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Case report

Spinal cord electrical stimulation for severe disturbance of consciousness after traumatic brain injury: A case report

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ABSTRACT

Background: Currently, the use of spinal cord electrical stimulations for patients with severe disorders of consciousness after traumatic brain injury remains limited, and long-term follow-up studies are even scarcer. To date, there have been few reports using near-infrared spectroscopy to evaluate the clinical effects and optimal parameters of spinal cord electrical stimulation for severe consciousness disorders. This report describes a case of a patient with severe disturbance of consciousness after traumatic brain injury who underwent spinal cord electrical stimulation implantation. Advanced near-infrared spectroscopy was employed to monitor and evaluate postoperative efficacy. The findings of this case report will provide a reference for the clinical treatment of severe consciousness disturbances.
Methods: A patient diagnosed with a severe disturbance of consciousness following traumatic brain injury presented symptoms of coma and lack of voluntary activity. The treatment regimen included conventional approaches (medication combined with rehabilitation training) and adjustments to the spinal cord electrical stimulation parameters. Advanced functional near-infrared spectroscopy (fNIRS) was used to explore changes in brain functional connectivity strength and assess clinical efficacy.
Results: The integration of conventional treatment and continuous modification of spinal cord electrical stimulation parameters, combined with fNIRS monitoring, demonstrated that conventional treatment and spinal cord electrical stimulation displayed a positive effect on increasing brain functional strength connection. The Glasgow Coma Scale(GCS) score significantly improved from the baseline. Optimal results were observed with spinal cord stimulation settings at 4.5 V amplitude, 210 μs pulse width, and 70 Hz frequency, operating from 8:00–20:00 in a cycling mode of 15 min on and 15 min off, where improvements in consciousness were markedly evident.
Conclusions: Patients with severe disturbances of consciousness after traumatic brain injury recover slowly. Conventional treatment combined with spinal cord electrical stimulation can improve the degree of disturbance of consciousness and promote recovery from the condition.

1. Introduction

Traumatic brain injuries (TBI) are injuries to the head. TBI has the highest mortality rate compared to other bodily injuries [1]. The development of the economy has led to more traffic accidents and falls. As a result, the incidence of traumatic brain injuries continues to rise annually [2]. Advances in surgical techniques have led to the successful rescue of an increasing number of TBI patients.

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However, this has also resulted in a growing number of patients suffering from post-traumatic consciousness disorders. Currently, the treatment of disturbances of consciousness after traumatic brain injury is limited, and the therapeutic effect is mainly evaluated by head computed tomography (CT), electroencephalogram (EEG), and their rating scales. Unfortunately, these methods often yield poor therapeutic outcomes and are considered outdated. There is a pressing need for more systematic treatment approaches and advanced evaluation methods.

There are few reports in the clinical literature on spinal cord electrical stimulation in the treatment of disorders of consciousness after traumatic brain injury. There is a paucity of studies on the effect of spinal cord electrical stimulation on awakening by adjusting different parameters. Consequently, this report introduces a case of a patient with severe disturbance of consciousness after traumatic brain injury who received conventional treatment combined with different spinal cord electrical stimulation parameters to improve brain function and promote awakening. The results of this study will provide a reference for the clinical treatment of severe disturbance of consciousness.

2. Case presentation

A 78-year-old man was admitted to the hospital with traumatic brain injury 5 months ago. He was found to have dilated pupils on both sides and was unconscious. Head CT indicated subarachnoid hemorrhage subdural hematoma with a concomitant skull fracture. The diagnosis was established as traumatic brain injury, cerebral hemorrhage, and disturbance of consciousness. The patient was healthy in the past, with no history of nervous system diseases, genetic diseases in the family, or mental illness before the onset of the disease, and no significant social history. Given the critical condition, the patient was transferred to the ICU. The patient was treated with cranial nerve nutrition, anti-infection, expectoration, fluid infusion, and nutritional support. 13 days after TBIonset, the patient's condition improved, and the spinal cord electrical stimulator was implanted successfully. The parameters of the spinal cord electrical stimulator were amplitude 1.50 V, pulse width 120 μs, frequency 5 Hz (running time: 8:00–20:00, cycle mode: start 15 min, turn off 15 min). The patient was transferred to our institution for further treatment four months ago. Physical examination after admission revealed: T: 36 °C, P: 65 beats/min, R: 17 beats/min, BP: 136/68 mmHg, height: 175 cm, weight: 70 kg. Bilateral pupils were equal and round, about 3 mm in diameter. Pupils are slow to reflect light. No ciliospinal reflex, no spontaneous movement of head and eyes. The patient showed signs of consciousness disturbance. Additionally, assessments of balance, coordination, and muscle strength could not be conducted. The modified Ashworth scale showed no spasticity. The Babinski sign was positive on the right side and negative on the left side. The patient was unable to maintain balance in the sit-to-stand position. The GCS score was $1 + T + 1$. The Activities of Daily Living (ADL) score, using the Barthel Index, was 0, indicating complete dependence in daily life. The improvement observed in the head CT examination suggested that there were changes in the bilateral frontal lobes after contusion and laceration. There was minimal hemorrhage in the bilateral lateral ventricles. The right parietal bone and occipital bone on both sides were fractured. The CT showed multiple ischemic lesions in the basal ganglia, thalamus, and pons in the white matter of both cerebral hemispheres accompanied by lacunae cerebral infarction. Some of these lesions represented senile-related brain changes. The diagnosis was established as brain trauma, disturbance of consciousness, and cerebral hemorrhage with multiple fractures. The NirSman (Danyang Huichuang, China), a 16-channel benchtop functional near-infrared spectroscopy (fNIRS) imaging device, was used for NIR acquisition. The acquisition cap follows the 10/20 international standard and includes six detectors and six light sources, which are separated by about 30 mm. The fNIRS has a sampling frequency of 11 Hz and a dual wavelength of 730 and 850 nm, which can detect the strength of brain functional connectivity in the prefrontal lobe of the subjects. The sampling location is illustrated in Fig. 1. The specific results suggest that the strength of brain functional connectivity was 0.131 (Fig. 2). Considering the patient's condition and GCS score, which

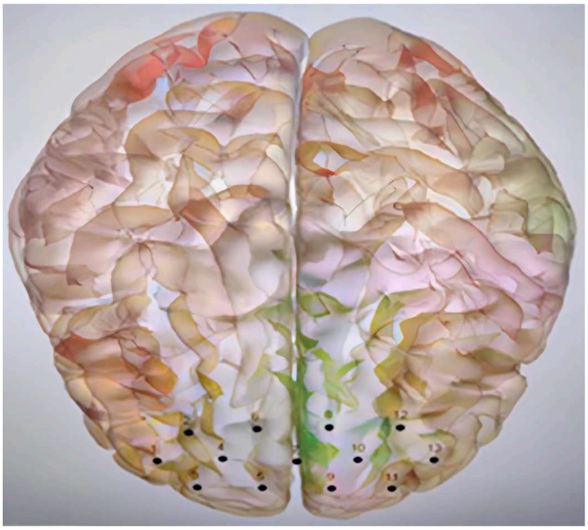

Fig. 1. ●Prefrontal network, PFN.

indicated a severe disturbance of consciousness and poor prognosis, the routine treatment plan was revised on the first day after admission (Table 1). It is considered necessary to adjust the parameters of spinal cord electrical stimulation based on conventional treatment and to combine this with near-infrared spectroscopy. This approach will evaluate changes in brain functional connectivity, thereby helping to assess the degree of consciousness recovery and treatment effectiveness. The details are as follows.

On the first day, the parameters of the spinal cord electrical stimulator were adjusted as follows: amplitude 1.50 V, pulse width 210 μs, frequency 6 Hz (running time: 8:00–20:00, cycling mode: 15 min on, 15 min off). The strength of brain functional connectivity was examined, as depicted in Fig. 3. After adjusting the pulse width of spinal cord electrical stimulation to 210 μs, the strength of brain functional connectivity remained low, which was higher than that at admission. It is believed that increasing the pulse width may have a beneficial effect on the recovery from consciousness disorders.

After 15 days, the parameters of the spinal cord electrical stimulator were adjusted as follows: amplitude 3.5 V, pulse width 210 μs, frequency 70 Hz (running time: 8:00–20:00, cycling mode: 15 min on, 15 min off). The strength of brain functional connectivity was evaluated, as manifested in Fig. 4. It can be concluded that after adjusting the amplitude and frequency, the strength of brain functional connectivity was slightly improved.

After 30 days, the parameters of the spinal cord electrical stimulator were adjusted as follows: amplitude 4.4 V, pulse width 230 μs, frequency 70 Hz (running time: 8:00–20:00, cycling mode: 15 min on, 15 min off). The strength of brain functional connectivity was checked, as depicted in Fig. 5. Considering the increase in amplitude and pulse width, the strength of brain functional connectivity was improved. The functional connectivity matrix in Fig. 5 shows localized changes in the left frontal lobe. The left frontal cortex is considered to play a vital role in maintaining and restoring consciousness because its extensive connection with other brain regions helps to coordinate the integration and processing of information. Studies have shown that the functional connection between the left frontal cortex and other brain regions (such as the parietal lobe, temporal lobe and posterior cingulate gyrus) plays a vital role in maintaining and restoring the state of consciousness. When spinal cord electrical stimulation promotes consciousness recovery, the left frontal cortex shows apparent changes in brain function.

After 45 days, the parameters of the spinal cord electrical stimulator were adjusted as follows: amplitude 2.0 V, pulse width 230 μs, frequency 6 Hz (running time: 8:00–20:00, cycling mode: 15 min on, 15 min off). The strength of brain functional connectivity was assessed, as presented in Fig. 6. The magnitude and frequency were decreased in response to a slight decline in brain function.

After 60 days, the parameters of the spinal cord electrical stimulator were adjusted as follows: amplitude 4.5 V, pulse width 210 μs, frequency 70 Hz (running time: 8:00–20:00, cycling mode: 15 min on, 15 min off). The strength of brain functional connectivity was evaluated, as demonstrated in Fig. 7. The reasoning could be that enhancing the amplitude and frequency significantly improves brain function.

From the above adjustment parameters, it can be concluded that the strength of brain functional connectivity is the highest under the parameters of amplitude 4.5 V, pulse width 210 μs, frequency 70 Hz (running time: 8:00–20:00, cycling mode: 15 min on, 15 min off), which is most conducive to consciousness recovery. Therefore, these parameters were maintained throughout the two months of subsequent treatment.

After two months of treatment, the patients were re-evaluated by physical examination. Physical examination showed T 36.5 °C, P 72 beats/min, R 18 beats/min, BP 124/84 mmHg. The pupils were bilateral, equal, and round, about 3 mm in diameter. Although the pupil is still slow to reflect light, its sensitivity to light reflection has improved since the first evaluation. With slight movement of the limbs. Movement is voluntary, not reflexive. Slight limb movements can be seen, but the amplitude is small. Babinski's sign was positive on the right and negative on the left. According to the modified Ashworth scale, there was no significant increase in muscle tone of the extremities. The patient could not maintain balance in the sit-to-stand position. The ADL score, using the Barthel Index, was 20. The improved items in the Barthel index are defecation and urination, both rising from 0 to 10 points, with 10 points being able to control defecation and urination. The GCS score was 4 + T + 3. According to the results of the physical examination, both

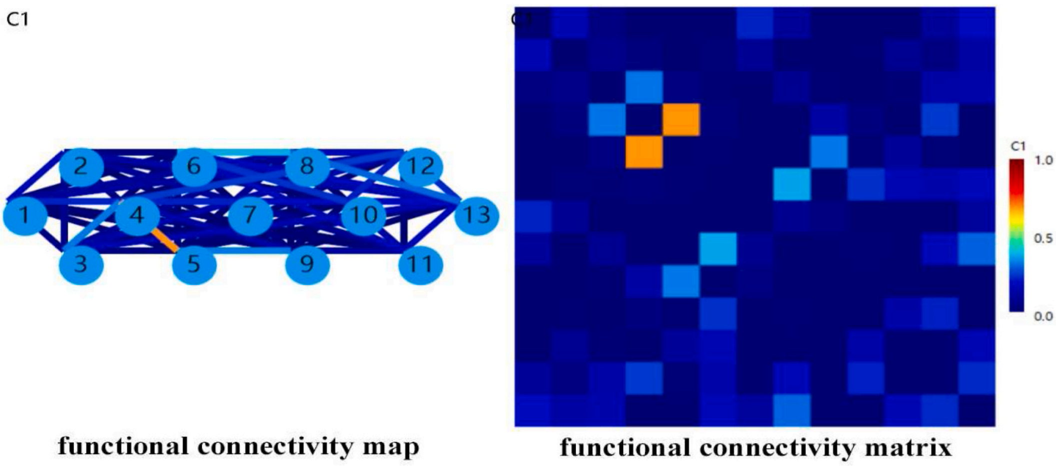

Fig. 2. Near-infrared spectral imaging pictures at admission.Brain functional connectivity strength 0.131.

Table 1
Treatment measures after admission.

Treatment	Specific measures
1	Sensory stimulation: Through visual, auditory, tactile, and other sensory stimulation, try to wake up the patient's consciousness. These methods include talking to the patient, playing music, using light touch or massage, and offering different tastes and smells. Each session lasts for 1 h, 5 times a week.
2	Physiotherapy: Include passive movement, postural changes in bed, and electric stand-up bed training to prevent muscle atrophy and joint stiffness—1 h per session, 5 times/week.
3	Occupational Therapy: Help patients with activities of daily living training, such as bed activities and transfer skills, as well as cognitive function and sensory function assessment and training: 1 h each time, 5 times/week.
4	Nutritional support: To ensure adequate nutrition, water, and electrolyte balance of patients, nutrition is provided through the nasogastric tube.
5	Psychological support and family education: Provide psychological support to the patient's family to help them understand the coma and recovery process and educate them on how to participate in their care.
6	Pain management: Assess the patient's possible pain and conduct reasonable pain management.
7	Nursing intervention: Include skin care to prevent pressure sores, oral care to maintain oral hygiene, eye care, and other nursing measures to maintain patient dignity.
8	Nerve rehabilitation drugs: Amantadine tablets 100 mg once a day by nasal feeding + levodopa and benserazide hydrochloride tablets 125 mg three times a day by nasal feeding.
9	Hyperbaric oxygen therapy: Hyperbaric oxygen can improve cerebral oxygen supply, improve brain function, and contribute to the recovery of consciousness. 2 h each time, 4–5 times a week.
10	Common acupuncture + Microneedle acupuncture points include Shenting, Renzhong, Yingxiang, Yifeng, Binao, Quze, Neiguan, Shenmen, Hegu, Taixi, and Taichong. The aforementioned points are commonly needled at regular depths, with each session lasting 30 min. Needles are rotated among selected points, with treatments occurring 5 times per week.

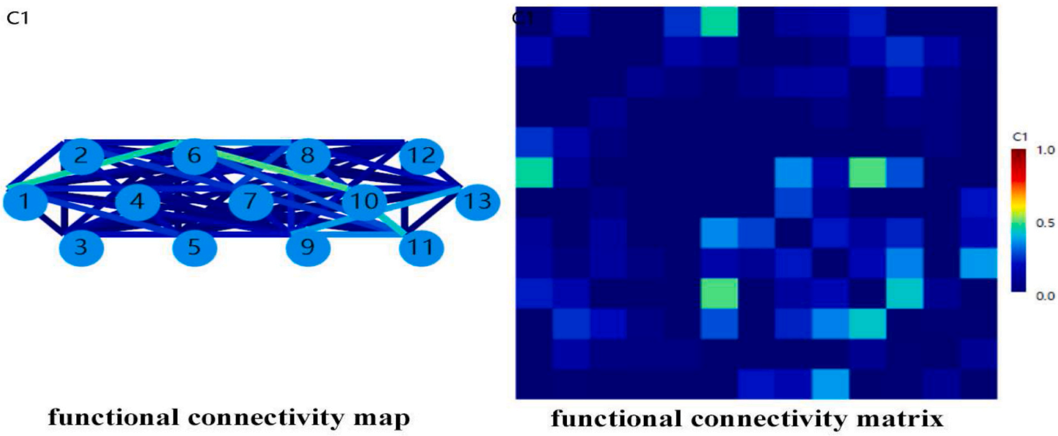

Fig. 3. Near-infrared spectrum imaging picture after the first parameter adjustment. Brain functional connectivity strength 0.154.

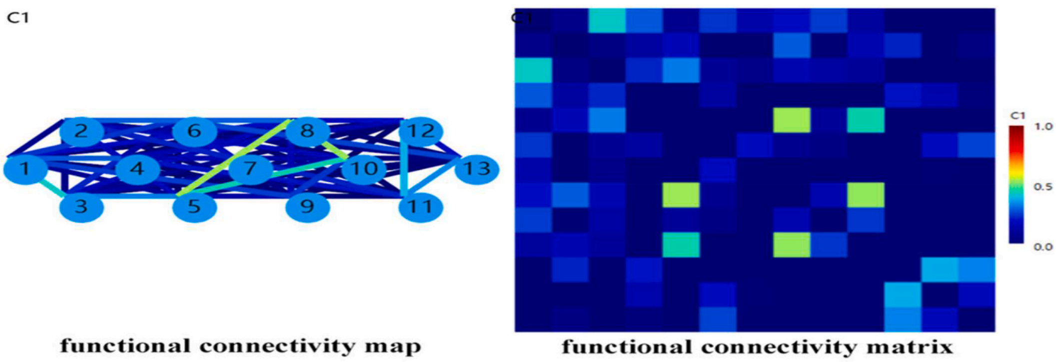

Fig. 4. The near-infrared spectrum image picture after that second parameter adjustment. Brain functional connectivity strength 0.19.

consciousness and limb function recovery were improved. Moreover, the near-infrared brain function analysis was performed again, and the results are displayed in Fig. 8. The strength of brain functional connectivity was 0.576, which was significantly higher than that at the time of admission. These results further indicated that the brain function was improved significantly. Cranial MRI of the bilateral frontal lobe and occipital lobe showed that there were changes after contusion and laceration. Extensive intracranial signal

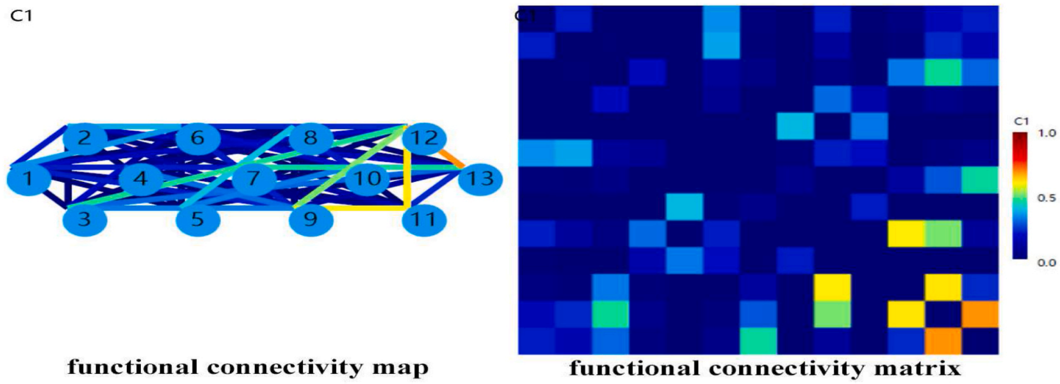

Fig. 5. Near-infrared spectrum imaging picture after the third parameter adjustment. Brain functional connectivity strength 0.222.

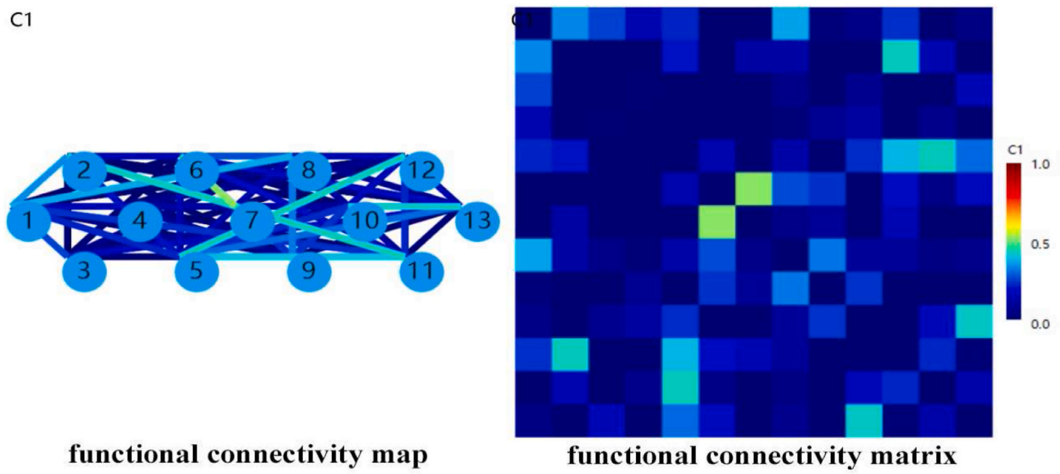

Fig. 6. Near-infrared spectroscopy imaging picture after the fourth parameter adjustment. Brain functional connectivity strength 0.181.

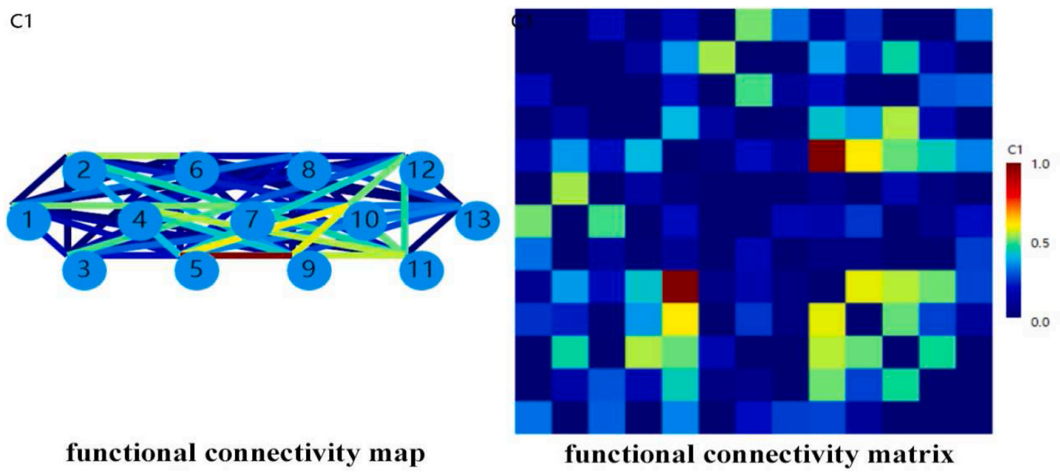

Fig. 7. Near-infrared spectroscopy imaging picture after the fifth parameter adjustment. Brain functional connectivity strength 0.273.

abnormalities and multiple ischemic foci with lacunae foci were observed. There was demyelination of the white matter corresponding to age-related brain changes. Fig. 9 shows one of the MRI images. The MRI results indicated that the cerebral hemorrhage had been absorbed. Throughout the treatment process, both the patients and their families demonstrated good compliance, and there were no

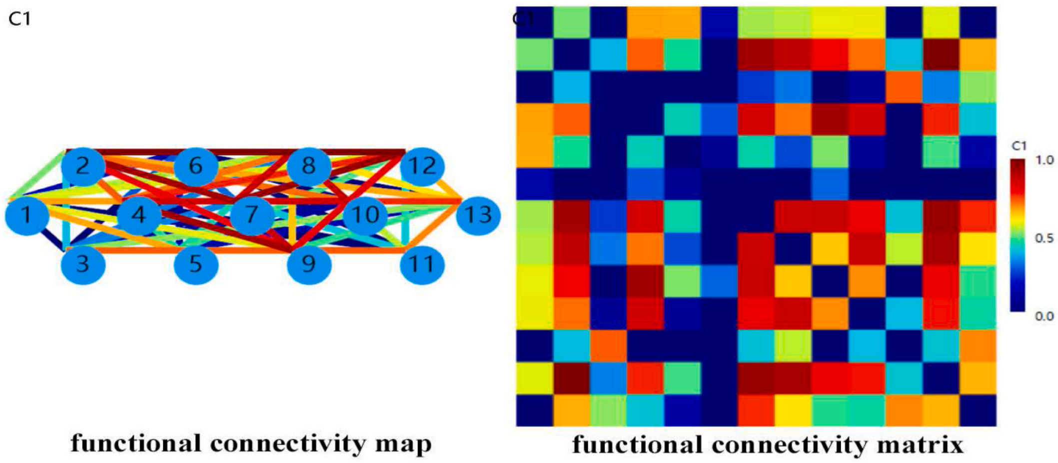

Fig. 8. Near-infrared spectral imaging images after 2 months of treatment. Brain functional connectivity strength 0.576.

adverse events or accidents.

3. Discussion

Spinal cord electrical stimulation is a treatment method in which the electrodes of a spinal cord stimulator are placed in the epidural space of the anatomical and functionally intact spinal cord, and the conduction tracts of the posterior column of the spinal cord and the sensory nerves in the posterior horn are stimulated by current pulses. In this case report, the spinal cord electrical stimulation electrode is placed in the cervical vertebra's 2–4 vertebral body, which is placed in the epidural space of the spinal canal. In clinical practice, it is primarily used for pain relief and heart failure treatment. It is found from the studies that spinal cord electrical stimulation is rarely used for treating consciousness disorders after traumatic brain injury. Only a few clinical studies have demonstrated that spinal cord electrical stimulation implantation is effective for patients with severe disturbance of consciousness, which is beneficial to promoting awakening [3,4]. The mechanism may affect cerebral blood flow or regulate the neural circuits directly connected to the brain. Numerous studies have shown that the cerebral blood flow of patients with consciousness disorder is obviously decreased, which leads to the lack of oxygen supply and nutrients in the brain, thus aggravating the necrosis of brain neurons and the degree of consciousness disorder [5]. Studies at home and abroad show that spinal cord electrical stimulation can increase cerebral blood flow, thus promoting the recovery of consciousness. The main mechanisms are as follows: exciting vascular motor centre, neuroregulation and humoral regulation [6]. The vascular motor centre refers to the group of nerve cells in the central nervous system that regulates vascular motion. Its high-level centre is in the cerebral cortex, and its low-level centre is under the cortex from the hypothalamus to the spinal cord. Studies have shown that spinal cord electrical stimulation can excite the vascular motor centre and increase cerebral blood flow by about 30 % [7]. In addition, spinal cord electrical stimulation can inhibit the activity of the sympathetic nervous system and reduce vasoconstriction. At the same time, the parasympathetic nerve is activated, which increases parasympathetic nerve activity, leads to vasodilation and increases cerebral blood flow [8]. Spinal cord electrical stimulation can also improve the expression levels of catecholamine (dopamine and norepinephrine) and B-cell lymphoma-2(Bcl-2) proteins in

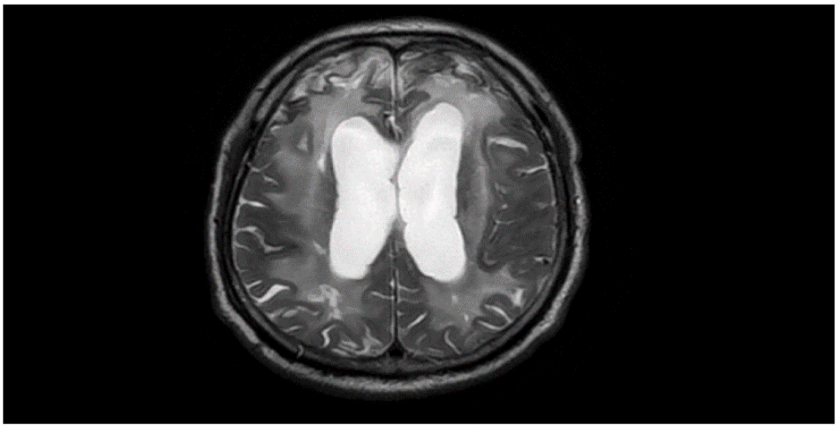

Fig. 9. One picture of MRI.

cerebrospinal fluid of patients with consciousness disorder through body fluid regulation, increase cerebral blood flow and glucose metabolism rate in the brain, improve energy metabolism of hypoxic and ischemic brain tissue, and further promote consciousness recovery [9,10]. In addition, spinal cord electrical stimulation can also promote the recovery of consciousness by affecting the brain's neural circuits. The regulation of spinal cord electrical stimulation on excitatory neurons can affect the sensory and motor signals transmitted to the brain. This may positively impact the rehabilitation process of consciousness disorder, such as enhancing the brain's response to motor and sensory signals, thus promoting rehabilitation. In addition, the nerve impulses generated by spinal cord electrical stimulation can activate the brain stem's ascending reticular activation system (ARAS) through conduction bundles at all levels and promote the secretion of acetylcholine. The activated ARAS can also activate Menette cells in the forebrain basal nucleus and release acetylcholine to the brain cortex extensively to encourage recovery consciousness [11]. Currently, the parameters of spinal cord electrical stimulation in the literature are fixed, and it is not possible to adjust the appropriate parameters to improve the clinical efficacy according to different patients. The advantage and innovation of this case report lie in its observation of the therapeutic effects on consciousness recovery from different patient-centric parameters, which is quite rare in current research.

Currently, brain CT, EEG, functional magnetic resonance imaging (fMRI), and GCS rating scales are commonly used to evaluate brain function and consciousness level in clinical research. The CT has a high radiation dose and low accuracy. The fMRI has poor portability and artifacts and cannot be performed for critical patients or patients with metal implants [12]. The spatial resolution of EEG is relatively low, and it is sensitive to motion, so the accuracy is general [13,14]. The fNIRS is a new brain functional imaging technology that takes advantage of the good scattering of 600–900 nm near-infrared light of the main components of blood. The fNIRS detects the changes in tissue optical parameters, reflects the changes of hemoglobin in the blood, and thus detects the neural activity and brain connectivity function [15]of the brain. Furthermore, fNIRS has the advantages of low cost, safety, anti-electromagnetic interference, anti-motion artifacts, and portability. It is gradually replacing the traditional detection and imaging tools and is a promising research tool in brain science research.

Some researchers have concluded [16] that consciousness is generated by neural activity and brain network connectivity in brain networks. The prefrontal network is closely related to consciousness. For instance, the awakening part of consciousness has been shown to be closely related to the prefrontal network. In contrast, the awareness part is closely related to the function of the prefrontal network and frontoparietal network [17]. The degree of functional connectivity of the prefrontal network is positively correlated with the level of consciousness, and the prefrontal network is used as a prediction tool to evaluate the prognosis of consciousness in patients with disorders of consciousness. The prediction accuracy was found to be about 80 % [18]. Kim et al. [19] reported that brain activity combined with connectivity neurofeedback can effectively regulate prefrontal brain connectivity and improve the state of consciousness. Therefore, using fNIRS to assess the functional connectivity of the prefrontal brain network is highly significant, as it provides an objective index for evaluating consciousness.

The parameters of spinal cord electrical stimulation can be divided into amplitude, pulse width, and Frequency. Amplitude is divided into low voltage amplitude (0–1.5V), medium voltage amplitude (1.5–4V) and high voltage amplitude (4–10V). The pulse width determines the duration of each electric pulse and then affects the activation mode of nerve fibres. It can be divided into short pulse width (50–200 μs), medium pulse width (200–400 μs) and long pulse width (400–500 μs). Frequency directly affects the excitability of neurons and the regulation of network activity. It is divided into low frequency (2–20 Hz), intermediate frequency (20–60 Hz) and high frequency (60–200 Hz). The higher the parameters, the better the general effect, but the more robust the side effects such as pain, discomfort, nervous dysfunction and so on. The parameters selected in this case report are summarised according to the literature and clinical experience. It is found that voltage amplitude of 1.50 V, 2.0 V, 3.5 V, 4.4 V, and 4.5 V, pulse width of 120 μs, 210 μs and 230 μs, frequency of 5 Hz, 6 Hz and 70 Hz are the most beneficial to the recovery of consciousness and the improvement of limb function [20,21]. The initial postoperative parameters were Amplitude 1.50 V, Pulse Width 120 μs and Frequency 5 Hz (running time: 8: 00–20: 00, cycle mode: start for 15 min, turn off for 15 min). These three low-level parameters help adjust the functional connection between cortex-cortex and cortex-subcortical structures to restore autonomic nerve function and consciousness level. It is mainly used for the initial stage of consciousness disorder. After a period of use, it was found that the effect was poor, so the parameters were gradually improved. Firstly, after admission, the pulse width was increased to 210 μs, and the frequency was slightly increased to 6 Hz on the premise that the circulation time and opening time were unchanged, and the effect was observed. After treatment, it was found that the strength of the brain functional connection was enhanced, and there was no obvious side effect. Therefore, after 15 days, the voltage amplitude was increased to 3.5V, the frequency was 70 Hz, and the pulse width remained unchanged. The effect was also slightly improved. After 30 days, the voltage amplitude was 4.4V, the frequency was 70 Hz, and the pulse width was 230 μs. The strength of the brain's functional connection was also slightly improved. Occasionally, the patient's heart rate was somewhat faster, fluctuating at 110–120 beats/min, and the side effects of spinal cord electrical stimulation were not ruled out. Therefore, after 45 days, the adjustment parameters were Amplitude 2.0 V, Pulse Width 230 μs, and Frequency 6 Hz. The strength of brain functional connection decreased significantly. After 60 days, the parameters were adjusted to Amplitude 4.5 V, Pulse Width 210 μs and Frequency 70 Hz (running time: 8: 00–20: 00, Cycling mode: 15 min on, 15 min off), and the strength of brain functional connection was obviously improved, with no obvious side effects. Therefore, this parameter is treated for a long time. After two months of continuous treatment, the patient's brain functional connectivity strength, GCS score, and limb motor function were significantly improved. It can be considered that this mode has a significant improvement in the recovery effect of consciousness disorders and has a significant reference value.

Some researchers have studied 110 patients undergoing spinal cord electrical stimulation with parameters set to an amplitude of 1–5 V, a pulse width of 210 μs, and a frequency of 70 Hz (running time: 8:00–20:00, cycling mode: 15 min on, 15 min off). The results suggested that the treatment of coma effective rate was close to 40 % for patients with severe disturbance of consciousness after craniocerebral trauma is positive [22]. These results are similar to the results of spinal cord electrical stimulation parameters reported in this case report. The mechanism may be that in this mode, the blood flow and oxygen supply to the prefrontal cortex are effectively increased, thereby contributing to the recovery [23] of consciousness.

FNIRS monitors brain function mainly through the functional connection matrix and brain functional connection strength. The principle and significance of functional connection matrix and brain functional connection strength are as follows [24]: ①the principle of functional connection matrix: Functional connection matrix is constructed by graph theory analysis, which is used to describe the correlation between brain regions of different nodes. It is generated according to the definition of nodes and connectivity. Each node represents a specific brain region, and connectivity represents the functional interaction between these brain regions. ②the significance of functional connection matrix: By analyzing the functional connection matrix, we can identify the patterns of specific networks in the brain and then explore the role of these networks in the conscious function. The abnormal pattern of the functional connectivity matrix may be related to many nervous system diseases, such as disturbance of consciousness, schizophrenia, Alzheimer's disease, and so on. ③the principle of brain functional connection strength: The strength of brain functional connection refers to the degree of synchronization or dependence of neural activities between different brain regions. The enhancement or weakening of the connection strength may reflect the dynamic changes of the internal functional organization of the brain, which may be related to many factors such as the state of consciousness, emotional state, disease state, and so on. ④the significance of brain functional connection strength: It is found that the highly complex consciousness function involves the coordination and cooperation among multiple brain regions, and the connection strength between these brain regions is very important for the realization of consciousness function. Many nervous system diseases (such as coma, etc.) are often accompanied by the loss or degradation of some connection strength, which leads to the decline of consciousness level. Therefore, the analysis of brain functional connection strength is helpful for us to understand and diagnose these diseases and explore potential treatment strategies.To sum up, the strength of the functional connection matrix and the brain's functional connection play an important role in consciousness research. They not only help us to understand the internal structure and functional organization of the brain but also provide a new perspective and strategy for the diagnosis and treatment of neurological diseases. Therefore, this case uses the functional connection matrix and brain functional connection strength to explore the changes in consciousness.

Throughout this case report, we conclude that spinal cord electrical stimulation can enhance brain function. This can not only improve cerebral circulation and reduce the focal points of cerebral ischemia and hemorrhage,but also excite the cerebral cortex, strengthen the functional connection of brain cells and promote the recovery of brain function and consciousness. These have specific therapeutic effects on cerebrovascular diseases, carbon monoxide poisoning, ischemic and hypoxic encephalopathy and dyskinesia. Further research can be carried out through clinical practice. In addition, combined with this case, patients with mild and moderate brain trauma usually maintain partial consciousness and respond to external stimuli. Emphasis should be placed on improving cognitive and motor functions during the treatment. Spinal cord electrical stimulation settings at 3.5–4.5 V amplitude, 210 or 230 μs pulse width, and 6 or 70 Hz frequency can be suggested. Operating from 8:00–20:00 in a cycling mode of 15 min on and 15 min off。 These parameters can improve brain function connections and promote brain function recovery. For severe brain injury, the recovery of consciousness disorder is often the most important. It is feasible to 4.5 V amplitude, pulse width 210 μs and frequency 70 Hz (running time: 8: 00–20: 00, cycling mode: 15 min on, 15 min off), because it can improve the recovery of consciousness.

FNIRS also has its side effects and safety considerations, which are mainly reflected in the following aspects [25]: ①Thermal effect. fNIRS uses near-infrared light to analyze substances. Because near-infrared light can be absorbed by biological tissues and converted into heat energy, under high energy or long-term irradiation, local temperature may rise, causing thermal damage to tissues. Although conventional light intensity generally does not lead to an obvious thermal effect, it is still necessary to pay attention to this risk under certain conditions. ②Phototoxicity. In some research and applications, near-infrared light may be combined with photosensitizers to produce phototoxic reactions. This photosensitizer may generate Reactive Oxygen Species, ROS) under the irradiation of near-infrared light, leading to cell damage or death. Although photosensitizers are not usually used in fNIRS, it is necessary to be alert to this risk in other near-infrared applications. ③Eye injury. Near-infrared light is potentially harmful to the eyes, especially the risk of thermal damage to the retina. The human eye is insensitive to near-infrared light and cannot perceive its existence, so long-term or high-intensity near-infrared light irradiation may unconsciously cause damage to the retina. When using near-infrared spectroscopy equipment, appropriate eye protection measures should be taken, such as wearing goggles. ④Electromagnetic radiation. Near-infrared spectroscopy equipment will produce certain electromagnetic radiation when it works. Although the radiation intensity of such equipment is usually low, long-term or frequent contact may have unknown effects on the human body. Therefore, the relevant safety operation procedures should be followed during use. ⑤Use environment and operation specifications. Environmental control: Near-infrared spectroscopy equipment should be used under suitable environmental conditions to avoid operating under high temperatures, high humidity or other unfavourable conditions. Training and education: Operators should receive adequate training, understand the use of equipment and potential risks, and master the correct operating specifications. Regular maintenance and calibration to ensure that it is in the best working condition and to reduce potential safety hazards caused by equipment failures or errors. From this case study, no side effects and safety problems occurred.

The patient's family members were satisfied with the overall treatment and evaluation. They were relieved to see that the patient's state of consciousness had improved compared to the time of onset and that he was now able to move slightly independently.

We have continued to follow up on this case, evaluating the patient's consciousness, muscle strength, muscle tension, daily living ability, and other related functions every 1–2 months on average. We have also used FNIR, brain MRI, brain CT, and EEG to assess changes in illness and brain function. Furthermore, we have strengthened our communication with the patient's family, carefully considering their opinions and needs to ensure an objective and sustainable evaluation. The limitation of this report is that due to the individual differences of patients, more case studies should be included in the future, and treatment methods such as acupuncture and rehabilitation training intervention time, transcranial magnetic stimulation, and median nerve electrical stimulation should be combined to draw more precise conclusions.

4. Conclusion

In conclusion, spinal cord electrical stimulation can effectively accelerate the recovery of patients, promote the recovery of consciousness, and improve the brain functional connectivity and consciousness level of patients. The effectiveness is enhanced when combined with medication and rehabilitation training. This approach can serve as one of the conventional treatment methods for disorders of consciousness following traumatic brain injury and is worthy of broader clinical adoption.

Ethical approval

This study was approved by The First Affiliated Hospital of Zhejiang Chinese Medical University (Hangzhou, China). Written informed consent was obtained from the patient's family (including minors), agreeing to publish the details and images of his anonymous case.

Funding statement

Not applicable.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Zhiwen Zhu: Writing – original draft, Conceptualization. **Xiaozhen Hu:** Resources, Data curation. **Yajun Mao:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Not applicable.

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