ORIGINAL ARTICLE

Coherent connections of brain biopotentials in military personnel during recovery from mine-blast closed craniocerebral injuries

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ABSTRACT

Aim: To investigate interhemispheric and intrahemispheric coherence of brain biopotentials in military personnel during the recovery period following mine-blast closed craniocerebral injuries (MBCCI), as well as to assess the cumulative effect of repeated injuries on coherence patterns.

Materials and Methods: The study included 28 military personnel with single (14 patients) and multiple (14 patients) MBCCIs, along with 11 healthy controls without neurotrauma. Background electroencephalograms recorded prior to treatment initiation were subjected to coherence analysis.

Results: Demonstrated a significant reduction in both inter- and intrahemispheric coherence in military personnel with single, and particularly multiple, MBCCIs, indicating impaired integrative brain functioning. In both groups of injured military personnel, the most pronounced reductions in interhemispheric coherence relative to healthy controls were observed within the delta, theta, alpha, and low-beta frequency bands, predominantly in the frontal and parietal regions. Multiple MBCCIs were associated with generalized interhemispheric dysfunction across all frequency bands, involving the central, occipital, and temporal regions, as well as an imbalance of intrahemispheric coherence–manifested as suppressed activity in the left hemisphere and compensatory hyperactivation in the right. These alterations in coherence parameters correlated with clinical manifestations of neurological, emotional, and cognitive impairments, reflecting varying degrees of functional reserve depletion in military personnel with single and multiple MBCCIs.

Conclusions: The findings may serve as a basis for the development of pathogenetically grounded, individualized neurorehabilitation programs.

KEY WORDS: mine-blast closed craniocerebral injuries; interhemispheric coherence; intrahemispheric coherence; neurophysiological criteria

Wiad Lek. 2025;78(9):1843-1848. doi: 10.36740/WLek/212519 DOI

INTRODUCTION

Mine-blast closed craniocerebral injuries (MBCCI) are a complex type of combat neurotrauma that leads to long-term cognitive, sensorimotor, and emotional disorders [1]. One of the important areas of such disorders research is the study of inter-hemispheric and intra-hemispheric coherence of electroencephalographic (EEG) signals as potential biomarkers of neuroplasticity and brain recovery in affected military personnel. Clinical studies have shown a significant decrease in EEG-phase coherence in individuals with MBCCI. In particular, diffusion tensor imaging and a highly-sensitive method of weighted phase coherence revealed a decrease in inter-hemispheric phase in the frontal lobes of the brain, which correlated with the white matter damage [2]. Synchronization disorders in the 25–40 Hz range associated with a decrease in fractional anisotropy in the lower cerebellar lobe were confirmed, indicating microstructural damage of the white matter. Improved phase synchronization analysis revealed a correlation between reduced coherence at high frequencies and microstructural changes in the brain [3].

Functional probing using magnetic-resonance tomography (MRT) at the state of rest revealed a decrease in connectivity in both diffuse mode network (DMN) and visual networks. It was found that veterans with mild MBCCI had significantly reduced DMN connectivity, as well as the participation coefficient in the frontal lobes of the brain. In addition, a decrease in functional connectivity between the structures of the visual system (LGN, V1, LO, FG) and the frontal cortex of the brain correlated with the degree of cognitive impairment [4, 5].

According to the functional MRT data, recurrent MBCCI causes hyper-connectivity between the thalamus and the cerebral cortex. A study using functional MRT at the state of rest revealed increased functional connectivity between the thalamic nuclei and the passive mode network of the brain in the acute period – approximately 6 ± 3 days after injury. It has been shown that repeated injuries lead to a progressive increase in thalamocortical connectivity, the degree of which increases depending on the number of injuries sustained [6].

Experimental animal models also confirm the cumulative nature of mine-blast injuries. In particular, subclinical seizures, disorders of the blood-brain barrier integrity, and increased expression of pro-inflammatory markers such as TDP-43 and Piezo2 have been detected after repeated explosive brain injuries [7]. Proteomic analysis of the hippocampus in rats revealed significant changes in the protein profile, indicating profound molecular transformations in brain tissues. In addition, high-density EEG-recording showed that the long-term effects of repeated mine-blast injuries include increased power in the alpha and beta ranges [8]. A link has also been established between post-traumatic amnesia, loss of consciousness, cognitive difficulties and changes in the EEG-spectrum. Additional studies that took into account the presence of post-traumatic stress disorder (PTSD) showed that although post-traumatic stress disorder (PTSD) and MBCCI cause spectral changes in the EEG, their topography differs: in MBCCI, it is the prefrontal and right-temporal areas, while in PTSD, it is the right temporo-parietal area [9].

According to the results obtained by using various neuroimaging methods, it has been determined that even so-called 'mild' MBCCI has the potential to cause profound structural, functional, and molecular changes in the brain. Of particular significance is the fact that repeated injuries have a cumulative negative effect, in particular by exacerbating disorders of neuronal network coherence [10, 11]. This, in turn, highlights the importance of systematic analysis of inter- and intra-hemispheric coherence as an effective diagnostic and monitoring tool in the rehabilitation of military personnel who have suffered MBCCI.

AIM

The aim of this study is to analyze inter-hemispheric and intra-hemispheric coherent connections of brain biopotentials in military personnel during recovery from MBCCI, as well as to study the cumulative effect of repeated MBCCI on the nature of coherent changes.

MATERIALS AND METHODS

Twenty-eight military personnel who suffered mild to moderate mine-blast trauma (MBT) (concussion and brain contusion, acoustic trauma) during combat operations due to the full-scale war in Ukraine in 2022-2024 were examined. The period since the last MBT confirmed by primary medical documentation ranged from 3 to 12 months. All patients were men with an average age of (33.9 ± 1.8) years.

The first group (14 men) included patients who had only one MBCCI, and the second group (14 men) included patients who had more than one c in the last two years, with an average of 2-3 injuries.

All examined patients who had undergone MBCCI had numerous complaints of neurological, vegetative and somatic nature. The most common were headache, photophobia, sensitivity to sounds, nausea, double vision, blurred vision, hearing loss, tinnitus, dizziness, unsteadiness when walking, speech disorders, pain in the spine, limited movement in the limbs, muscle pain, cramps, paresthesia, weakness, tremor, limb movement disorders, general asthenia, local or generalized hyperhidrosis, tachycardia, and arterial hypertension. Cognitive disorders were noted, in particular, decreased memory, attention, difficulty concentrating, as well as emotional disorders – increased anxiety, irritability, sleep disorders.

Clinical-and-neurological examination revealed a predominance of liquor-hypertensive, vestibule-cochlear, and vestibule-ataxic syndromes. In a number of cases, disorders of functioning of the cranial nerves, mainly the auditory nerves, as well as oculomotor disorders were recorded. Symptoms of peripheral nervous system damage were detected, with a predominance of manifestations of cerebrastenic syndrome, combined with signs of vegetative dysfunction and general brain disorders. The course of the post-traumatic recovery period in patients was significantly complicated by the presence of mine-blast injuries of internal organs, soft tissues and bones, most often of a multiple or combined nature. Analysis of clinical data showed that the severity of neurological symptoms was significantly greater in patients in the second group.

The control group included patients (11 persons) who did not have MBCCI. The average age of the control group patients was (31.8 ± 2.3) years.

All categories of examinees underwent EEG recording using a "Neuron-Spectrum-4/P" computerized electroencephalograph with 20 standard monopolar leads according to the <10-20> system. For coherent analysis, four artefact-free epochs (5.12 s each) of the background EEG recording were selected, followed by calculation of interhemispheric and intra-hemispheric coherence indices of bio-potentials for five frequency ranges, corresponding to delta – (0.5 – 3.9 Hz), theta – (4.0 – 7.9 Hz), alpha – (8.0-12.9 Hz), low-frequency beta

(LF) – (13.0 – 19.9 Hz) and high-frequency beta (HF) – (20.0 – 35.0 Hz) rhythms. Interhemispheric coherence analysis was performed in 8 pairs of leads (Fp1-Fp2; F3-F4; F7-F8; T3-T4; T5-T6; C3-C4; P3-P4; O1-O2), and intra-hemispheric coherence in 12 pairs of leads (Fp1-F3; F3-C3; C3-P3; P3-O1; Fp2-F4; F4-C4; C4-P4; P4-O2; F7-T3; T3-T5; F8-T4; T4-T6).

Statistical data processing was performed using Excel and SPSS software, the mean values (M) and standard error of the mean (m) were calculated, and the significance of differences between indicators was determined using the nonparametric Wilcoxon-Mann-Whitney criterion at a significance level of $p \leq 0.05$.

RESULTS

A comparison of inter-hemispheric coherent connections in patients in the first group and in healthy subjects was performed. The data are presented in Table 1.

Table 1 shows that patients in the first group, compared to the control group, had a statistically significant ($p \leq 0.05$) decrease in inter-hemispheric coherent connections, mainly in pairs of frontal lobes (Fp1-Fp2; F7-F8) and parietal (P3-P4) leads in the delta-, theta-, alpha-, and beta- low-frequency ranges. In the delta-range, a weakening of inter-hemispheric coherent connections was also observed in pairs of central (C3-C4) and temporal (T3-T4) leads. Similarly, a comparison of inter-hemispheric coherent connections was performed in patients of the second group and in the control group. The data are presented in Table 2.

As can be seen from Table 2, patients in the second group, unlike healthy subjects, showed significantly lower inter-hemispheric coherence in frontal pairs (Fp1-Fp2; F3-F4), central (C3-C4) and parietal (P3-P4) leads in all studied frequency ranges of brain bio-potentials. In patients of the second group, a significant decrease in inter-hemispheric coherence was also determined in pairs of lower frontal (F7-F8) and central (C3-C4) leads in the delta-, theta-, alpha-, and beta- low-frequency ranges. Low inter-hemispheric coherence indices in patients of the second group were also noted in pairs of temporal (T3-T4; T5-T6) leads in the delta-, theta-, and beta- low frequency ranges (Table 2).

We also conducted a comparative analysis of inter-hemispheric coherence indicators in patients from the first and second groups. Significant differences were found only in the delta- and beta- frequency ranges. In the delta- range, there were mixed changes, namely, in pairs of frontal (F3-F4) leads, inter-hemispheric coherence indices in patients in the first group were significantly ($p=0.03$) lower than in patients in the second group (0.32 ± 0.09 and 0.38 ± 0.04, respectively), while in the pairs of central (C3-C4) leads, they are significantly ($p=0.03$) higher (0.55 ± 0.06 and 0.34 ± 0.03, respectively). In the beta- low frequency range in pairs of occipital (O1-O2) and temporal (T5-T6) leads, inter-hemispheric coherence indices are significantly lower in patients in the second group. To confirm this, we present data in pairs of occipital (O1-O2) leads in patients of the first group, where inter-hemispheric coherence indices of beta- frequency range bio-potentials corresponded to a value of 0.39 ± 0.06, and in the second group – 0.24 ± 0.03; and in pairs of temporal (T5-T6) leads, these indicators in the first group were 0.24 ± 0.03 and in the second group – 0.13 ± 0.01, which has a high reliable ($p=0.01$) discrepancy.

Thus, analysis of interhemispheric coherence indicators revealed a general tendency toward a decrease in functional interaction between hemispheres in patients in both groups – both with single and multiple MBCCI – compared to the control group. The most pronounced decreases in coherence were observed in the delta-, theta-, alpha-, and beta- frequency ranges, with predominant localization in the frontal and parietal regions of the cerebral cortex. In patients with multiple MBCCI, a significantly greater number of significant differences were recorded, in particular low coherence indices also extended to the central, occipital and temporal regions, covering the theta-, beta- LF and beta- HF ranges, indicating a more generalized dysfunction of interhemispheric connections. A comparative analysis of patients with single and multiple MBCCI demonstrated that it is precisely in multiple injuries that a significant decrease in coherence in the beta- HF range is observed, mainly in pairs of occipital and temporal leads. These changes correlate with clinical manifestations – more pronounced neurological symptoms, emotional instability and cognitive disorders, which is probably due to a wider damage to the brain network structures responsible for the integration of sensory information, regulation of attention, memory and emotional reactivity.

Changes in intra-hemispheric coherence of brain bio-potentials were analyzed in all observation groups. In patients of the first group, who had only one MBCCI in their medical history, compared with the control group, a significant ($p=0.05$) decrease in intra-hemispheric coherence indices was determined only in the delta- frequency range in the pair of frontal (Fp1-F3) leads of the left hemisphere of the brain (0.43 ± 0.08 and 0.67 ± 0.03, respectively). In patients in the second group with multiple MBCCI, there were significantly more significant differences from the control group. The data are presented in Table 3.

Table 1. Significant differences in inter-hemispheric coherence indices in patients of the first group and in the control group.

Frequency range	EEG pairs	Inter-hemispheric coherence indices		Intergroup differences P≤0,05
		Patients of Group 1	Control group	
Delta-range	FP1-FP2	0,37 ± 0,09	0,68 ± 0,06	0,01
	C3-C4	0,55 ± 0,06	0,61 ± 0,04	0,04
	P3-P4	0,45 ± 0,02	0,53 ± 0,04	0,04
	F7-F8	0,37 ± 0,06	0,49 ± 0,04	0,03
	T3-T4	0,30 ± 0,06	0,52 ± 0,03	0,05
Theta-range	P3-P4	0,53 ± 0,07	0,60 ± 0,03	0,05
Alpha-range	FP1-FP2	0,44 ± 0,06	0,72 ± 0,03	0,01
	F7-F8	0,36 ± 0,03	0,52 ± 0,03	0,01
Beta-low frequency range	P3-P4	0,35 ± 0,04	0,52 ± 0,03	0,01
	F7-F8	0,24 ± 0,04	0,35 ± 0,02	0,03

Source: compiled by the authors of this study

Table 2. Significant differences in inter-hemispheric coherence indices in patients of the second group and in the control group

Frequency range	EEG pairs	Inter-hemispheric coherence indices		Intergroup differences P≤0,05
		Patients of Group 2	Control group	
Delta-range	FP1-FP2	0,43 ± 0,07	0,68 ± 0,06	0,02
	F3-F4	0,38 ± 0,04	0,62 ± 0,05	0,00
	C3-C4	0,34 ± 0,03	0,61 ± 0,04	0,00
	P3-P4	0,35 ± 0,03	0,53 ± 0,04	0,01
	O1-O2	0,30 ± 0,03	0,47 ± 0,03	0,00
	F7-F8	0,23 ± 0,04	0,49 ± 0,04	0,00
	T3-T4	0,27 ± 0,05	0,52 ± 0,03	0,00
	T5-T6	0,20 ± 0,04	0,39 ± 0,03	0,01
Theta- range	FP1-FP2	0,42 ± 0,07	0,66 ± 0,06	0,01
	F3-F4	0,47 ± 0,05	0,68 ± 0,05	0,02
	C3-C4	0,45 ± 0,05	0,68 ± 0,04	0,01
	P3-P4	0,44 ± 0,05	0,60 ± 0,03	0,03
	O1-O2	0,38 ± 0,04	0,48 ± 0,03	0,05
	T3-T4	0,28 ± 0,05	0,42 ± 0,04	0,02
Alpha- range	FP1-FP2	0,44 ± 0,06	0,72 ± 0,03	0,00
	F3-F4	0,49 ± 0,05	0,70 ± 0,02	0,00
	C3-C4	0,49 ± 0,05	0,66 ± 0,03	0,01
	P3-P4	0,51 ± 0,04	0,64 ± 0,03	0,04
	F7-F8	0,36 ± 0,03	0,52 ± 0,03	0,01
Beta- low frequency range	FP1-FP2	0,24 ± 0,07	0,55 ± 0,04	0,01
	F3-F4	0,27 ± 0,07	0,57 ± 0,03	0,01
	C3-C4	0,25 ± 0,06	0,54 ± 0,03	0,01
	P3-P4	0,24 ± 0,05	0,52 ± 0,03	0,00
	O1-O2	0,24 ± 0,03	0,43 ± 0,03	0,00
	F7-F8	0,21 ± 0,05	0,35 ± 0,02	0,04
	T5-T6	0,13 ± 0,01	0,22 ± 0,02	0,00
Beta- high frequency range	FP1-FP2	0,20 ± 0,05	0,33 ± 0,03	0,03
	F3-F4	0,17 ± 0,03	0,31 ± 0,03	0,01
	C3-C4	0,18 ± 0,03	0,32 ± 0,03	0,01
	P3-P4	0,19 ± 0,03	0,29 ± 0,03	0,02

Source: compiled by the authors of this study

Table 3. Significant differences in intra-hemispheric coherence indices in patients in the second group and in the control group

Frequency range	EEG pairs	Intra-hemispheric coherence indices		Intergroup differences P≤0,05
		Patients of Group 2	Control group	
Delta-range	Fp1-F3	0,54 ± 0,04	0,67 ± 0,03	0,02
	Fp2-F4	0,52 ± 0,04	0,65 ± 0,03	0,03
	T3-T5	0,47 ± 0,06	0,73 ± 0,04	0,01
Theta- range	T3-T5	0,53 ± 0,06	0,69 ± 0,06	0,04
Beta- low frequency range	C4-P4	0,87 ± 0,04	0,78 ± 0,02	0,02
Beta- high frequency range	C4-P4	0,85 ± 0,05	0,77 ± 0,01	0,03

Source: compiled by the authors of this study

The data presented in Table 3 show that patients in the second group have a significant decrease in intracerebral coherence in pairs of frontal (Fp1-F3; Fp2-F4) of the left and right hemispheres of the brain in the delta-activity range and in pairs of temporal (T3-T5) leads of the left hemisphere of the brain in the delta- and theta- frequency ranges. In the beta- low and beta- high frequency ranges, a significant increase in intra-hemispheric coherence indices was recorded in pairs of central-parietal (C4-P4) leads of the right hemisphere of the brain. When comparing intra-hemispheric coherence indices in both groups of patients, no significant differences were recorded.

DISCUSSION

Analysis of intra-hemispheric coherence showed higher stability of functional connections in patients with single MBCCI, indicating partial preservation of integrative activity of local neural networks within each hemisphere. In patients with multiple MBCCI, on the contrary, multidirectional changes in intra-hemispheric coherence were recorded: a decrease in its indicators in the delta- and theta- ranges in the frontal and temporal regions of mainly the left hemisphere of the brain, as well as an increase in coherence in the beta- range in the central-parietal areas of the right hemisphere. This pattern of changes may indicate a disorder of regulatory mechanisms within the hemispheres, as well as an imbalance between excitatory and inhibitory neural networks – a probable consequence of the cumulative effect of repeated traumatic injuries [7]. Decreased coherence in the left hemisphere frontal-temporal areas correlates with cognitive-emotional resource depletion, executive function and attention disorders, while increased coherence in the right-hemispheric central-parietal areas may reflect compensatory processes aimed at preserving adaptive capabilities in the context of chronic psycho-emotional stress characteristic of combat conditions [9]. This combination of neurophysiological changes is associated with clinical manifestations of autonomic nervous system dysfunction, increased emotional tension, and symptoms of asthenia, indicating depletion of the brain's functional reserves and a decrease in the effectiveness of its regulatory mechanisms.

CONCLUSIONS

1. Military personnel with single and especially multiple MBCCI showed a significant decrease in inter-hemispheric and intra-hemispheric coherence, indicating a disorder in the integrative activity of the brain.
2. In both groups of military personnel, the most pronounced changes in interhemispheric coherence compared to healthy individuals were recorded in the delta-, theta-, alpha- and beta- frequency ranges, mainly in the frontal and parietal areas of the brain.
3. In cases of multiple traumatic brain injury, generalized dysfunction of interhemispheric interaction was detected in all studied frequency ranges, involving the central, occipital, and temporal areas, as well as an imbalance in intra-hemispheric coherence: with suppression of activity in the left hemisphere and compensatory hyperactivity in the right.
4. The obtained changes in coherence indicators correlate with clinical manifestations of neurological, emotional and cognitive disorders, reflecting varying degrees of depletion of functional reserves in the brains of military personnel with single and multiple MBCCI, and may form the basis for the development of pathogenetically sound, individualized neuro-rehabilitation programs.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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RECEIVED: 16.04.2025
ACCEPTED: 29.08.2025