, at the sight of an unfamiliar picture or memorizing some words, and plays an important role in the research of cognitive neuroscience.

Data acquisition

Most fMRI studies use standard MR scanners to detect changes in brain blood flow during the performance of cognitive tasks or paradigms designed to elicit neural activation.

Generally, the intensity of MR signal is proportional to the strength of magnetic field. However, the ultrahigh magnetic field is harmful to

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Received: February 05, 2018; **Accepted:** February 22, 2018; **Published:** February 25, 2018

human being and always to be applied in animal research. Clinically, the most used magnetic field is 1.5T.

Besides the strength of magnetic field, different fMRI images can be obtained by selecting the scanning sequences. The commonly used are spin echo (SE) sequence and echo planar imaging (EPI) sequence, which have an ideal time resolution and less motion artifacts.

Additionally, the setting of scanning parameters, such as the repetition time (TE), the echo time (RE), the flip angle, the slice oblique, the slice thickness, the slice gap and the matrix size should also be designed according to different experimental needs.

Preprocessing

The goal of fMRI data analysis is to explore correlations between brain activation and a task the participant performs during scanning. Before the data analysis, the raw images should be preprocessed.

The aim of preprocessing is to improve the signal-to-noise ratio (SNR), which mainly includes the following procedures:timing correction, motion correction, normalization, temporal filtering and spatial smoothing [13].

The MR scanner acquires different slices within a single brain volume at different times, and hence the slices represent brain activity at different time points. a timing correction is applied to bring all slices to the same time point reference.

Since the fMRI signal is so weak that a slight head movement or rotation may produce artifacts in it. Motion correction is applied to produce the smoothest time course for all voxels.

In order to make a comparison of fMRI scanning results among different participants, a normolization is implemented to adjust all the results to align to a standard template. The commonly used brain atlas are the Talairach one and the Montreal Neurological Institute (MNI) one.

Temporal filtering is the removal of frequencies of no interest from the raw signal, while spatial smoothing is aimed to average the intensities of nearby voxels to produce a smooth spatial map of intensity change across the brain or region of interest.

All the procedures in preprocessing on the raw data, a four-dimensional (4D) magnitude time-series, can be implemented through SPM software, thus, a spatially aligned and normalized dataset for each participant is obtained for the following data analysis.

Data analysis: Brain area localization or brain functional connectivity

Until now, there is no standard data analysis method or result evaluation criterion. The classical statistic analysis, such as correlation analysis, t-test and non-parametric statistics has been originally used as a tool for fMRI data analysis, which is also named as the hypothesis-driven approach. Recently, some methods of pattern recognition, like, clustering technique, principal component analysis (PCA) and independent component analysis (ICA) have been applied increasingly, which is regarded as the data-driven approach [14-16]. Data processing and analysis techniques play an important role in the research of brain science based on fMRI, which is also a research hotspot in the field of fMRI.

Application

In the last 20 years, extensive applications of fMRI in the research of brain science have been reported, which could be summarized into two topics [17,18]: one area of study is brain functional connectivity, which aims to localize brain areas linked to basic functions, such as vision [19], auditory [20,21], language [22,23], moving [24], cognition[25-27], etc. The other one is the neurophysiological mechanism of severe brain diseases. Clinically, fMRI is carried out to anatomically examine the brain and provides insights into the physiopathogenesis of brain injury or diseases, such as epilepsy [28,29], stroke [30], Alzheimer's disease [31], Parkinson's disease [32], schizophrenia [33], conduct disorder [34,35], etc. It is regarded as an predictive supplementary method for diagnosis, treatment and prognosis.

Conclusion

As a promising brain mapping technique, some meaningful progress and valuable research results have been obtained in the study of brain science based on fMRI. However, fMRI has a limited time resolution, is highly sensitive to motion artifact and can only provide an indirect measurement of neural activity. An increasing number of studies have focused on the multimodal brain mapping techniques for the research in neuroscience or physiopathology [36-39]. The other well-known functional imaging techniques include electroencephalography (EEG), magnetoencephalography (MEG), positron emission tomography (PET) and functional near infrared spectroscopy (fNIRS). It is believed that these techniques in combination could effectively improve the precision and accuracy and will grow more and more important in future study.

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