Brain-computer interfaces based on near-infrared spectroscopy and electroencephalography registration in post-stroke rehabilitation: a comparative study

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Motor imagery training under the control of a brain-computer interface (BCI) facilitates motor recovery after stroke. The efficacy of BCI based on electroencephalography (EEG-BCI) has been confirmed by several meta-analyses, but a more convenient and noise-resistant method of near-infrared spectroscopy in the BCI circuit (NIRS-BCI) has been practically unexamined; comparisons of the two types of BCI have not been performed.
Objective: *to compare the control accuracy and clinical efficacy of NIRS-BCI and EEG-IMC in post-stroke rehabilitation.*
Material and methods. *The NIRS-BCI group consisted of patients from an uncontrolled study (n=15; 9 men and 6 women; age – 59.0 [49.0; 70.0] years; stroke duration – 7.0 [2.0; 10.0] months; upper limb paresis – 47.0 [35.0; 54.0] points on the Fugl-Meyer Assessment for motor function evaluation of the upper limb – FM-UL). The EEG-IMC group was formed from the main group of the randomized controlled trial “iMove” (n=17; 13 men and 4 women; age – 53.0 [49.0; 70.0] years; stroke duration – 10.0 [6.0; 13.0] months; upper limb paresis – 33.0 [12.0; 53.0] points on the FM-UL). Patients participated in a comprehensive rehabilitation program supplemented by BCI-guided movement imagery training (average of 9 training sessions).*
Results. *Median of average BCI control rates achieved by the patients was 46.4 [44.2; 60.4]% in the NIRS group and 40.0 [35.7; 45.1]% in the EEG group (p=0.004). For the NIRS-BCI group, the median of the maximum BCI control accuracy achieved was 66.2 [56.4; 73.7]%, for EEG-BCI – 50.6 [43.0; 62.3]% (p=0.006). The proportion of patients who achieved a clinically significant improvement according ARAT and the proportion of patients who achieved a clinically significant improvement according FM-UL were comparable in both groups. The NIRS-BCI group showed greater improvement in motor function compared to the EEG-BCI group according to Action Research Arm Test (ARAT; an increase of 5.0 [4.0; 8.0] points compared to an increase of 1.0 [0.0; 3.0] points; p=0.008), but not according to FM-UL scale (an increase of 5.0 [1.0; 10.0] and 4.0 [2.0; 5.0] points, respectively; p=0.455).*
Conclusion. *NIRS-BCI has an advantage in control accuracy and ease of use in clinical practice. Achieving higher control accuracy of BCI provides additional opportunities for the use of game feedback scenarios to increase patient motivation.*

Keywords: *post-stroke rehabilitation; paresis; brain-computer interfaces; near-infrared spectroscopy; neurofeedback.*
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Brain-computer interfaces (BCIs) convert electrical or metabolic brain activity data into signals controlling an external device. Non-invasive BCIs can be used for motor imagery training with neurofeedback for rehabilitation of patients with stroke, brain injury, or cerebral palsy. Motor imagery training accompanied by neurofeedback was shown to enhance neuroplacticity and motor recovery or learning [1,2].

In recent years, extensive evidence has been accumulated with the use of BCIs in stroke rehabilitation. Published systematic reviews and meta-analyses demonstrated advantages of these technologies in restoring motor function of the upper limbs and improving activity of daily living [3–13]. A positive effect of BCI control training on cognitive functions has been described [14, 15]. BCI training includes an active motor imagery paradigm and is the only active rehabilitation option for patients with severe paresis.

There are several challenges that do not allow a wider use of BCIs in clinical practice. Electroencephalography (EEG)-based systems are the most studied and available kind of BCI for stroke rehabilitation [12]. However, it requires additional time to install sensors and apply electrode gel under them, while EEG systems with dry electrodes rarely allow recording the signal of the appropriate quality. Near-infrared spectroscopy-based brain-computer interfaces (NIRS BCIs) are non-invasive portable brain-computer interfaces that also support motor imagery training with neurofeedback. NIRS allows optical recording of hemodynamic changes in a depth of up to 4 cm from the skull. Near-infrared light (760 to 850 nm) is emitted by sources located on the surface of the patient's head; detectors record changes in absorption intensity and light scattering, which depend on changes in cerebral hemoglobin levels [16]. Several optically measured parameters such as changes in oxyhemoglobin, deoxyhemoglobin or total hemoglobin levels (HbO, HbR or HbT, respectively) can be used as indicators of brain activity. No electrode gel is required in this technology, and electromagnetic noise and patient movements during training do not result in serious signal distortion [17]. These advantages of NIRS BCI may contribute to higher BCI control accuracy and motor function recovery. NIRS BCI is now much more expensive than EEG BCI and remains understudied for clinical applications [16, 18–20]. No direct comparisons of NIRS BCI and EEG BCI in clinical practice have been described yet.

Aim. The study aimed to compare control rate and clinical efficacy of NIRS BCI and EEG BCI in stroke rehabilitation.

Materials and methods. We conducted a non-randomized clinical trial with historical control to compare NIRS BCI and EEG BCI effects in comprehensive stroke rehabilitation. The NIRS BCI group (n=15) included all participants from one-arm study [19, 21]. The EEG BCI group (n=17) was formed from the BCI group of the randomized controlled iMove study [22]. Both studies included clinically stable patients with upper limb paresis due to the first or recurrent stroke. The studies did not include patients with severe impairment of vision, speech or other cognitive functions or with hand contracture. Since the inclusion criteria for the iMove study were broader than those for the NIRS BCI study, to match two studies samples we included patients with cortical or cortico-subcortical stroke and comparable severity of arm paresis and duration of the disease from the total population of the BCI iMove group.

Protocols of previous studies had been approved by the Local Ethics Committee of Research Center of Neurology (Report 5-4/22 as of June 01, 2022 for NIRS BCI and Report 12/14 as of December 10, 2014 for iMove study). All patients provided written informed consent to participate in the respective study. All procedures were performed in compliance with relevant laws and institutional guidelines.

Key clinical and demographic patient characteristics were comparable in both groups. The number of BCI training days and total training time were also comparable (Table 1).

In both studies, patients received comprehensive hospital stroke rehabilitation supplemented by motor imagery training with BCI, i.e. a total of 4 to 15 (mean: 9) training daily sessions except for weekends. During each training session, the patient sat at a table in front of a computer monitor. There was a fixation point consisting of a circular shape in the center of the dark screen to fix the patient's gaze with three arrows surrounding the fixation point. Following one of three commands, the patient either kinesthetically imagined slow motion of their left or right hand (with the left or right arrow changing its color, respectively) or relaxed and directed their gaze towards the center of the screen (with the upper arrow changing its color). If the task was successfully recognized by the classifier, the gaze fixation point in the center of the screen turned green. The EEG BCI study (iMove), besides visual feedback, involved kinesthetic feedback using an exoskeleton that opened the hand (Fig. 1).

The NIRScout system (NIRx Medical Technologies) with 16 sources and 8 detectors was used for NIRS. In the iMove study, EEG signals were recorded using 30 electrodes arranged according to the International 10–20 System (NVX52, Medical Computer Systems, Zelenograd, Russia). EEG BCI used frequency filtration from 5 to 30 Hz in order to process signals online and a Bayesian classifier based on covariance matrices calculated for three mental tasks in order to classify motor imagery. NIRS BCI used a filtra-

Table 1. *General characteristics of patients in each study group*

Characteristic	NIRS BCI (n=15)	EEG BCI (n=17)	p
Age, full years	59.0 [49.0; 70.0]	53.0 [49.0; 70.0]	0.100
Sex	9 M, 6 F	13 M, 4 F	0.450
Time from stroke onset, months	7.0 [2.0; 10.0]	10.0 [6.0; 13.0]	0.122
Affected hemisphere	8 left, 7 right	11 left, 6 right	0.720
ARAT score	35.0 [10.0; 44.0]	21.0 [0.0; 43.0]	0.396
FMA-UE score	47.0 [35.0; 54.0]	33.0 [12.0; 53.0]	0.093
Training days	10.0 [9.0; 12.0]	9.0 [8.0; 10.0]	0.067
Total BCI exposure, minutes	218.0 [91.0; 314.0]	210.0 [190.0; 256.0]	0.737

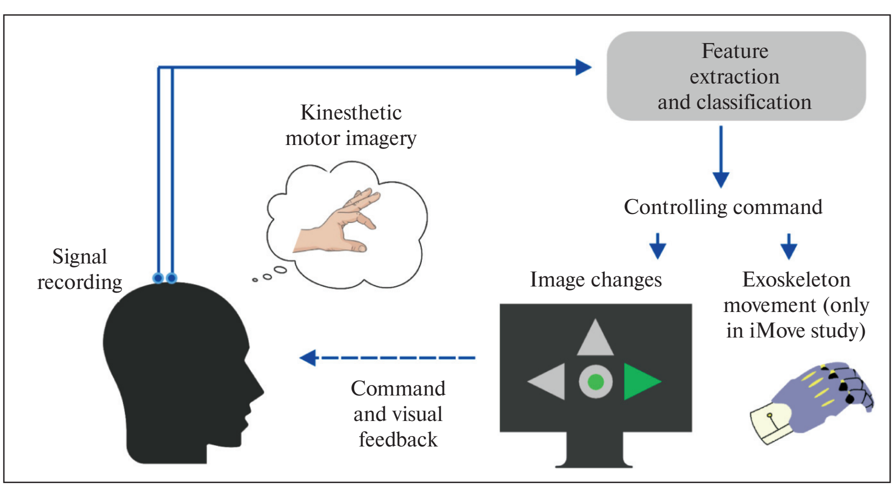

Fig. 1. *General scheme of the BCI system and the training process*

tion method that considered the frequency of command presentation in order to minimize the time delay, and classification was sequential: at first, the resting state was differentiated from motor imagery using linear discriminant analysis, then, if motor imagery was identified, the system determined the movement of which hand was imagined [23]. The detailed protocol for NIRS BCI study [19, 21] and the protocol for EEG BCI study (iMove) [22] were described in our previous publications. Key differences between procedures of BCI training in both studies are summarized in Table 2.

Table 2. *Main differences in the training protocols for motor imagery in the NIRS-BCI and EEG-BCI studies*

Показатель	**NIRS BCI**	**EEG BCI (iMove)**
Preparation for the procedure	Put on a cap with electrodes, perform signal calibration procedure	Put on a cap and apply gel under each electrode, check EEG impedance and signal quality and reapply gel if necessary
Recorded signal	Changes in hemodynamic response (relative HbO, HbR, HbT levels) in the cerebral cortex recorded by NIRS	Spatial and frequency changes in EEG rhythms within the range from 5 to 30 Hz
Imagined movements	Movements from the ARAT test that were the most difficult for the patient; an attempt to perform the target movement was used as priming before each training session	Slow opening of the hand (extension of the fingers)
BCI calibration	The first few motor imagery attempts of the first session took place without feedback. In sessions, following the first one, a classifier trained on all previously recorded data of this patient was used to recognize mental tasks in the first block.	The first few motor imagery attempts took place without feedback, the BCI classifier was retrained during each session
Feedback	Visual	Visual and kinesthetic: using an exoskeleton

The Action Research Arm Test (ARAT; with the highest score of 57 and a minimal clinically important difference of 6 or 12–17 points in the chronic or acute stroke periods, respectively) [24] and the Fugl-Meyer Motor Assessment for Upper Extremity (FMA-UE; with the highest score of 66 and a minimal clinically important difference of 5 or 9 points in the chronic or acute stroke period, respectively) were used to assess the hand function before and after stroke rehabilitation [24–27].

Classification accuracy or BCI control rate, which was assessed in this study, is an average probability of correct identification, i.e. the mean proportion of cases with correct identification of the task among all presentations of the corresponding command. With BCI control rate of over 33%, signal identification is considered to be higher than random because the patient performed three mental tasks according to the command (100%:3=33%). BCI control rate depends on both classifier performance and the participant's ability to imagine movement.

Statistical analysis was performed using Mann–Whitney test, Wilcoxon test, and Fisher's exact test on a personal computer using STATISTICA v 6.0 software package (Statsoft). Data are presented as median and 25%, 75% quartiles. Results were considered statistically significant at $p < 0.05$.

Results. The median of the average BCI control rates achieved by the patients was 46.4 [44.2; 60.4]% in the NIRS group and 40.0 [35.7; 45.1]% in the EEG group (p=0.004). There were between-group differences in the maximal control rate (66.2 [56.4; 73.7]% in the NIRS BCI group and 50.6 [43.0; 62.3]% in the EEG BCI group) (p=0.006) (Fig. 2)

The motor recovery assessed with FMA-UE, the proportion of patients who achieved clinically significant improvement in ARAT score, and the proportion of patients who achieved clinically significant improvement in FMA-UE score were comparable in both groups. Improvement in ARAT motor function score in the NIRS BCI group was higher than in the EEG BCI group (increase by 5.0 [4.0; 8.0] vs. increase by 1.0 [0.0; 3.0], p=0.008) (Table 3).

Discussion. This comparative study showed that stroke patients achieved higher BCI control accuracy with NIRS BCI than with EEG BCI. This can be explained by two factors. Firstly, several parameters, i.e., changes in HbO, HbR or HbT, levels can be used as indicators of brain activity, which simplifies the classifier's task. Secondly, compared with EEG, NIRS has higher noise resistance when recording brain signals [16, 17]. It should be noted that different nature of EEG and NIRS signals inevitably requires slightly different approaches to their pre-processing and classification; however, the approaches are quite simple from the mathematical point of view. Therefore, differences in classification approaches are unlikely to be the main cause of observed differences in BCI control rate.

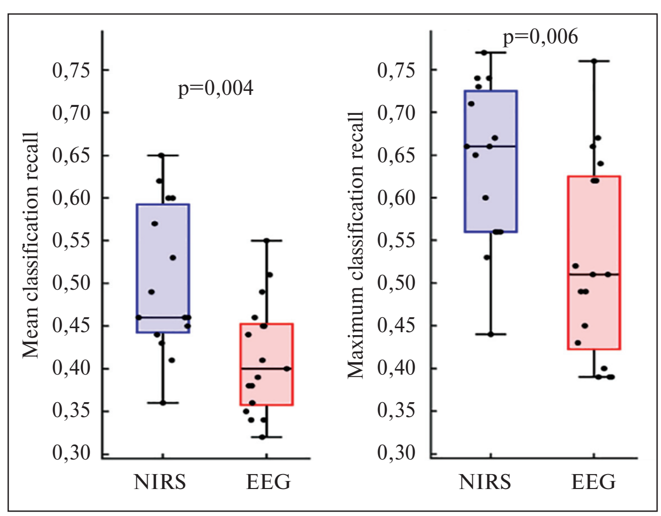

Fig. 2. *Indicators of the quality of NIRS-BCI or EEG-BCI control in post-stroke patients, as fractions of one. Boxes: median, 25th; 75th percentiles; whiskers – minimum and maximum values of the sample*

Table 3. *Dynamics of motor recovery during the rehabilitation process*

Scale	NIRS BCI (n=15)	EEG BCI (n=17)	p
Improvement in ARAT score	5.0 [4.0; 8.0]	1.0 [0.0; 3.0]	0.008
Improvement in FMA-UE score	5.0 [1.0; 10.0]	4.0 [2.0; 5.0]	0.455
Number of patients who achieved minimal clinically important difference in ARAT score (%)	4 (26.7)	2 (11.8)	0.383
Number of patients who achieved minimal clinically important difference in FMA-UE score (%)	5 (33.3)	5 (29.4)	1.000

Motor function improvement with motor imagery training sessions using NIRS BCI and EEG BCI was comparable, and a higher effect of NIRS BCI on hand movements was seen when assessed by ARAT score. Since the NIRS BCI study was conducted several years after the iMove study, other factors, such as changes in the comprehensive stroke rehabilitation protocol or more prolonged hospitalization, could have contributed to the differences in ARAT score improvement. Therefore, this result should be interpreted with caution. In addition, the iMove study involved a hand exoskeleton, while the NIRS BCI study involved priming (an attempt to perform the target movement before imagining it). A more precise comparative analysis of the two BCIs in regard of their clinical effect would require a randomized parallel-group clinical study and the same type of feedback (only visual or both visual and kinesthetic in each group). However, the factors associated with different study timing were unlikely to affect BCI control rate, as the paradigm and interface control scenario were the same, and the total time of training sessions was comparable.

To date, several studies reported effects of NIRS-BCI in motor stroke rehabilitation. In two studies, NIRS was used to measure post-stroke motor cortex laterality and its correlation with motor impairment [28, 20, 18]. It is of note that one of these studies showed that NIRS-BCI can be used at home [20].

In a randomized study in 20 patients M. Mihara et al. demonstrated the efficacy of NIRS BCI in MI-based training in patients with subcortical stroke. Six training sessions resulted in a better improvement of motor function measured as FMA-UE score in the active group than in the sham NIRS BCI group. In contrast to the system used in our study, the NIRS BCI technology used by M. Mihara et al. did not involve any online signal classification: the patient just had to control the signal level in the biofeedback paradigm[18].

The main *limitation* of our study is its retrospective, non-randomized design. The obtained results suggest a clinical advantage of one type of BCI over another, but should be interpreted with caution. An adequately powered randomized controlled trial should be conducted, which may confirm the assumption about the advantage of NIRS BCI.

To the best of our knowledge, our study is the first to compare control accuracy and clinical efficacy of NIRS BCI and EEG BCI in motor stroke rehabilitation.

Conclusion. Therefore, with at least comparable clinical efficacy of the two kinds of BCI, the NIRS BCI was shown to be superior in control accuracy and ease of use in real-world clinical practice. Higher noise resistance and BCI control rates provide additional opportunities for the use of game feedback scenarios to increase patient motivation.

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Conflict of Interest Statement

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