UDC 612.821:612.82/83

Partial deactivation of default-mode brain network during simple motor task execution

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We used model based functional MRI independent component analysis approach for the detection and characterization of the described networks functioning during simple motor task execution. Direct connection between the task execution and anticorrelated functional connectivity of sensory-motor and default mode networks was shown. We observed blood oxygenation level dependent signal (BOLD) frequency characteristics of the default mode network (DMN) together with the sensory motor network (SMN). The results demonstrate a reproducible specific configuration of BOLD low-frequency spectrum. Neural network BOLD spectral profile approach may be used for future analysis of its functioning and dynamics rules of brain regions connectivity. Regions of precuneus and posterior cingulate cortex were shown to deactivate just partially. Sensorimotor and default-mode networks were functionally connected in the anticorrelated manner with the prevailing frequencies of the BOLD signal oscillation $f1 = 0.0153 \pm 0.0051$ Hz and $f2 = 0.0204 \pm 0.0051$ Hz, where f – frequency of BOLD oscillation. At our study we have found out, that only some separate parts of pC and PCC were deactivated during the task execution. This possibly might support the hypothesis that non deactivated regions of precuneus (pC) and posterior cingulate cortex (PCC) remain active to regulate the transitions from the activated state to the deactivated and back while monitoring the external environment and commands. The last may support the hypothesis of the role of posterior cingulate cortex as a "hub" in default mode networks where non deactivated parts remain active for further control of others default mode networks region state switching.

Key words: default mode network; sensory-motor network; fMRI; independent component analysis.

INTRODUCTION

It was shown that BOLD signal, originally proposed for functional MRI (fMRI) by S. Ogawa [1], arises from the increases in neural activity [2], thus BOLD signal time course can be extrapolated onto synchronized population neural oscillations. Since the application of independent component analysis (ICA) method for the fMRI data analysis, resting state fMRI gained considerable interest. It was shown that different regions of human brain function coherently thus forming large-scale compound functional neural networks [3]. But ICA decomposition of the model-based fMRI data is not so widespread, although it is powerful instrument for the analysis.

Task execution is supported by task-positive (TPN) and task-negative (TNN) neural networks [4]. The execution of movement is supported by sensory-motor neural network (SMN) increased activity [5]. So, SMN can be defined as TPN. Also, impellent act is accompanied by deactivation of the ipsilateral primary motor cortex, which is dedicated to intercallosal interhemispheric inhibition [6]. Brain regions of the precuneus (pC), posterior cingulate cortex (PCC), bilateral inferior parietal lobule (IPL) and medial prefrontal cortex (MPFC) were shown to be functionally connected [3, 7]. It was assumed that they form so-called default mode network (DMN) because of its specific functioning in the resting-state at the time of mind-wandering, memory recall, or future planning, without any external input [3]. Also, this network was shown to decrease its activity specifically with task execution [3, 6, 7]. So, DMN can be defined as TNN.

Although the structure of SMN and DMN was largely studied, the frequency spectrum of BOLD oscillations at these regions is less examined. Also, DMN is poorly described in its direct functions [8]. Several studies conclude that primarily BOLD signal oscillations at the DMN regions are located in the lower frequency range [4]. But more precise frequency analysis of BOLD signal at the functional neural networks still remains ill-defined. Thus, we aimed to examine whether BOLD signal frequency estimation could be used as analytical approach for TPN and TNN analysis during the task execution.

METHODS

The group of young adult volunteers was examined with fMRI using 1.5T Signa Excite HD ("General Electric", USA). The group included 20 healthy volunteers with no signs of neurological disorders (12M, 8F, 21-35 y.o.). All subjects were right-handed and gave informed consent about participation in the study, approved by local bioethical committee. During examination, the volunteers were asked to lay motionless, except executing finger tapping task, with closed eyes and supine palms, thinking of nothing in particular.

Full-brain fMRI data were acquired using MRI scanner 1.5T Signa ExciteHD ("General Electric", USA). Multislice T2*-weighted gradient echo EPI images were obtained with such parameters: TR/TE = 3000/71 ms, FA = 90°, NEX = 1, voxel dimensions 4×4×6 mm. 25 slices covering brain from the cerebellum to the vertex for each volunteer were acquired. High resolution T1-weighted anatomical scans were obtained for each subject with pulse sequence FSPGR. Parameters for pulse sequence TR = 11.6 ms, TE = 5.2, TI = 450 ms, voxel dimensions = 0.98×1×1.5 mm. The model-based fMRI data were acquired during 4 min scanning session, 50 timepoint images were received. Task execution was formed into 3 blocks of rest and activation, each lasting for 30 s, so the period of paradigm oscillation was 60 s (Figure, B). Thus, the frequency of modelled oscillation was $f = 0.0167$ Hz.

Model-based fMRI data processing was carried out using FEAT, part of FSL (FMRIB's Software Library) [9]. Activation and deactivation were modelled with GLM as an opposite contrasts. Model-based two-step ICA analyses was done using GLM design matrix. Single subject and group ICA analysis was carried out using MELODIC, part of FSL [10].

SMN and DMN networks were delineated by visual analysis of its' correspondence to earlier mentioned brain structures. Based on the conditions of the study, we measured the frequency of BOLD signal in the range of 0.0051 to 0.1275 Hz. Taking the data from ICA analysis, specifically frequencies and related power value at specific frequency, we separated whole spectrum into significant and insignificant range. Significant part of the spectrum was defined within of 0.0051-0.0357 Hz, where power values were much higher than in another range (P = 0.05). Data out of this range were considered insignificant.

RESULTS AND DISCUSSION

Neural oscillatory activity which may be estimated by the single cell recording or local field potential technique is compressed and flattened if measured by BOLD signal oscillations because of the restriction of MRI sampling rate (TR value), hemodynamic response delay and smoothing character of hemodynamic response function. Thus, evaluation of BOLD signal oscillations is not direct measurement of neuronal electrical or metabolic events, but rather indirect characteristic of neural activity. As in EEG, oscillation analysis by its mean power values at defined frequencies can be used for BOLD signal oscillation characteristics.

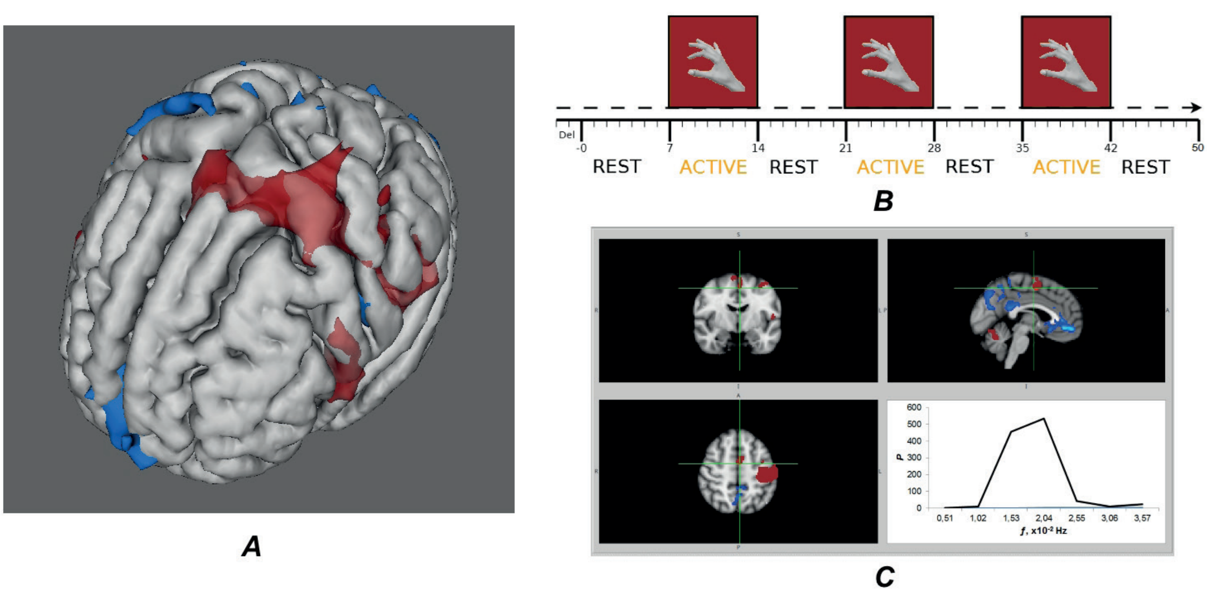
By using the GLM, we have found that simple unilateral finger tapping task is accompanied by the activation and deactivation of the human brain as described [6]. Regions of activation were found in the contralateral hemisphere of the brain (Table; Figure, A), particularly, at the site of primary sensory-motor cortex ($M1/S1_{contr}$), supplementary and ventral premotor cortex (SMA_{contr}, PMV_{contr}), ipsilateral hemisphere of the cerebellum ($Cereb_{ispi}$).

Such pattern of activation was widely described [6]. Pattern of deactivation included regions of ipsilateral sensory-motor cortex ($M1/S1_{ipsi}$), and regions of DMN, particularly regions pC, PCC, MPFC, bilateral IPL. Deactivation of such regions is consistent with previous analyses of task-dependent DMN decrease and functional connectivity [3]. Noteworthy, pC and PCC were deactivated incompletely during the motor task execution. It is widely accepted that during the rest conditions whole pC and PCC are functionally connected to form DMN [7].

Analysis of fMRI data with ICA revealed synchronization of the $M1/S1_{contr}$, SMA_{contr}, $Cbell_{ipsi}$, PM_v in terms of BOLD signal oscillation at the described regions of SMN. The last observation testifies the functional connectivity in the described regions and supports the finding of the GLM analysis. Also, it is supported by other observations [3, 4]. Results of the ICA showed the functional connectivity of the regions of pC, PCC, MPFC and bilateral IPL, and are accepted to form DMN [3]. Noteworthy, SMN and DMN were functionally connected in the anticorrelated manner (opposite in correlation ratio values and phase of the signal time course) with the prevailing frequencies of the BOLD signal oscillation $f_1 = 0.0153 \pm 0.0051$ Hz (P = 456) and $f_2 = 0.0204 \pm 0.0051$ Hz (P = 533), where f – frequency of BOLD oscillation, and P – relative power (Figure, C). Described frequency spectrum corresponds to the previously estimated frequency of paradigm execution ($f = 0.0167$ Hz). The last testifies the direct connection between the task execution and anticorrelated functional connectivity of SMN and DMN. The topography of DMN functional connectivity was the same as measured by the GLM analysis.

DISCUSSION

Presently, more and more papers showing functional connectivity of different regions of



Task-positive and task-negative neural networks functioning under simple unilateral motor task execution. A – activation of contralateral SMN (red) and deactivation of DMN and ipsilateral primary sensory-motor cortex. B – paradigm of motor task execution. C – ICA decomposition of task based fMRI data with BOLD frequency spectrum (red and blue show anticorrelated manner of SMN and DMN functioning)

Regions of brain activation and deactivation under the execution of simple unilateral finger tapping task

Topography			BA	Coordinates MNI152		
				x	y	Z
Activation						
Precentral and postcentral gyri	$M1/S1_{contr}$	L	4,3	-38	-20	58
Dorsal medial part of the superior frontal gyrus	SMA_{contr}	L	6	-8	-2	52
Inferior part of precentral and adjacent inferior frontal gyri	PM_v	L	6	-60	4	26
Upper part of cerebellum hemisphere	$Cereb_{ipsi}$	R	-	14	-54	-18
Deactivation						
Precentral and postcentral gyri	$M1/S1_{ipsi}$	L	4,3	24	-30	78
Precuneus and posterior cingulate cortex	pC, PCC	C	7,31	0	-68	22
Medial prefrontal cortex and ventral anterior part of cingultate gyrus	MPFC	C	9,32	2	54	-4
Inferior parietal lobule	RIPL	R	39	38	-80	40
Inferior parietal lobule	LIPL	L	39	-46	-74	32

Notice: R – right, L – left, C – center, BA – Brodmann's area.

the human brain are arising [3, 4, 7]. SMN is involved in motor task execution [6]. Functioning of DMN is involved in many cognitive and task-related processes, and its disruption is related to several diseases [3].

This is one of the first attempts to analyze dominating frequencies of the BOLD signal oscillation in the regions of SMN and DMN during the motor task execution. We observed BOLD frequency characteristics of the DMN together with the SMN. The results demonstrate a reproducible specific configuration of BOLD low-frequency spectrum. This study extends the trend in exploration of the frequency characteristics of fMRI data and neural networks and provides new insights into the functional organization of the brain.

It is widely accepted that cortical control of a simple movement is controlled by SMN neural network consisted of $M1/S1_{contr}$, SMA_{contr}, PM_v, $Cbell_{ipsi}$ [6]. Previous study [5] evidences that neural code of the memorized movement, as a scheme of spatial extremity translocation, is formed in the PM_v independently of the extremity lateralization. Possibly, further movement is lateralized in the contralateral PM_d and SMA_{contr} [11]. After the lateralization, the efferent signal moves to the dentate nucleus of the $Cbell_{ipsi}$, where the command of the movement starts, the synthesis of afferent data and muscles coordination takes place. From the $Cbell_{ipsi}$ through the ventrolateral nucleus of the thalamus signal forthcoming to the somatotopically organized $M1/S1_{contr}$, from which, through the pyramidal tract, it comes to the alfa-motoneurons of the ventral horns of the spinal cord [6, 11].

Although the structure of DMN is widely studied, its function remains poorly defined [8]. Analysis of the separate nodes of the DMN with the MACM has shown functional heterogeneity of its structure [8]. Also, in this paper the existence of functionally different loops, which are connected through the "hub", the PCC, was shown. As described, DMN can dynamically change its structure, while transforming from synchronized regions at rest to the desynchronized state at the task execution period and restoring its synchronized structure when returning to the resting state [12]. We show here that only some separate parts of pC and PCC were deactivated during the task execution. This possibly might support the hypothesis that non-deactivated regions of pC and PCC remain active to regulate the transitions from the activated state to the deactivated and back, while monitoring the external environment and commands.

We have tested the implementation of ICA method for the analysis of task-based fMRI data. The ICA and GLM analyses revealed comparable pattern of activation and deactivation. The ICA revealed the spectrum of BOLD signal oscillation in the regions of activation and deactivation. Thus, using the estimated frequency of oscillation one can analyze the correspondence of the topography to the task executed with the defined paradigm. One important remark should be considered: this approach could be used only for periodical block design paradigms and possibly for periodical resting state BOLD oscillation analysis.

CONCLUSIONS

1. Simple unilateral hand movement is accompanied by simultaneous functioning of the SMN and DMN.

2. Neural network BOLD spectral profile approach may be used for future analysis of its functioning and dynamics rules of brain regions connectivity.

3. Partial deactivation of precuneus and posterior cingulate cortex may support the idea of its important role as a “hub” in DMN connectivity.

The authors confirm that the research and publication of the results were not associated with any conflicts regarding commercial or financial relations, relations with organizations and/or individuals who may have been related to the study, and interrelations of co-authors of the article.

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ЧАСТКОВА ДЕАКТИВАЦІЯ МЕРЕЖІ ПАСИВНОЇ РОБОТИ МОЗКУ ПІД ЧАС ВИКОНАННЯ ПРОСТОГО МОТОРНОГО ЗАВДАННЯ

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Нами було використано метод аналізу незалежних компонент для даних функціональної магнітно-резонансної томографії (фМРТ), отриманих під час виконання простих рухових завдань. Було показано обернену кореляцію між виконанням рухового завдання та функцональною зв’язністю між сенсомоторною і дефолтною нейронними мережами. Ми аналізували частотні характеристики коливання залежного від насичення крові киснем сигналу (blood oxygenation level dependent signal, BOLD) при фМРТ. Результати демонструють відтворювану специфічну конфігурацію низькочастотного спектру BOLD-сигналу. Використаний підхід до аналізу спектрального профілю коливання BOLD-сигналу у ділянках нейронних мереж може бути використаний для подальшого аналізу їх функціонування та вивчення динаміки функціональної зв’язності різних ділянок мозку. Показано, що ділянки передклина та заднього відділу поясної кори деактивуються лише частково. Сенсомоторна і дефолтна нейронні мережі були функціонально зв’язані у вигляді оберненої кореляції коливання BOLD-сигналу на частотах $f1 = 0.0153 \pm 0.0051$ Hz і $f2 = 0.0204 \pm 0.0051$ Hz, де f – частота коливання BOLD-сигналу. Під час нашого дослідження ми з’ясували, що під час виконання рухового завдання деактивувалися лише окремі ділянки дефолтної мережі, а саме частково передклин та задня поясна кора. Це може підтвердити гіпотезу про те, що не деактивовані області передклина та задньої ділянки поясної кори залишаються активними для регулювання переходів із активованого стану в деактивований і назад під час моніторингу зовнішнього середовища та команд. Останнє може підтвердити гіпотезу про роль задньої поясної кори як «перемикача» дефолтної мережі, де не деактивовані частини якої залишаються активними для подальшого контролю перемикання окремих ділянок дефолтної мережі.

Ключові слова: прості рухові завдання; магнітно-резонансна томографія; сенсомоторна і дефолтні мережі; аналіз незалежних компонент.

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Received 20.12.2021