Resting-State Blood Oxygen Level–Dependent Functional Magnetic Resonance Imaging for Presurgical Planning

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KEYWORDS

• Functional MR imaging • Resting-state functional MR imaging • rsfMR imaging • Resting-state networks • RSNs • Multilayered perceptron • MLP • Eloquent cortex

KEY POINTS

- Resting-state functional MR imaging (rsfMR imaging) is a promising technique for presurgical planning with the objective of decreasing morbidity while maximizing complete resection of pathologic tissue. However, the methodology is still in early stages of development.
- Further research is necessary to make these tools more accurate and available in the operating room.
- Additional research is needed to explore the differences between rsfMR imaging, task fMR imaging, and electrocortical stimulation mapping, and to better understand the consequences of disrupted resting-state networks outside the motor and language systems.
- Related engineering development should incorporate the presurgical MR imaging results into intraoperative neuronavigation systems, including the rsfMR imaging results in conjunction with white matter fiber bundle anatomy derived from diffusion tensor imaging.

INTRODUCTION

Background

Functional MR imaging (fMR imaging) detects changes in the blood oxygen level–dependent (BOLD) signal that reflect the neurovascular response to neural activity. Traditionally, fMR imaging has been used to localize function within the brain by presenting a stimulus or imposing a task (eg, presenting a flashing checkerboard pattern or generating verbs from nouns) to elicit neuronal responses.[1,2] This type of experiment has been very effective at localizing functionality within the brain, as evidenced by the many thousands of publications using task-based fMR imaging.

The human brain consumes a disproportionate amount of energy relative to its weight. The brain constitutes approximately 2% of the body's weight but consumes 20% of the body's energy use.[3] Performance of a task only minimally increases

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energy expenditure.[4] Thus, task-based experiments ignore most of the brain's activity, which is largely devoted to signaling.[4–8]

Biswal and colleagues[9] were the first to demonstrate that spontaneous fluctuations in the BOLD signal in the resting state correlated within the somatomotor system. Before this observation, spontaneous fluctuations in the BOLD signal in the resting state were regarded as noise and generally averaged out over many trials or task blocks.[10,11] More recent studies have shown that these spontaneous fluctuations reflect the brain's functional organization.[12] Correlated intrinsic activity is currently referred to as functional connectivity MR imaging or resting-state fMR imaging (rsfMR imaging). The development of these methods has opened up many exciting possibilities for future neurocognitive research as well as clinical applications. This article focuses on the application of rsfMR imaging to presurgical planning. Table 1 summarizes key features of both task-based fMR imaging and rsfMR imaging. Snyder and Raichle[12] give a historical review of the resting state.

Resting-State Networks

Correlated intrinsic activity defines functional connectivity. Functionally connected regions are known as resting-state networks (RSNs); equivalently, intrinsic connectivity networks.[13] The rsfMR imaging scans generally are acquired while the subject is in a state of quiet wakefulness.[14] The importance of RSNs is that their topography closely corresponds to the topography of responses elicited by a wide variety of sensory, motor, and cognitive tasks.[15] Intrinsic activity persists, albeit in somewhat modified form, during sleep[16,17] or even under sedation.[18] The persistence of the spontaneous fluctuations during states of reduced awareness suggests that intrinsic neuronal activity plays an important role in the maintenance of the brain's functional integrity.[19] Spontaneous BOLD activity has been detected in all mammalian species investigated thus far,[20–22] which reinforces the notion that this phenomenon is important from a physiologic and evolutionary point of view. However, the precise physiologic functions of intrinsic activity remain unknown. Examples of important RSNs follow and are summarized in Table 2.

Table 1
Key features of task-based fMR imaging and rsfMR imaging

Task-Based fMR Imaging	rsfMR Imaging
Neuronal activity is studied while performing a well-defined task (eg, finger tapping or object naming).	Neuronal activity is studied in the absence of a task (when the subject in the scanner is in a state of quiet wakefulness).
Maps a single functional system at a time	Maps all functional systems simultaneously
Task-related changes in the BOLD signal are measured. Regions in the brain associated with a given task are localized.	Spontaneous fluctuations in the BOLD signal are measured. Correlated intrinsic activity defines functional connectivity.
Immune to spurious variance in the BOLD signal (eg, P_{CO_2} levels, head motion)	Vulnerable to contamination and requires denoising to remove sources of spurious variance

Default mode network

Perhaps the most fundamental RSN is the default mode network (DMN) (Fig. 1A), first identified by a meta-analysis of task-based functional neuroimaging experiments performed with positron emission tomography.[23,24] The defining property of the DMN is that it is more active at rest than during performance of goal-directed tasks. The DMN was first identified using rsfMR imaging by Greicius and colleagues.[25] This finding has since been replicated many times over using a variety of analysis methods.[15,26–32] Some investigators have hypothesized that there are two large anticorrelated systems in the brain,[33,34] one anchored by the DMN and the other composed of systems controlling executive and attentional mechanisms. This dichotomy has been variously referred to as task-positive versus task-negative[28,32,33,35,36] and intrinsic versus extrinsic.[34,37] Although the nomenclature associated with the DMN remains controversial,[38,39] the topography of the DMN is remarkably consistent across diverse analysis strategies.

Sensory and motor resting-state networks

The somatomotor network, first identified by Biswal and colleagues,[9] encompasses primary and higher order motor and sensory areas (see Fig. 1B). The visual network spans much of the occipital cortex (see Fig. 1C).[15,26–29] The auditory network includes Heschl gyrus, the superior temporal gyrus, and the posterior insula.[15] The language network includes Broca and Wernicke areas but also extends to prefrontal, temporal, parietal, and subcortical regions (see Fig. 1D).[40–42]