Case Report

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Treating Severe Traumatic Brain Injury: Combining Neurofeedback and Hyperbaric Oxygen Therapy in a Single Case Study

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Abstract

In 2014, a 26-year-old male was involved in a motor vehicle accident resulting in a severe traumatic brain injury (TBI). The patient sustained a closed-head left temporal injury with coup contrecoup impact to the frontal region. The patient underwent a left side craniotomy and was comatose for 26 days. After gaining consciousness, he was discharged to a brain injury treatment center that worked with physical, speech, and occupational issues. He was discharged after eight months with significant speech, ambulation, spasticity, and cognitive issues as well as the onset of posttraumatic epilepsy. His parents sought hyperbaric oxygen treatment (HBOT) from a doctor in Louisiana. After 165 dives, the HBOT doctor recommended an addition of neurofeedback (NFB) therapy. In March 2019 the patient started NFB therapy intermixed with HBOT. The combination of NFB and HBOT improved plasticity and functionality in the areas of injury and the correlated symptoms including short-term memory, personality, language, and executive function, as well as significantly reducing the incidence of seizures. Severe brain injuries often leave lasting deficits with little hope for major recovery and there is a need for further research into long-term, effective neurological treatments for severe brain injuries. These results suggest that HBOT combined with NFB may be a viable option in treating severe brain injuries and should be investigated.

Keywords

neurofeedback, hyperbaric oxygen therapy, HBOT, TBI, posttraumatic epilepsy, EEG

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Introduction

Traumatic brain injuries (TBIs) affect around 1.7 million people in the United States every year and can greatly affect one's quality of life.[1] Depending on the severity and location of the injury, symptomatology can include cognitive dysfunction, diminished physical functioning, emotional and mood issues, and sleep dysfunction.[2] Despite vast research on traumatic brain injuries, there is a need for further research on clinically effective neurological treatments.

Temporal lobe injury, one of the most common TBIs, can result in temporal dysfunction, including disruption of cognitive skills, memory deficits and language dysfunction.[3,4] Injury to the left temporal lobe impairs verbal memory, leading to further language deficits.[5] Damage to either Broca's or Wernicke's areas of the temporal lobe can result in impairments of speech production and understanding of language respectively.[6] Injury to the temporal lobe can also result in posttraumatic epilepsy. Posttraumatic epilepsy (PTE), a common short and long-term consequence of TBIs, is the development of seizures, secondary to a traumatic brain injury through the mechanism of epileptogenesis, and can be indicated through epileptiform spike activity on a qEEG.[7,8] This type of seizure activity often does not subside with the use of anticonvulsants and other medications, with 30% of those with epilepsy being refractory on these medications.[9] Furthermore, over 50% of those affected by a severe TBI develop posttraumatic epilepsy, with TBI's accounting for 4% of epilepsy cases. Further research on an effective intervention is vital.[10]

Although minimal, the current effective neurological interventions to treat TBIs take an indirect or compensatory approach, focusing primarily on addressing and improving symptoms that compensate for deficits.[3] These indirect approaches typically include a combination of individual and family psychotherapy, speech or physical therapy, pharmacotherapy, and psychiatric medications like selective-serotonin reuptake inhibitors (SSRIs), stimulants, and cholinergic

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augmentation medications.[3,11] While compensatory approaches help improve the quality of life in patients diagnosed with TBI, there is a vital need for more research on direct neurological treatments. Neurofeedback (NFB) and hyperbaric oxygen therapy (HBOT) have been promising in directly treating the neurological and physiological aspects of TBI.

NFB is a form of biofeedback that operates on the principle of operant conditioning, using EEG and quantitative electroencephalography (qEEG) brain mapping techniques to view abnormalities in brain waves to create NFB protocols that subsequently improve cognitive functioning.[12] Using visual and/or auditory stimuli, NFB provides real-time feedback that alerts the brain when dysregulated brain waves are detected, thus guiding the brain to a healthy EEG signal.[13,14] Typically, a positive change in psychiatric symptoms (ie, anxiety, depression, attentional deficits) is reached after 5 to 60 sessions, involving two sessions per week to optimize treatment effects.[12] However, TBIs are extremely diverse in location and severity, and therefore the typical amount of sessions for symptom reduction vary greatly.

Neural plasticity is the basis of treating TBIs with NFB. The patient's improvements correlated with previous research in veteran TBI populations showed improvements in attention, short-term memory, and processing speed, with the implementation of NFB.[14] Because NFB increases plasticity in the brain, the damaged area is more likely to form and strengthen new connections, thus reducing symptoms and aiding in healing the injured area. NFB is also known to lower susceptibility and incidence of seizures in non-epileptic and epileptic patients. Training the sensory motor rhythm (12-15 Hz) leads to an increase in excitation thresholds of the sensory and motor circuits, resulting in a reduced susceptibility to seizures.[15] Furthermore, early research in epilepsy and NFB show that NFB has been an effective modality in treating refractory epilepsy, resulting in a promising approach to treating posttraumatic epilepsy following a TBI.[16]

HBOT is a treatment in which a patient is exposed to 100% oxygen at a higher atmospheric pressure than sea level and at fluctuating levels over multiple sessions.[17] HBOT is known for its neuroprotective effects, specifically allowing collateral circulation through the growth of new blood vessels to provide oxygen to affected areas of the body.[18] This mechanism results in increased oxygenation improving mitochondrial metabolism and tissue oxygenation, increasing cerebral blood flow and cellular survival, helping immune cells fight off bacteria, and reducing overall patient mortality.[17] HBOT has also been found to significantly reduce neuroinflammation and correlating symptoms in rodent models of TBI cases.[19] In TBI patients, HBOT has been found to reduce intracranial pressure, brain swelling, and lesion volume, in turn speeding up the recovery process and addressing symptoms such as fatigue, restlessness, disorientation, and impaired attention.[17,18] Recent animal models have assessed the use of long-term HBOT to treat TBIs in rats and show induced and increased remyelination of axons in the injured brain area.[20] HBOT stimulates oxygenation and remyelination, thus leading to neurogenesis in injured areas of the brain, exhibiting a promising mechanism in treating TBI.

Traumatic brain injuries are a prominent issue that require further research to find effective neurological treatments. NFB and HBOT have shown promising results in treating TBIs and subsequent symptoms. Because TBIs vary in severity and location, research is needed for specific and individualized treatments assessing both short-term and long-term functioning. The case study at hand assesses the use of long-term NFB and HBOT to treat a left temporal TBI both neurologically and functionally.

Case Presentation

At age 26, the male patient, was involved in a motor vehicle accident (MVA) with an 18-wheeler, which resulted in a closed left temporal TBI. The patient had numerous injuries including a crushed eye socket, broken ribs, fractured vertebrae (2 thoracic cracks and L2 burst), a fractured left femur, and loss of the left eyelid that led to a corneal rupture resulting in vision loss. Upon entry to this hospital, the patient had a left side craniotomy with a drainage tube inserted to relieve swelling in the brain. The patient was comatose for 26 days and moved to TIRR Memorial, a rehabilitation facility, upon regaining consciousness. The patient displayed extreme motor deficits, including inability to move the right arm and legs. Due to the location of the initial injury, the patient developed Broca's aphasia, resulting in severe speech deficits that are still persisting. The injury led to many cognitive deficits as well, including short-term memory loss, executive dysfunction, and affect issues. Two months following the injury, the patient began physical therapy (PT), occupational therapy (OT), and speech therapy (ST). The patient had his first seizure three months post-injury (complex-partial seizure) and the seizures persisted, occurring in a group of 2 seizures about every 6 weeks (see Figure 1). The patient was prescribed lamotrigine, an anticonvulsant, to help treat the posttraumatic seizures. The gains being made did not justify continuing treatment through TIRR Memorial Herman and he was discharged. The indirect treatments (ST, PT, OT, and medication) were not producing the desired outcomes, thus alternative treatment options were explored. Although there were diminishing returns with the original indirect treatments, the patient continued as a way to validate improvements with NFB and HBOT.

Three and a half years following the injury, the patient began HBOT following a single-photon emission computed tomography (SPECT) scan. The patient completed 205 dives, or HBOT sessions, before beginning NFB training. The patient had his initial qEEG almost 5 years after the injury and began NFB to treat cognitive deficits and seizure activity. The patient has completed 430 HBOT dives and 238 NFB sessions and is still continuing both treatments. Speech therapy was continued to see if progress was being made still with HBOT and NFB.

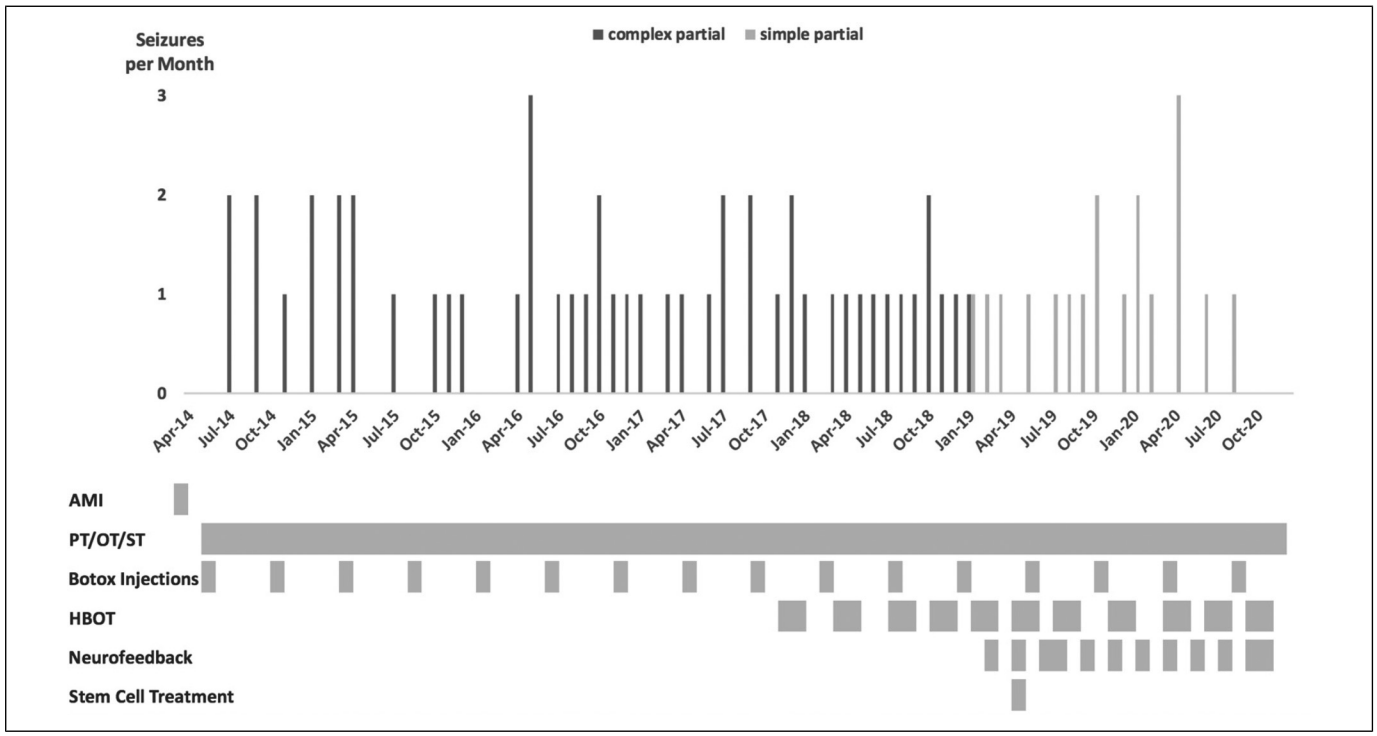

Figure 1. Timeline of treatments and seizure activity following TBI.

EEG and SPECT Presentation

The patient's initial EEG and qEEG brain maps revealed multiple abnormalities consistent with TBI. Spike activity was found in the left hemisphere, primarily in the temporal areas (T5 and T3) that coincide with the area of injury, signifying posttraumatic seizure activity. Sharp and slow wave activity was seen in the left hemisphere, mainly in the parietal areas, that occurred in conjunction with mild diffuse slowing (see Figure 2). The background alpha range was seen at 6 to 10 Hz with a peak in the posterior areas at 7 to 8 Hz. The left hemisphere spikes, diffuse slow activity, and slowing of background alpha, indicate the possibility of diffuse encephalopathy. The theta/beta ratio was abnormally high with atypical distribution throughout the brain. Mu rhythm was noted in the left midline area at 8 to 9 Hz and was disproportionate with frontal mirror neuron disturbances.

The patient's initial SPECT scan showed significantly diminished perfusion throughout much of the left hemisphere, especially temporal and parietal areas around the area of injury. There was also diminished perfusion in the frontal region, with the left hemisphere more severe than the right (see Figure 3).

Method of Intervention

Hyperbaric Oxygen Therapy

The patient began HBOT 3 years post-injury, with the initial 40 dives, at 45 min in length, in a hard chamber at 1.15 atmospheric levels (atm). Brain activity was continuously monitored through EEG to monitor O2 levels and pressure. The patient used a home chamber for his remaining dives and adjusted the protocol to 1.3 atm and 10 liters per minute (Lpm) with a 50% diluter so that the patient received 50% oxygen. Each round consisted of 40 dives that were each 45 min in length, 5 days per week. N.T. was reevaluated using SPECT imaging 5 years and 5 months post-injury, after 245 dives. The protocol was kept at 1.3 atm and 10 Lpm, but decreased to a 35% diluter so that the patient received 65% oxygen. The patient has completed a total of 430 dives and currently continues HBOT.

Neurofeedback

The patient began NFB following his initial qEEG, about 5 years post-injury, and after 165 HBOT sessions. Mitsar EEG equipment was combined with both DeyMed Truscan NFB software and BetterFly Home NFB training software with Genius hardware. Written consent was obtained from the patient and his parents to use archived and current data for the case study. The protocols were guided by qEEG data, EEG data, and clinical presentation in order to treat cognitive deficits and posttraumatic seizure activity and were adjusted upon changes in data and presentation (see Figure 4). Each round consisted of 40 sessions at 35 min in length 3 times per week. The patient completed 30 sessions using the BetterFly Home NRB Training software and the rest of the sessions were completed in clinic using the DeyMed TruScan NFB software. The patient has completed a total of 238 sessions and currently continues NFB training. The data from this case presentation was from an IRB approved data archive.

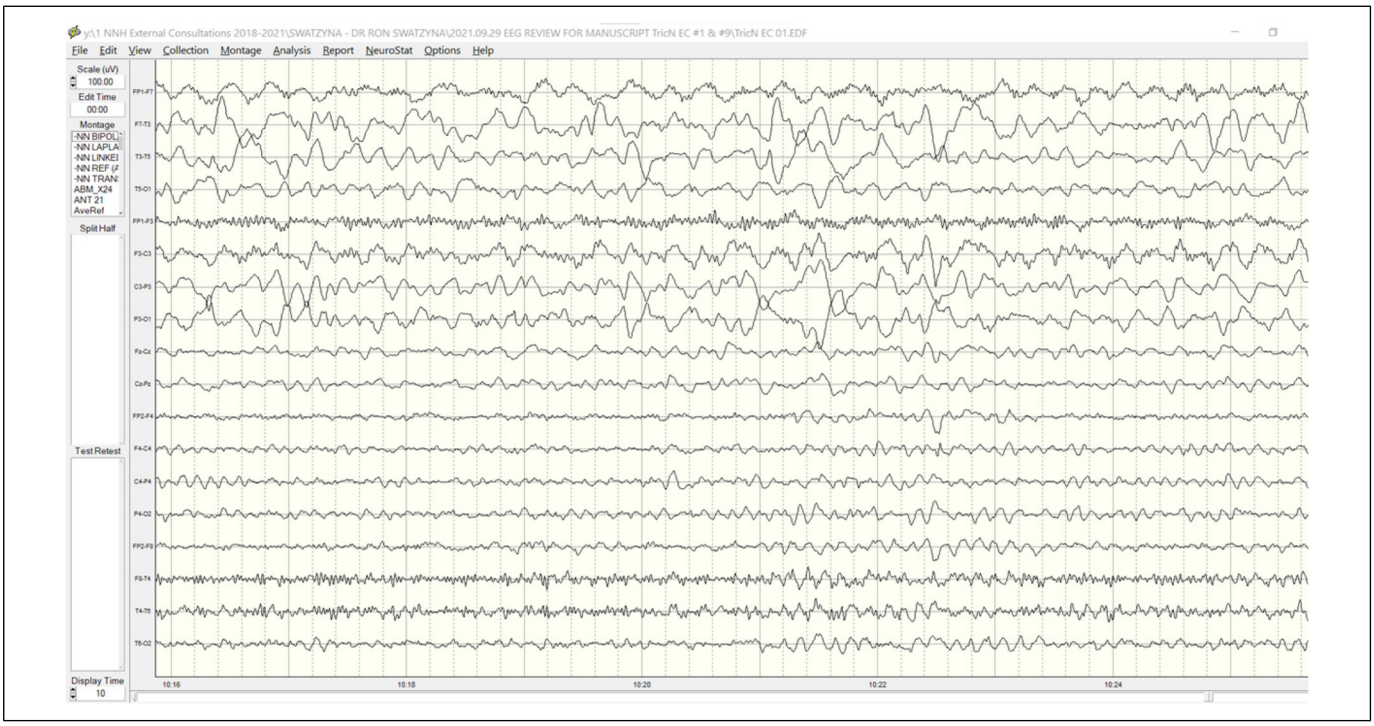

Figure 2. Sharp and slow activity pre-NFB- frequent 50 to 150 uV left temporal and parietal sharp/spike waves; markedly asymmetric background, increased slowing and absence of PDR over the left posterior regions.

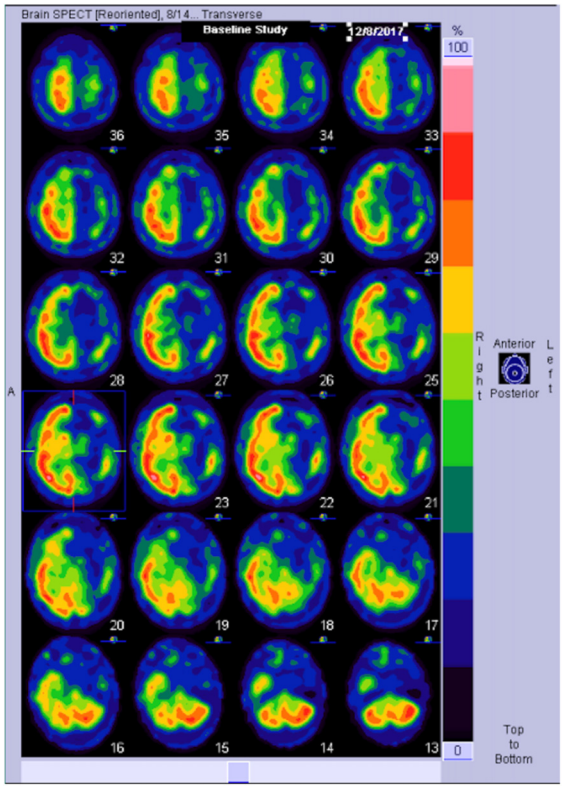

Figure 3. Pre-HBOT SPECT scans showing significantly diminished perfusion.

Questionnaires and Symptomatology

Given the current case, an in-depth screening questionnaire was needed in order to assess symptomatology and pathology of the injury at hand. We used a 300-item screening questionnaire, the Comprehensive Neurodiagnostic Checklist, (CNC1020; EEG Professionals, The Netherlands) to assess various psychological aspects and changes in symptoms. The patient completed the CNC questionnaire with the help of his parents and their subjective observations. Given this, there is a potential response bias that must be acknowledged due to the subjective nature of this assessment. This psychometric assessment was the best fit to assess aspects of the patient's TBI. Data from the initial CNC questionnaire and the most recent one was utilized to assess changes in symptomatology and cognitive functioning. Each

Neurofeedback Protocols	
Active Electrode	**Reference Electrode**
T5	Cz
P3	Cz
C4	Pz
T6	Cz
Cz	A1/A2

Figure 4. Neurofeedback protocols.

symptom area was made up of multiple questions about functioning and compiled to give a percent score for each symptom area. The percent score indicates the level of dysfunction reported in the symptom area.

In order to objectively measure changes in language and communication, the patient was evaluated using the Scales of Cognitive and Communicative Ability for Neurorehabilitation (SCCAN). SCCAN is a norm-referenced measure of cognitive and communicative abilities for individuals between the ages of 18 and 95 with suspected or known neuropathology. It is comprised of eight scales that measure cognitive areas including language processing and general cognitive abilities. This measure yields a total percentile rank, SCCAN index, and degree of severity. The SCCAN index provides a standardized score with a mean of 200, and scores between 85 and 100 are considered within an average range. SCCAN evaluates oral expression, orientation, memory, speech comprehension, reading comprehension, writing, attention, and problem solving. This evaluation was completed by the patient's speech pathologist on 09/11/2018, before any treatments, and 10/28/2021 after HBOT and NFB, approximately 3 years apart.

Data Analysis

SPECT scans were used to evaluate the degree of improvement following the implementation of 245 HBOT dives. Pre- and post-NFB qEEG data was used to evaluate the degree of success in the treatment of TBI with HBOT and NFB after 238 sessions of NFB and 410 HBOT dives. Abnormalities in the EEG were signified by *P*-values less than .05. The degree of improvement in EEG scores was measured by change in *P*-value, with increasing or larger non-significant (>.05) *P*-values indicating improvement. Self-report CNC data was used to evaluate the degree of change in symptomatology and presentation.

Results

Following 238 rounds of NFB, the patient's alpha range increased to 6.5 to 11 Hz with a peak at 8.3 Hz. Sharp and slow wave activity was still detected at T5 and P3 (injury sites), but no spike activity was detected (see Figure 5).

We saw the largest change (increase) in *P*-value at locations F8, F3, F7, P3, Fz, and T5, and in the frequency bands of theta: 5 to 6 Hz, alpha: 10 to 11 Hz and 11 to 12 Hz, beta: 21 to 25 Hz and 25 to 29 Hz, and gamma: 33 to 37 Hz (see Figure 6).

CNC and SCCAN

Self-report CNC data was used to assess changes in symptomology. The areas with the largest degree of change were somatosensory perception (Cz & Pz), language and reading perception (T5, P3, Pz, O1, O2), language and reading comprehension (T5, P3, Pz, O1, O2), executive cognitive dysfunction (F7, Fp1, Fp2, F8), ADD distractibility (F7, Fp1, Fp2, F8), hypoactivity (F3, F7, F4), fine and gross motor functioning (F3, F7, F4), and visual, spatial, and facial memory dysfunction (P4 &

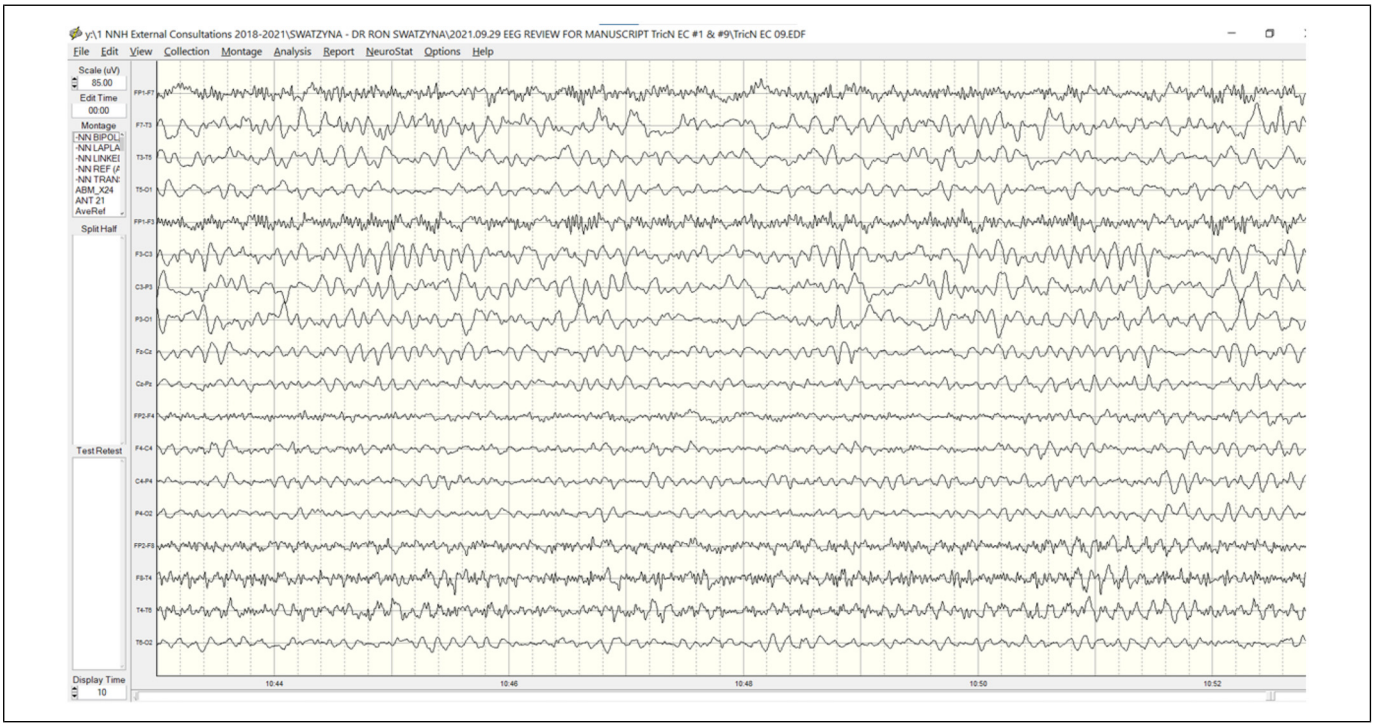

Figure 5. Post-NFB EEG activity showing significantly less left hemisphere slowing.

freq band		location																											
		Fp1		Fp2		F7		F3		Fz		F8		T3		C3		Cz		C4		T4		T5		P3		O1	
		pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post
theta	4-5 Hz					0	0.149	0	0.767													0	0.222						
	5-6 Hz					0.002	0.123									0	0.216									0.005	0.213		
	6-7 Hz					0	0.189																						
alpha	7-8 Hz									0	0.11																		
	8-9 Hz																												
	9-10 Hz																												
	10-11 Hz					0.004	0.715	0.009	0.12			0.002	0.592					0.006	0.922	0.005	0.161			0.002	0.892	0.004	0.364	0.009	0.489
	11-12 Hz			0.009	0.305							0.006	0.104	0.003	0.532									0	0.261	0.007	0.366		
beta	12-17 Hz					0.002	0.353																						
	17-21 Hz					0	0.117	0.003	0.188			0	0.364																
	21-25 Hz			0.007	0.46			0	0.645			0.001	0.548													0	0.099		
	25-29 Hz							0.001	0.863			0.003	0.819																
	29-33 Hz											0.001	0.525																
gamma	33-37 Hz									0.003	0.15	0	0.49													0	0.202		
	37-41 Hz	0	0.237									0	0.729	0	0.513														

Figure 6. Major improvements signified by pre- and post-NFB p-values derived from EEG data.

T6) (see Figure 7). Improvements were seen in the 10/20 areas correlating with improvement in these symptoms: T5, P3, O1, F7, Fp1, Fp2, F8, and F3.

SCCAN data was used as an objective measure of cognitive functioning, both before and after NFB and HBOT. The initial evaluation resulted in a total raw score of 30/94, signifying severe impairments in cognitive functioning (see Figure 8A). The most recent SCCAN evaluation resulted in a raw score of 49/94, signifying moderate impairment (see Figure 8B). The patient's score improved in the areas of oral expression, orientation, memory, speech comprehension, reading comprehension, attention, and problem solving (see Figure 8C).

Eyes Open Power spectra Deviations from Normality

Improvements were noted in the theta frequency: 4 to 5 Hz range at T4 (pre: $P = .000$, post: $P = .222$) and in the 5 to 6 Hz range at C3 (pre: $P = .007$, post: $P = .223$). Major improvements were noted in the fast alpha frequency: 10 to 11 Hz range at F7 (pre: $P = .004$, post: $P = .719$), F3 (pre: $P = .009$, post: $P = .129$), F8 (pre: $P = .002$, post: $P = .594$), Cz (pre: $P = .006$, post: $P = .928$), T5 (pre: $P = .009$, post: $P = .901$), and O1 (pre: $P = .009$, post: $P = .498$) and in the 11 to 12 Hz range at Fp2 (pre: $P = .009$, post: $P = .314$), F8 (pre: $P = .006$, post: $P = .110$), T5 (pre: $P = .000$, post: $P = .261$), and P3 (pre: $P = .007$, post: $P = .373$) (see Figure 9A and B).

Eyes Closed Relative Normalized Power spectra

Improvements were found in the alpha range: 7 to 8 Hz at Fz (pre: $P = .007$, post: $P = .117$) and in the 10 to 11 Hz range at C4 (pre: .005, post: $P = .167$), T5 (pre: $P = .002$, post: $P = .512$), and P3 (pre: $P = .004$, post: $P = .368$). Improvements were found in the beta range: 17 to 21 Hz at Fp1 (pre: $P = .002$, post: $P = .119$) and in the 21 to 25 Hz range at P3 (pre: $P = .003$, post: $P = .102$). Additional improvements were found in the gamma range: 33 to 37 Hz at P3 (pre: .006, post: $P = .208$) (see Figure 10A and B).

CNC Symptom Areas	Pre-NFB	Post-NFB	10/20 locations
Somatosensory perception	87%	50%	Cz, Pz
Language & Reading Perception	100%	87%	T5, P3, Pz, O1, O2
Language & Spelling Perception	100%	100%	T5, P3, Pz, O1, O2
Language & Reading	100%	92%	T5, P3, Pz, O1, O2
Language & Reading Comprehension	95%	88%	T5, P3, Pz, O1, O2
Executive Cognitive Dysfunction	100%	79%	F7, Fp1, Fp2, F8
ADD distractibility	88%	73%	F7, Fp1, Fp2, F8
Language & Speaking Dysphasia	100%	96%	F7, Fp1, F3
Language & Writing Dysgraphia	100%	100%	F7, Fp1, F3
Hypoactivity	94%	52%	F3, F7, F4
Fine Motor Dysfunction	100%	69%	F3, F7, F4
Gross Motor Dysfunction	73%	52%	F3, F7, F4
Neurosensory Integration Disorder	100%	91%	T5, P3, Pz, P4, T6
Memory Dysfunction: Auditory, language, & Listening	100%	94%	T5, P3
Memory Dysfunction: Visual, Language, & Reading	100%	97%	T5, P3
Memory Dysfunction: Visual, Spatial, & Facial	76%	54%	P4, T6

Figure 7. Pre- and post-NFB/HBOT CNC questionnaire.

(A)

Total Raw Score	Percentile Rank	SCCAN Index	Degree of Severity
30/94	<1	50	Severe Impairment

(B)

Total Raw Score	Percentile Rank	SCCAN Index	Degree of Severity
49/94	<1	50	Moderate Impairment

(C)

Scale	Pre- Raw Score	Post Raw Score	Pre- Percentage Score (%)	Post- Percentage Score (%)	Percentage Difference
Oral Expression	6	8	32	42	+10
Orientation	6	9	50	75	+25
Memory	4	7	21	37	+16
Speech Comprehension	3	8	23	62	+39
Reading Comprehension	2	6	17	50	+33
Writing	3	3	43	43	-
Attention	3	4	19	25	+6
Problem Solving	7	9	30	39	+9

Figure 8. (A) Pre-NFB/HBOT SCCAN evaluation performed on 09/11/2018. (B) Post-NFB/HBOT SCCAN evaluation performed on 10/28/2021. (C) Pre- and Post-NFB/HBOT SCCAN raw data.

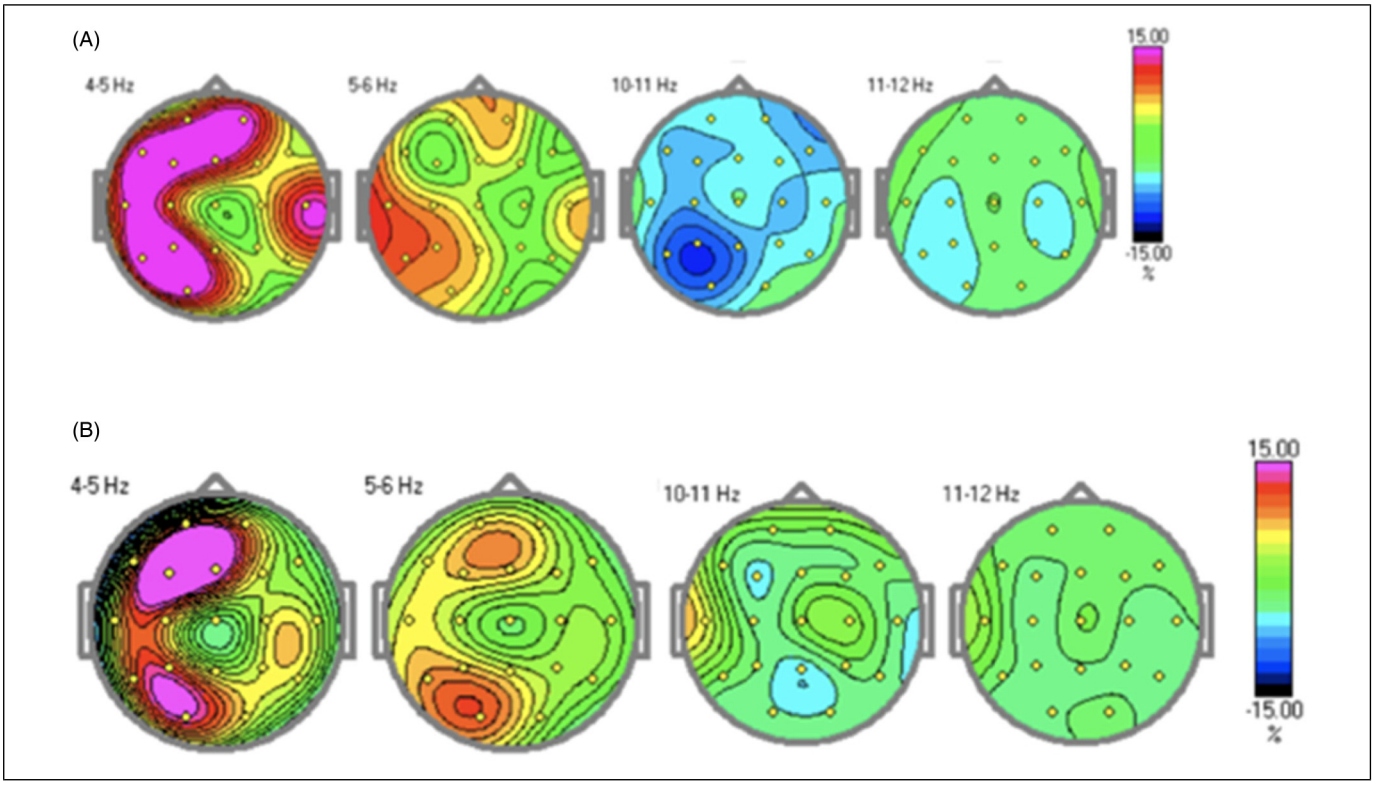

Figure 9. (A) Eyes open power spectra deviations from normality (pre-NFB). (B) Eyes open power spectra deviations from normality (post-NFB).

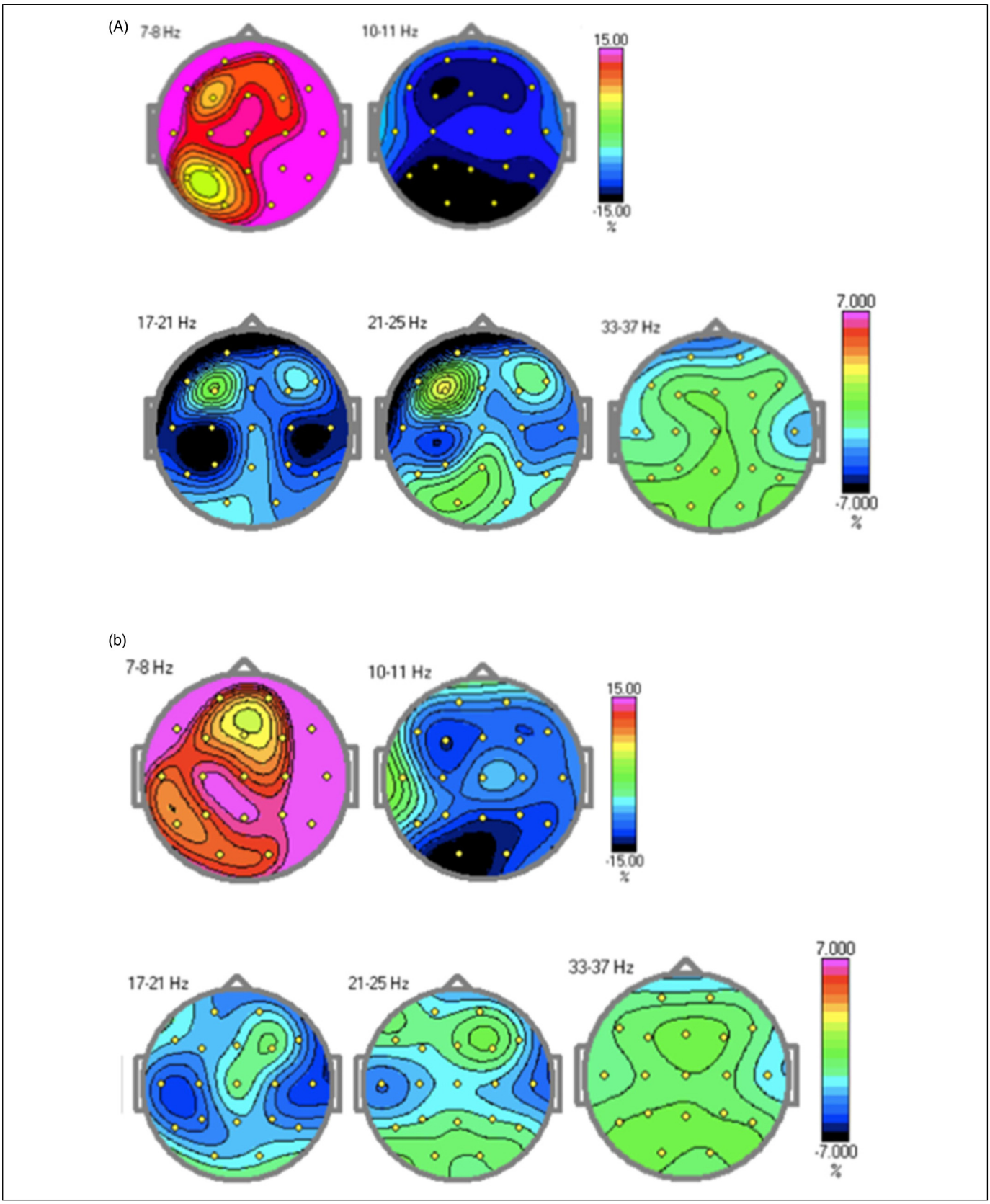

Figure 10. (A) Eyes closed relative normalized power spectra (pre-NFB). (B) Eyes closed relative normalized power spectra (post-NFB).

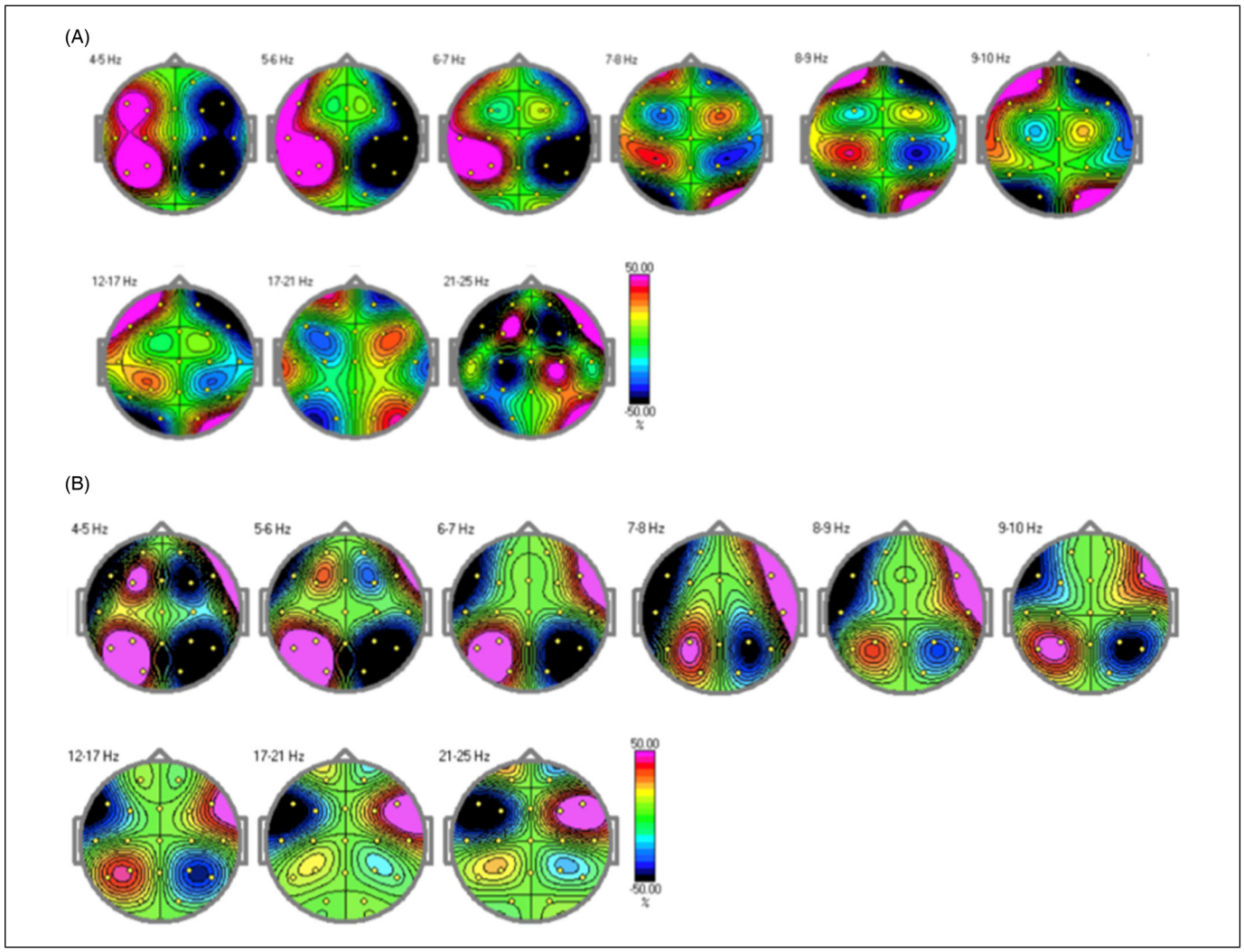

Figure 11. (A) Eyes open comparison of asymmetry power spectra (pre-NFB). (B) Eyes open comparison of asymmetry power spectra (post-NFB).

Eyes Open Comparison of Asymmetry Power spectra

Improvements were noted in the theta range: 4 to 5 Hz range at T4/T3 (pre: $P = .007$, post: $P = .299$), in the 5 to 6 Hz range at C4/C3 (pre: $P = .000$, post: $P = .374$) and T4/T3 (pre: $P = .000$, post: $P = .691$), and in the 6 to 7 Hz range at C4/C3 (pre: $P = .003$, post: $P = .457$). Improvements were also found in the alpha range: 7 to 8 Hz at F4/F3 (pre: $P = .006$, post: $P = .251$), in the 8 to 9 Hz range at O2/O1 (pre: $P = .000$, post: $P = .136$), and in the 9 to 10 Hz range at Fp1/Fp2 (pre: $P = .002$, post: $P = .526$). Additional improvements were found in the beta range: 12 to 17 Hz at O2/O1 (pre: $P = .000$, post: $P = .236$), in the 17 to 21 Hz range at O2/O1 (pre: $P = .009$, post: $P = .797$), and in the 21 to 25 Hz range at C4/C3 (pre: $P = .002$, post: $P = .354$) and T6/T5 (pre: $P = .008$, post: $P = .442$) (see Figure 11A and B).

Eyes Closed Comparison of Asymmetry Power spectra

Improvements were found in the theta range: 4 to 5 Hz at C4/C3 (pre: $P = .000$, post: $P = .137$) and in the 5 to 6 Hz range at C4/C3 (pre: $P = .001$, post: $P = .652$). Improvements were found in the alpha range: 7 to 8 Hz at O2/O1 (pre: $P = .000$, post: $P = .269$), in the 8 to 9 Hz range at F4/F3 (pre: $P = .008$, post: $P = .130$), in the 9 to 10 Hz range at C4/C3 (pre: $P = .009$, post: $P = .374$), in the 10 to 11 Hz range at O2/O1 (pre: $P = .000$, post: $P = .115$), and in the 11 to 12 Hz range at O2/O1 (pre: $P = .004$, post: $P = .929$). Additionally, improvements were found in the beta range: 12 to 17 Hz at O2/O1 (pre: $P = .000$, post: $P = .304$), in the 21 to 25 Hz range at F4/F3 (pre: $P = .000$, post: $P = .128$), and in the 25 to 29 Hz range at F4/F3 (pre: $P = .000$, post: $P = .446$). Improvements were also found in the gamma range: 29 to 33 Hz at F8/F7 (pre: $P = .002$, post: $P = .238$), in the 33 to 37 Hz range (pre: $P = .000$, post: $P = .277$), and in the 37 to 41 Hz range (pre: $P = .000$, post: $P = .332$) (see Figure 12A and B).

SPECT

Following HBOT and NFB, SPECT scans showed significantly increased perfusion compared to the initial SPECT scans.

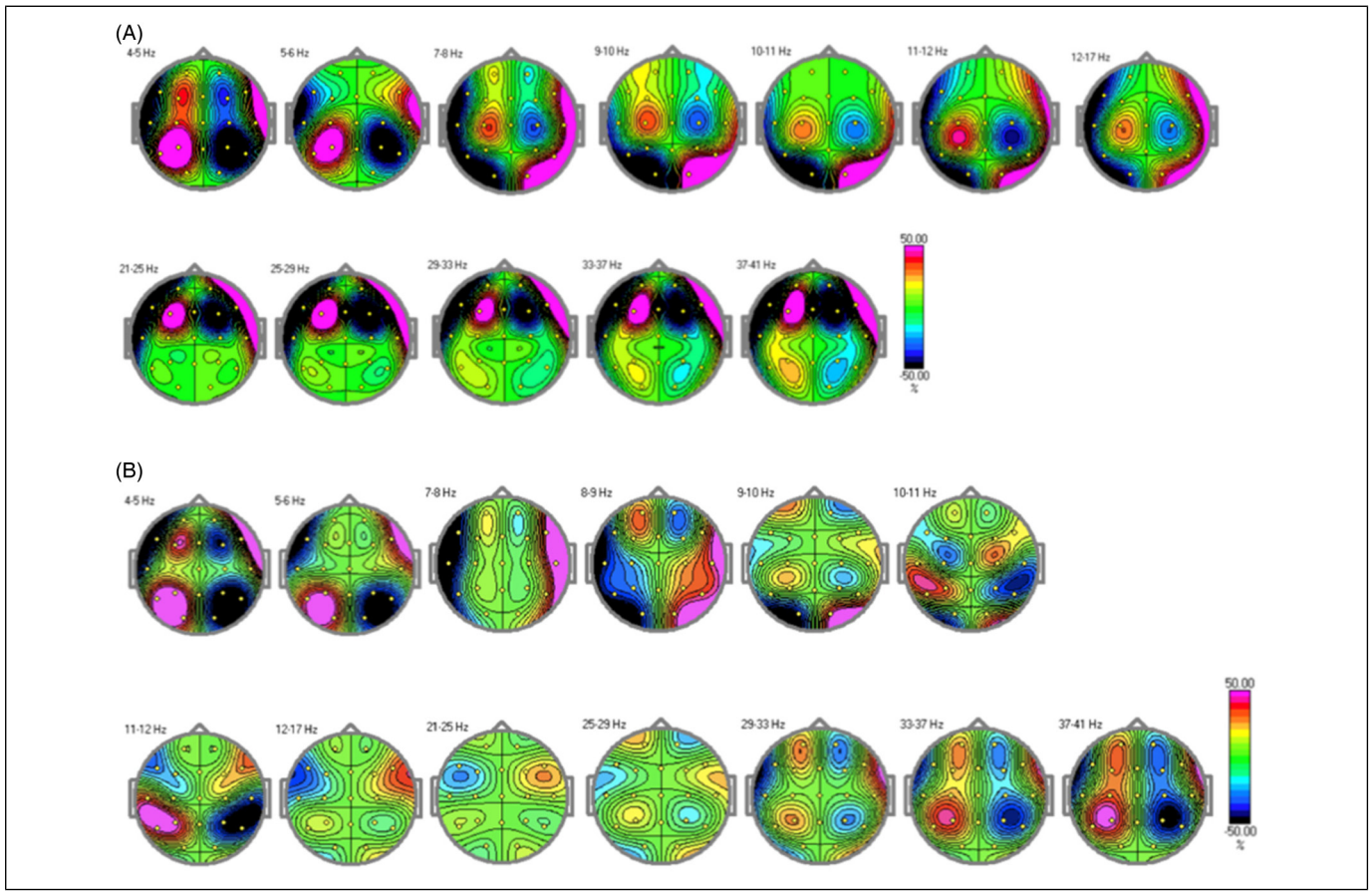

Figure 12. (A) Eyes closed comparison of asymmetry power spectra (pre-NFB). (B) Eyes closed comparison of asymmetry power spectra (post-NFB).

Perfusion increased significantly in the left hemisphere, especially in the more lateral areas of the cortex. There was still moderately diminished perfusion in the left midline parietal and temporal areas, around the area of injury. Overall, perfusion in the overall cortex increased significantly, however there is diminished perfusion in the areas of the brain where the initial TBI occurred (see Figure 13).

Discussion

The results indicate that, with the implementation of NFB training, there were major improvements in F8, F3, F7, Fz (frontal lobe), P3 (left parietal lobe), and T5 (left temporal lobe). Both T5 and P3 are located at the main site of the patient's injury, showing that neurofeedback did contribute to functional improvements and rewiring at the site of injury. The frontal lobe improvements, primarily F8, were at the site of the coup contrecoup injury. These frontal lobe changes also indicate improvements at the injury site and overall functioning with NFB. There were improvements in the frequency bands of theta, alpha, beta, and gamma with the largest amount of improvements being seen in the alpha and beta ranges. The improvements in the electrical activity in the brain correlate with improvements in seizure activity and symptomatology, primarily improvements with memory, language dysfunction, and executive dysfunction.

The patient initially had sharp and slow activity with the presence of epileptiform spikes that coincided with complex partial seizures. The patient was prescribed lamotrigine which lowered the severity and incidence of the seizures, but did not remove them entirely. Following 238 rounds of NFB, epileptiform spike activity was not detected. Throughout the course of NFB, the seizures improved from complex partial to simple partial and decreased in frequency. Prior research has shown, by training the SMR frequency (12-15 Hz), NFB can result in a reduction in the rate of seizures as well as spikes and sharp and slow activity recorded by the EEG.[16] Furthermore, Sterman's early research shows that the SMR frequency has a functional relationship to the thalamo-cortical inhibitory networks, suppressing both motor behavior and drug-induced convulsions in cats.[21] Therefore, training the SMR rhythm can contribute to increased inhibitory discharges and subsequently, reduced seizure activity. Consistent with our findings, prior research has shown that NFB has greatly improved severity and frequency of seizures and lowered spike activity in patients with TBI and seizure activity.[15]

Prior research has revealed that Broca's aphasia is the result of injury to both Broca's and Wernicke's area, due to the

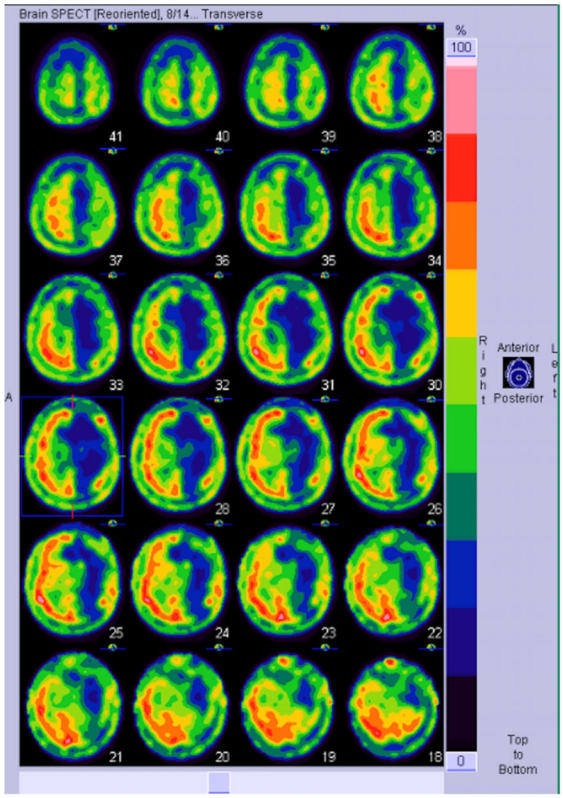

Figure 13. Post-HBOT SPECT scan showing moderately increased perfusion.

subsequent lack of information flow through a large bundle of nerve fibers known as the arcuate fasciculus.[22] More recent studies demonstrate that by directly targeting Wernicke's area in NFB training, connections between the temporal and frontal lobe in the left hemisphere are strengthened. Subsequently, researchers found that upregulation or training of Wernicke's area aided the processing of expression of speech in Broca's area, leading to increased production of meaningful language.[23] The patient developed Broca's aphasia due to the primary insult to Wernicke's area and coup contrecoup impact to Broca's area, subsequently damaging the connection between the two. Training at T5 (Wernicke's area) was utilized to address language dysfunction (Broca's aphasia). Therefore, in order to target Broca's aphasia and the damage to Wernicke's area, Wernicke's area and the arcuate fasciculus were targeted in treatment. By training Wernicke's area, we were able to make improvements in abnormalities related to the Broca's aphasia. Specifically, fast alpha (10-12 Hz) activity increased at T5, which relates to verbal memory. Additionally, beta activity increased at P3, one of the primary injury sites that is implicated in Broca's aphasia, and at F7 (Broca's area). Increased beta production in these areas correlates to improved semantics and syntax, as well as normal speech production.[24] By improving circulation to damaged brain areas with the use of HBOT and followed by neurofeedback to influence brain connectivity and neural plasticity, there was a reduction in symptoms related to speech dysfunction and a large improvement in the patient's articulation abilities. These improvements were reflected in both the CNC questionnaire and the SCCAN evaluation.

Improvements were seen in the patient's short-term memory abilities, and the EEG results reflect this finding. In addition to the injury sites (T5 and P3), improvements were seen at Fz, F3, and Fp1. By using neurofeedback training at the hippocampal and frontal areas of the brain, the patient's short-term memory improved significantly. The patient's SCCAN evaluation also showed significant improvement in memory. Prior research shows the efficacy of NFB for short-term memory dysfunction following a traumatic brain injury, showing hope for further treatment options.[25]

Improvements in the frontal areas and the injury site (T5 and P3) were noted in the gamma range. Prior research shows that following a TBI, gamma waves tend to be abnormally elevated and asynchronous.[26,27] Elevation in gamma waves contributes to symptoms such as poor cognitive function and executive dysfunction, consistent with TBI symptoms.[26] Prior to NFB, the patient displayed abnormal gamma asymmetry as well as asynchrony, with elevated gamma in the left frontal midline area and right lateral frontal area. Results from the SCCAN evaluation reflected this, with improvements in attention and problem solving. Consistent with findings in the literature, neurofeedback improved gamma asymmetry and normalization, with improvements in related symptoms such as cognitive functioning.[26,27] There is a dearth of research on TBI and gamma waves, and these findings, as well as further research, could be promising in the treatment of TBI.

A limitation to the findings of the present case study is the loss of vision in one eye as a result of corneal rupture. The EEG equipment used is intended to assess electrical signals from brains with two streams of visual data, so it could be hypothesized that eyes closed EGG data would show more improvements. When evaluating the EEG data, we saw greater improvements in the eyes open portion compared to the eyes closed portion, contrary to what was expected. There is evidence in the literature that correlates complete or partial vision loss with impaired synchrony in temporal neural firing patterns, specifically in the high-alpha frequency band (11-13 Hz).[28] Improvements were noted in both Fp2 and O1, the patient's working eye and visual field, that appear to compensate for the loss of vision in the left eye in eyes open EEG data. We also found improvements in the asymmetry of O2/O1, which indicates that NFB may help compensate for the partial loss of vision. A study by Bola et al[29] revealed that prolonged vision loss parallels sensory deprivation that can lead to indirect functional and anatomical consequences. By providing visual stimulation for the working eye, the increase in sensory information and processing through neurofeedback could help compensate for the loss of function in the right occipital cortex. However, EEG data is not enough to conclude this as a causal relationship, and much more research is needed in the field of NFB and vision loss.

Another limitation to this case study is that HBOT and SPECT raw data was not able to be fully attained and analyzed.

While it is clear that HBOT contributed greatly to neuronal regeneration and neurogenesis in the subject's brain, the pre- and post-HBOT SPECT scans and accessible reports were limited, and therefore we were unable to fully analyze the quantitative results of the HBOT treatment.

It can be concluded that NFB and HBOT improved overall functioning, increased plasticity, and resulted in healing of structural damage caused by the TBI. Both NFB and HBOT, both separate and combined, show promising results and more research is needed to further validate the use of both therapies in the treatment of TBI.

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Ethical Approval

Not applicable, because this article does not contain any studies with human or animal subjects.

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