Afifi *Egypt J Neurol Psychiatry Neurosurg* (2024) 60:54
https://doi.org/10.1186/s41983-024-00825-9

The Egyptian Journal of Neurology, Psychiatry and Neurosurgery

REVIEW

Open Access

A new era of current and future treatment applications of transcranial magnetic stimulation

Shrief Y. Afifi[1*]

Abstract

Background Transcranial magnetic stimulation (TMS) equipment has advanced dramatically over the years thanks to considerable advancements in signal motors, coils, placement devices, and modeling, optimization, and treatment scheduling programs. In this review, a primary assessment of the impact of transcranial magnetic stimulation (TMS) on seizure course in people with and without epilepsy has been done through search in the Embase, PubMed, Scopus, and Web of Science databases. Other proposed roles of TMS in various studies has been reported. The features of TMS protocols for several potential disorders was assessed and the key TMS findings has been documented starting from 1985 until 2023.

Results More than 500 papers were found that describe various research populations, TMS techniques, and TMS functions in 16 various medical conditions.

Conclusion After reviewing recent updates in TMS, further researches are needed to improve the technical part of the used TMS protocols and to have definitive results not experimental one with regard to TMS usage in various psychiatric and neurological disorders.

Keywords TMS, Mental disorders, Treatment, Applications

Background

In 1819, Hans Christian Oersted made the discovery that a wire carrying an electrical current may also generate a magnetic field. In contemporary studies, Baker and colleagues' idea from 1985 was the initial study to suggest employing a magnetic field to activate the brain [1]. Following their limited success in that area, they continued to work on electric brain stimulation, but this time they used magnetic induction to generate the electricity. This led to the creation of the first formal proposal for a device that generated a magnetic field to cause physiological responses in the brain [2]. Other research has supplemented that initial suggestion by modifying the coils, enhancing the forms, or suggesting intricate patterns for certain uses [3, 4].

After Barker and colleagues article, a commonly used coil in the shape of an eight (now known as a figure-of-eight coil, or FoE coil) was successfully employed [3], and it was soon used to generate motor-evoked potentials (MEPs) and perform functional brain mapping (FBM). Due to the pain that TES [2] caused in conscious people, it was not possible for researchers to completely understand the localization of motor zones in the brain until they developed this novel design and application. The near-zero pain of TMS, however, was beneficial for a larger range of applications, with FBM [3, 5, 6] and assessing the perioperative spinal cord performance by MEP production [2] being two of the most significant. This field of inquiry has expanded recently to include

*Correspondence:
Shrief Y. Afifi
sad19941989@gmail.com
[1] Okasha Institute of Psychiatry, Neuropsychiatry Department, Ain Shams University, Cairo, Egypt

using TMS for monitoring celiac patients and measure neuroplasticity for specific illnesses [7–9], as well as using TMS as a diagnostic tool to investigate central motor neural networks [10, 11]. The early TMS researchers employed this method to identify the cortical areas that housed the motor pathways [3, 5, 6]. Indeed, using this method, the majority motor areas of the brain were found.

When this technique was first used for brain therapy, questions arose regarding the TMS repeating pulses impact on the brain and possible benefits for therapy. Initially, TMS tools for brain mapping needed brief but crucial recovery intervals before generating the next pulse. While repeated TMS (rTMS), which was suggested for the management of a wide range of health issues [12–16] was intended for therapeutic TMS, quicker devices with reduced rehabilitation periods were. Theta-burst stimulation (TBS), a different type of TMS, has recently been shown to be equally effective as "classical" TMS but requiring fewer treatment sessions [17, 18] for fostering neuroplastic effects in people with brain illnesses and injuries. According to certain investigations, the effects of TBS might linger for up to hours [19] producing a substantial suppression of cortical excitability owing to alterations in synaptic transmission that resemble long-term depression [20, 21]. After one-time and repeated TBS treatments, behavioral and structural neuroplasticity have both been seen [22, 23].

Main text

The use of transcranial magnetic stimulation (TMS), which enables the direct activation of human neocortical neurons and has shown to be essential for causative testing of hypotheses in cognitive neuroscience, can be beneficial for treating a range of clinical disorders. Multiple studies have shown the promise of this non-invasive brain stimulation technology to explore physiological pathways and regain brain function [24].

The motor cortex of the appropriate muscle (in the hand or foot) is covered by the TMS coil. While administering single TMS pulses, the coil's position and orientation are changed until the ideal location on the head for stimulating the motor cortex is localized and the rMT is established. The rMT is the lowest stimulator power output necessary to enhance motor response [25].

The role of repetitive transcranial magnetic stimulation (TMS) in multiple psychiatric and neurological problems are briefly discussed in this review some as following:

Alzheimer disease (possible therapeutic purpose)

A new non-invasive therapeutic approach in the fight against Alzheimer disease is repetitive transcranial magnetic stimulation (rTMS). The default mode network, for which the precuneus is a critical node, is substantially altered in patients having Alzheimer disease. A study which has been done on fifty patients of mean age of 73 years for 24 weeks reported that precuneus rTMS may help delay the cognitive and functional loss associated with Alzheimer disease where Clinical Dementia Rating Scale-Sum of Boxes scores for patients who received precuneus repeated magnetic stimulation remained steady, whereas scores for patients who received sham treatment worsened. Patients in the precuneus stimulation group also performed significantly better on the Mini-Mental State Examination, the Activities of Daily Living scale from the Alzheimer Disease Cooperative Study, and the Alzheimer Disease Assessment Scale-Cognitive Subscale, compared to those in the sham stimulation group [26]. A unique therapy strategy for people with Alzheimer disease may use repetitive TMS targeting the default mode network [27].

Depression

For major resistant depression (therapeutic purpose)

Treatment-resistant depression (TRD) can be successfully treated with repetitive transcranial magnetic stimulation (rTMS), which has been given FDA approval. However, there is not much data to support the need for maintenance protocols. The majority of studies showed a substantial reduction in relapse risk with maintenance protocols, indicating that providing two or fewer stimulations per month is inefficient in maintaining an antidepressant effect or in lowering the risk of relapse in responder patients. Five months following the end of the acute therapy was when the risk of recurrence was at its highest. To preserve the effects of acute antidepressant therapy, maintenance TMS looks to be a clever method, considerably lowering the likelihood of relapse. When assessing the potential use of management TMS protocols, it is important to take into account how simple they are to administer and how easy it is to track patient adherence Additional research is required to determine the therapeutic significance of acute TMS effects that coincide with repair protocols and to assess the efficiency of these procedures over the long run [28].

Bipolar depression (possible therapeutic purpose)

One to two percent of the world's population is affected by bipolar disorder (BD), which has a high prevalence of functional impairment. The majority of patients with BD experience depressive episodes, and up to one-third of them do not react to medication dosages that are appropriate. Although there is no universally accepted diagnosis of treatment-resistant bipolar depression (TRBD), a common characteristic of TRBD is the failure of symptom improvement despite an appropriate trial of two therapeutic medications. TRBD has been studied with a number of medicinal substances. Along with scant information on racemic intravenous ketamine, adjunctive pramipexole and modafinil have studies demonstrating short-term effectiveness in TRBD. Patients with insulin resistance who received metformin therapy and celecoxib augmentation of escitalopram exhibited encouraging outcomes. When compared to medicine, right unilateral electroconvulsive treatment showed a statistically significant degree of response and enhancement, but not remission. In conclusive data about TMS for its possible therapeutic effect, transcranial magnetic stimulation (TMS) trials have not been able to distinguish themselves from sham therapy in TRBD. There is little effectiveness data available for the available TRBD therapy methods. For TRBD to be successfully treated, more research is required. Innovative treatment modalities and successful therapies are being researched and may hold promise [29].

Depression with a seizure disorder (possible therapeutic purpose)

As iTBS has a 0.02% risk for inducing seizures, the rate of seizure induction in individuals without a seizure disease is rather low. These epileptic episodes are often self-contained and do not result in the emergence of a new seizure disease. Precautions must be taken while treating people who already have a seizure problem. Although these individuals have a slightly higher risk of rTMS-induced seizures, it is still very low. Only a 2- to 3-percent risk of seizures is reported in the literature for epilepsy patients receiving rTMS. Patients who were taking drugs that decreased the seizure threshold accounted for the majority of reported incidents of seizures. Safety recommendations also advise against using high frequency (> 1 Hz) rTMS stimulation on individuals with seizure disorders in order to avoid inducing seizures. High-frequency rTMS and iTBS for individuals with seizure disorders still require additional research [30].

In adolescent depression (possible therapeutic purpose)

Random-effects models were used to combine the data from the relevant studies after a thorough literature search. Individual-patient data (IPD) exploratory analysis looked at interactions between the treatment and the covariates. To date, there is no data suggestive of possible therapeutic effect of TMS. Only one large-scale randomized experiment has found TMS to be no more beneficial than sham stimulation, and the two published randomized controlled studies on TMS in teenage depression are both small-scale. Future randomized, sham-controlled studies should be conducted on a wide scale. Future studies should guarantee proper patient selection for TMS therapy and direct precision medicine strategies for stimulation regimes [31].

Possible therapeutic approach of major depressive disorder by accelerated TMS protocols

The FDA-approved procedures for TMS to treat major depressive disorder (MDD) are broadly supported by the available literature, which typically demonstrates comparable effectiveness and safety profiles. However, accelerated TMS research is still in its infancy. The few used protocols have not been standardized and differ greatly among a few basic components. There are nine components, including the target and dose of the treatment, individualized parameters (frequency and inter-stimulus interval), cumulative exposure (number of therapy days, sessions per each day, and vibrations per class), and brain state (context and concurrent treatments). Uncertainty still exists over which of these components is crucial and which criteria are best for treating MDD. The capacity and benefit of individualized functional neuronavigation, the use of biological readouts, availability for patients most in need of the therapy, and duration of impact are additional essential factors for accelerated TMS. Overall, accelerated TMS seems to have promise for reducing treatment duration and achieving immediate relief from depressive symptoms, but a lot more work has to be done before it can be considered fully effective [32].

Schizophrenia (possible diagnostic and therapeutic effect)

Schizophrenia may disrupt daily life of a person and has an impact on their physical and mental health. According to Fitzgerald and colleagues [33], TMS therapy for schizophrenia patients resulted in a significantly higher level of activity in the left precentral gyrus, left temporoparietal areas, and left inferior frontal cortex which might help in treatment of negative symptoms of schizophrenia. In their investigation of 30 patients with schizophrenia using pseudocontinuous magnetic resonance-arterial spin labeling, Kindler and colleagues [34] discovered that repetitive transcranial magnetic stimulation decreased cerebral blood flow in the left primary auditory cortex, cingulate gyrus, and Broca region, which might help in treatment of resistant auditory hallucination of schizophrenia. In addition, Palm and colleagues [35] discovered that transcranial direct current stimulation treatment significantly increased the functional connectivity between the right insula and the right dorsolateral prefrontal cortex, the right thalamus and the right subgenual grey matter in the resting state, which might be used as possible biomarker in schizophrenia, which is known as dis- connectivity syndrome.

Obsessive compulsive disorder (OCD) (therapeutic purpose)

Multiple anatomical structures and brain networks exhibit aberrant signaling in OCD, and these pathways provide a number of TMS targets. The efficacy of TMS in treating OCD has been examined in a variety of randomized control studies. The number of participants, frequency of stimulation, number of treatments, duration of follow-up, and effectiveness in lessening OCD symptom load vary significantly throughout these trials, though. Notably, according to the GRADE methodology, the authors rate the overall quality of this evidence as very low to poor. These findings support current treatment recommendations that point to the "possible efficacy of low frequency rTMS of the right DLPFC [36]".

Stroke (diagnostic and therapeutic purpose in cerebro-vascular stoke rehabilitation)

Rehabilitation is an efficient way to lower disability rate of patients after a stroke since it has a high incidence and disability rate. TMS among the primary biomedical testing methods for stroke patients' rehabilitation assessments. While fMRI offers relatively rapid and thorough access to whole-brain neural activity in the brain during external stimulation or while the patient is engaged in a particular task, as diagnostic method TMS offers independent and controlled activation of neuronal excitation in certain brain areas. Therefore, these methods are frequently used to enhance evaluation of the brain neurological recovery and to provide light on the brain functional reorganization following a stroke. TMS can be used in conjunction with structural imaging methods like DWI in addition to functional imaging methods to improve the prediction of motor rehabilitation levels in stroke patients and as therapeutic tool TMS enhance motor and sensory defect beside other rehabilitation tools [37].

Post-stroke dysphagia

As a possible therapeutic hypothesis, one of the most frequent stroke symptoms, dysphagia can affect 50–81% of people who have an acute stroke. The specific processes underpinning therapy success remain debatable despite the emergence of several treatment modalities. Previous research has shown that neurological impairment is connected to the development of dysphagia. Post-stroke dysphagia (PSD) is commonly treated with neuroplasticity-based transcranial magnetic stimulation (TMS), a recently developed therapy, which accelerates changes in neural pathways through synaptogenesis, reorganization, network strengthening, and inhibition [38].

Correlating with language and TMS usage in post-stroke aphasia

The neurological correlates of language have been demonstrated by transcranial magnetic stimulation (TMS). Temporoparietal regions are more commonly excited in regard to the incorporation of sentential meaning and thematic role assignment, while frontal areas are most frequently stimulated in relation to morphosyntactic procedures and the semantics of action verbs. The effect sizes for anterior in comparison to posterior areas do not differ for semantic or morphosyntactic differences, according to a meta-analysis of 72 effect sizes of the examined publications. TMS has a tiny overall effect size [39].

When applied to the ventral circuit, TMS might has a possible therapeutic approach through affects single word recognition and contextual reading, whereas phonological processes are modulated when applied to the dorsal circuit. TMS also affects semantic judgements when applied to the anterior areas of the reading circuit. Findings imply that changes in particular reading behavior traits after TMS may aid in pinpointing foci for use in reading treatments [40].

For smoking cessation therapy (FDA therapeutic approach)

The FDA recently approved deep repetitive transcranial magnetic stimulation (Deep TMS™) as a short-term smoking cessation therapy. Which volunteers, though, are more likely to gain from the therapy remains uncertain. According to the research by Gersner [41], individuals who are younger, better educated, Caucasian, and have a shorter smoking history are more likely to successfully kick their smoking habit after three weeks of Deep TMS treatment. Participants who are older, have less education, and have smoked more frequently may require a longer course of treatment or a combination of treatment methods. Possible explanations might have to do with the difficulties in causing neural alterations in those who have higher levels of physical and psychological reliance. There is a need for more research.

In multiple sclerosis

A prevalent chronic autoimmune-mediated inflammatory and neurodegenerative condition of the central nervous system is known as multiple sclerosis (MS). illness-modifying medications have made great strides in MS therapy, but the illness complexity and its clinical manifestations necessitate individualized care and management of the illness, including alternatives to medication treatment. Neurological illnesses have made extensive use of transcranial magnetic stimulation

(TMS), a painless and non-invasive brain stimulation treatment [42].

Nearly ten years ago, TMS clinical guidelines were established regarding the use and interpretation of MEPs in the diagnosis and monitoring of cortico-spinal tract integrity in people with multiple sclerosis. These guidelines primarily refer to the use of TMS implementation, which entails connecting a magnetic stimulator to a standard EMG unit and positioning the coil using external landmarks on the head [43].

The mechanism of TMS in multiple sclerosis, and the indications of using TMS in MS

Many theories can explain the mechanism of TMS as diagnostic and therapeutic tool in MS The TMS affects oligodendrocytes by increasing their number as an important mechanism for inducing myelin sheath regeneration. Furthermore, it is known that TMS can be used to assess cortical excitability and connectivity. Those not only provide essential diagnostic elements of MS, but also monitor treatment-induced neuronal changes. Also, numerous studies had shown that TMS can be a surrogate marker for MS, such as testing disability in MS [43].

Indications of using TMS in MS A: Diagnostic: TMS can be a surrogate marker for MS through assessing the impairment in cortical excitability and connectivity associated with the demyelinating process occur in MS [43, 44].

B: Therapeutic: TMS can change the course of MS, (through promoting the remyelination of neurons with demyelinating lesions by activating axonal fibers and neurons and increasing the number of oligodendrocytes) and improve the symptoms, including spasticity, fatigue, pain, cognitive impairment [43, 44].

In assessment of spinal cord injury (SCI)

As possible diagnostic method in both the acute and chronic stages of SCI, transcranial magnetic stimulation (TMS) is considered a non-invasive neurophysiology approach that can support clinical assessment in the area of body structure and function. Compared to a clinical examination alone, TMS provides a better understanding of neurophysiology and aids in the better identification of residual corticomotor connection after SCI. Studying excitatory and inhibitory pathways after SCI is made possible by the motor-evoked potential generated by TMS and the length of the quiet period. Neuroplastic alterations arising from SCI or after rehabilitation can be captured by changes in muscle representations in the form of a shift in the center of gravity of the motor map created by TMS or changes in the map area. Paired-pulse TMS measurements provide insight into the cortical networks' compensatory reorganization after SCI. TMS may be utilized in conjunction with peripheral stimulation to examine central motor conduction time and spinal reflex modulation, which can be applied for more complex diagnostic applications. Future research will need to establish the psychometric features of TMS-based assessments in the SCI community, standardize the assessment methods, solve population-specific issues, and increase the usefulness of TMS in SCI evaluation [44].

In secondary dementia

Although fundamental degenerative illnesses are the most common cause of dementia, a sizable number of individuals may have a secondary cognitive problem that may be treated. So it is necessary to have diagnostic instruments that can detect them early, keep track of them, and forecast how they will respond to therapy. Using a non-invasive neurophysiological tool like transcranial magnetic stimulation (TMS) can be used as possible diagnostic tool through evaluation of the motor regions, the cortico-spinal tract, and the neurotransmission pathways in cognitive decline and dementia. Despite the lack of a recognizable TMS pattern that could be used to predict the onset or progression of cognitive decline in a particular condition, some TMS-associated assessments of cortical activity and development (for example: as the short-latency afferent suppression, the short-interval intracortical restriction, and the cortical silent period) might add helpful information in the majority of secondary dementia, especially when combined with suggestive cMRI data. There is still a gap in the research that has to be filled on the potential to identify defective cortical circuits, monitor the progression of the illness, assess the response to therapy, and develop novel neuromodulatory therapies in secondary dementia [45].

In epilepsy (combined with electroencephalography)

New therapeutic hypothesis of the combination of transcranial magnetic stimulation (TMS) with electroencephalography (EEG), or TMSEEG, may help to treat epilepsy. To investigate the potential of TMS-evoked EEG measurements as a proxy for cortical excitability in epilepsy, it is vital to standardize techniques and reporting. This is especially important for variables like adequate coil location to maintain goal consistency, which have a significant impact on how study data should be interpreted. These advancements will facilitate the evaluation of TMS-evoked EEG responses as illness and treatment-response for impacts on seizure likelihood [46, 47].

Role of TMS in movement disorders

Many studies have reported the roles of TMS in movement disorders as following.

Parkinson disease (possible therapeutic role)

It has been suggested by experimental research that changes in neurotransmitter release, transsynaptic efficiency, signaling pathways and gene transcription are induced by rTMS Also its known that repetitive transcranial magnetic stimulation (rTMS) stimulates neurogenesis, neuronal survival, and the release of neuroprotective chemicals in Parkinson's disease patients One possible mechanism of action may relate to high-frequency rTMS-enhanced activity in the caudate nucleus as well as a relief of dopamine deficiency in nigrostriatal-thalamo-cortical circuitry For instance, rTMS over M1 seems to affect dopamine release in nigrostriatal regions, which might have therapeutic role in improving symptoms of Parkinson disease mainly tremors [48].

Dystonia (possible therapeutic role)

The exact mechanisms of action and the possible therapeutic role of rTMS in management of dystonia remain unknown. Although motor cortex hyper-excitability appears to be the cause of aberrant co-contraction and overflow to adjacent muscles, several studies have shown that plasticity processes and integrated sensorimotor processing might explain the improvement of the symptoms using rtms yet further studies are needed [49].

Tourette syndrome (possible therapeutic role)

Very little is known about mechanisms of action of rTMS in Tourette syndrome It was suggested that low frequency rTMS may have possible therapeutic role with tics and obsessive behaviors by resetting a hyperactive motor cortex But there are currently a limited number of rTMS studies in adult Tourette syndrome, overall showing mixed results Some LF-rTMS (1 Hz) and HF-rTMS (15 Hz) studies targeting motor and premotor cortical sites demonstrated no success or a limited benefit in severe Tourette syndrome On the other hand, several open-label studies targeting SMA with LF-rTMS (1 Hz) demonstrated a decrease in the frequency and intensity of tics[50].

Huntington's disease (possible therapeutic role)

A neurological condition that worsens over time is Huntington's disease (HD). There is mounting evidence that non-invasive neuromodulation techniques can be effective treatment options for neurodegenerative illnesses. 19 papers have been published in the literature looking into HD therapy and TMS usage. Using the JBI's (Joanna Briggs Institute) critical appraisal tools, quality evaluations were conducted. There are encouraging early reports of TMS's effectiveness for symptoms connected to HD without significant side effects, thus more research is unquestionably necessary [51].

Essential tremor

rTMS can regulate brain functions through plasticity effects and it has been targeted to the tremor network to achieve therapeutic effects). One rTMS protocol that has been tested in clinical trials is LF-rTMS of the cerebellum However, this protocol did not show any improvement in tremor variables in essential tremor or in resting tremor in PD Other researchers tried stimulating the left M1 or premotor cortical targets but did not find any appreciable benefit in tremor reduction [52].

Clinical effects of RTMS in cerebellar ataxias (possible therapeutic role)

Cerebellar low frequency TMS works by lowering the inhibitory regulation of the cerebellar cortex over the dentate nucleus, hence potentiating some of the impaired functionality of dentate nucleus. Furthermore, a reduced inhibitory signal from Purkinje cells may boost the activation of the vestibular nuclei, so its possible therapeutic role might improve balance in patients with cerebellar ataxias [52].

Addiction

Methamphetamine

The road to drug sobriety is a long one, and methamphetamine's greater recurrence rate than other substances can make it more difficult. Therefore, real-time physiological surveillance of patients before and during cravings to lower the risk of relapse may aid in improving therapeutic results. Transcranial magnetic stimulation (TMS) with an intelligent closed-loop might have a therapeutic role by decreasing craving to methamphetamine more successfully and in real time. The idea of a continuous closed-loop neuromodulation with three primary components—a real-time brain signal tracking framework, a computerized brain signal processing system, and a personalized neuromodulation system—is presented in order to increase the efficacy of TMS therapy for methamphetamine addiction [53].

Possible therapeutic role in management of craving in alcohol use disorder

Studies examining the effects of repeated transcranial magnetic stimulation (rTMS) in alcohol use disorder (AUD) frequently utilize a small number of rTMS sessions at various rTMS settings, with variable results on effects on alcohol demand. High-frequency rTMS over the right dorsolateral prefrontal cortex (dlPFC) was effective in reducing alcohol demand and use in newly detoxified individuals with AUD during the initial months after detoxification, according to a small-scale randomized controlled experiment. These results call for replication in future large-scale research because they raise the possibility that rTMS may be a useful adjunct in the treatment of AUD patients [54].

Traumatic brain injury

A primary contributor to disability brought on by cognitive, neurological, and psychiatric illnesses is traumatic brain injury (TBI). Preclinical investigation into electrical stimulation techniques as a possible remedy for TBI aftereffects has just lately received considerable pace. Although these techniques are expected to improve things, the underlying mechanisms are still not well understood. It is yet unknown at what point following TBI they should be used to provide the optimum therapeutic result, ideally with long-lasting benefits. These issues are investigated in studies using animal models, which also look at the positive long- and short-term effects mediated by these innovative modalities. It is challenging to make clear comparisons across activation regimens and treatment result since the parameters employed in research on each of these stimulation techniques differ greatly. Electrical simulation's long-term positive effects and negative side effects are seldom studied, which raises concerns regarding their applicability for therapeutic uses. However, we conclude that the stimulation techniques mentioned here have promising outcomes and might have possible therapeutic role that may be further confirmed by subsequent studies in this area [55].

TMS combined with EEG for diagnostic purposes

Neuronal activity is elicited by transcranial magnetic stimulation (TMS) in the targeted cortex and associated brain areas. Electroencephalography (EEG) can be used to assess the evoked brain response. TMS and simultaneous EEG are frequently used together (TMS-EEG) to research brain connection and reactivity with great spatiotemporal resolution. TMS and EEG are a difficult methodological combination, and there are still a lot of unanswered issues. For data collection and processing, several TMS-EEG tools and methods are employed. Lack of standardization may compromise repeatability and restrict the capacity to compare findings from other research labs. Furthermore, there is debate regarding how much somatosensory and auditory inputs contribute to transcranially elicited EEG. The improvement of low frequencies rhythms, repression of high-frequency rhythms, decrease in dynamic intricacy, and the decomposition of networks associated with declining consciousness are all electroencephalogram features related to the frontal and parietal regions that have consistently demonstrated high relevance with consciousness. Existing research has not yet shown which of the frontal and parietal lobes takes precedence in consciousness damage or recovery due to the limits of EEG. Methods for improving EEG awareness locations include source restoration with high-density EEG, artificial intelligence with huge data, and TMS-EEG mapping [56–60].

Important remarks

TMS is a cost-effective treatment for patients who have failed to receive sufficient benefit from initial traditional modalities of treatment in certain disorders for example resistant major depressive disorder and obsessive compulsive treatment (FDA approved), TMS has great rule in rehabilitation of post stoke aphasia and cerebro-vascular stoke motor rehabilitation yet further future studies is needed to apply this high expensive technology [61].

TMS is a relatively safe procedure. A systematic review of 93 RCTs found the TMS group had 2.60 times higher (95% CI 1.75 3.86) odds of experiencing an adverse event (AE) than placebo ($p < 0.00001$). Headache and dizziness were the most common AEs. However, the overall pooled estimate of treatment discontinuation due to an AE was 2.5% (95% CI 1.9–3.2%) with TMS and 2.7% (95% CI 2.0–3.5%) with placebo [62]. Besides, a Cochrane review of seven studies analyzing the effect of TMS in epilepsy found that adverse effects were uncommon; most reported adverse effects were headache, dizziness, and tinnitus and did not lead to a significant change in medications A meta-analysis of 17 RCTs evaluating rTMS to left DLPFC (10 Hz) at 60–110% resting motor threshold (rMT) reported a significant incidence of headache in the treatment group. Besides, a Cochrane review of seven studies analyzing the effect of TMS in epilepsy found that adverse effects were uncommon; most reported adverse effects were headache, dizziness, and tinnitus and did not lead to a significant change in medications A meta-analysis of 17 RCTs evaluating rTMS to left DLPFC (10 Hz) at 60–110% resting motor threshold (rMT) reported a significant incidence of headache in the treatment group [63]. Furthermore, TMS use in epilepsy may induce seizures in patients with a known neurological disorder and clinicians should be aware and alert about this complication However, the risk is very low, most incidences are transient and self-limiting and do not have any long-term sequelae [64].

The Food and Drug Administration (FDA) has approved TMS for individuals between the ages of 18 to 70 Although there are currently no guidelines for the use of TMS in pregnancy, limited studies have been done to evaluate the short-term and long-term efficacy and safety of TMS during pregnancy for MDD. Past studies showed improvement in maternal functioning and depressive symptoms after being treated with TMS [65].

Conclusions

The number of persons that receive TMS each year is only partially known. TMS is nonetheless extensively accessible, with recognized and certified suppliers in several nations throughout the world. After a TMS session, the majority of people may resume their regular activities and schedule right afterwards. It is uncommon for some people to need a few minutes to allow adverse effects subside. Numerous research investigations on TMS have been carried out by specialists. None of the investigations found any evidence connecting TMS to negative brain alterations. Significant adverse effects have been documented in a very small number of individuals. Such cases are quite uncommon, and there have only been a few number of them where doctors have determined that TMS was most likely or certainly the cause. TMS offers hope to patients who have not experienced gains from other, more conventional therapies even if it is not a first-line therapy. TMS is a therapy with the potential to save lives when used to treat severe or treatment-resistant depression as well as OCD. Researchers are also looking into whether it may cure a variety of other brain-related diseases, which expands the treatment's potential applications.

Abbreviations

TMS	Transcranial magnetic stimulation
rTMS	Repeated transcranial magnetic stimulation
MEPs	Motor-evoked potentials
TES	Trans electrical stimulation
FBM	Functional brain mapping
TBS	Theta-burst stimulation
rMT	Resting motor threshold
BD	Bipolar disorder
TRBD	Treatment-resistant bipolar depression
iTBS	Intermittent theta burst stimulation treatment
DLPFC	Dorsolateral prefrontal cortex
fMRI	Functional magnetic resonance imaging
TMS™	Transcranial magnetic stimulation technology modified (modified technology of the applied technology)
PSD	Post-stroke dysphagia
MEPs	Motor-evoked potentials
SCI	Spinal cord injury
HD	Huntington's disease
TBI	Traumatic brain injury
AUD	Alcohol use disorder

Acknowledgements
Non-applicable.

Author contributions
S.Y.A. contributed to the study concept and design, wrote the primary draft of the review revision of the manuscript. S.Y.A revised and edited the manuscript. Author has read and approved the final manuscript.

Funding
Non-applicable.

Availability of data and materials
The manuscript contains all of the data that were created or examined during this study.

Declarations

Ethics approval and consent to participate
Non-applicable.

Consent for publication
Not applicable.

Competing interests
The author states that there are no interests at conflicting with one another.

Received: 18 October 2023 Accepted: 28 March 2024
Published online: 15 April 2024

References

1. Barker A, Jalinous R, Freeston I. Non-invasive magnetic stimulation of human motor cortex. Lancet. 1985;1:1106–7. https://doi.org/10.1016/S0140-6736(85)92413-4.
2. Kraus K, Gugino L, Levy W, Cadwell J, Roth B. The use of a cap-shaped coil for transcranial magnetic stimulation of the motor cortex. J Clin Neurophysiol. 1993;10:353–62. https://doi.org/10.1097/00004691-199307000-00009.
3. Ueno S, Tashiro T, Harada K. Localized stimulation of neural tissues in the brain by means of a paired configuration of time-varying magnetic fields. J Appl Phys. 1988;64:5862–4. https://doi.org/10.1063/1.342181.
4. Roth Y, Zangen A, Hallett M. A coil design for transcranial magnetic stimulation of deep brain regions. J Clin Neurophysiol. 2002;19:361–70. https://doi.org/10.1097/00004691-200208000-00008.
5. Ueno S, Matsuda T, Fujiki M. Functional mapping of the human motor cortex obtained by focal and vectorial magnetic stimulation of the brain. IEEE Trans Magn. 1990;26:1539–44. https://doi.org/10.1109/20.104438.
6. Müri RM, Hess CW, Meienberg O. Transcranial stimulation of the human frontal eye field by magnetic pulses. Exp Brain Res. 1991;86:219–23. https://doi.org/10.1007/BF00231057.
7. Desarkar P, Rajji TK, Ameis SH, Daskalakis ZJ. Assessing and stabilizing aberrant neuroplasticity in autism spectrum disorder: the potential role of transcranial magnetic stimulation. Front Psychiatry. 2015;6:124. https://doi.org/10.3389/fpsyt.2015.00124.
8. Bhandari A, Lissemore JI, Rajji TK, Mulsant BH, Cash RF, Noda Y, et al. Assessment of neuroplasticity in late-life depression with transcranial magnetic stimulation. J Psychiatr Res. 2018;105:63–70. https://doi.org/10.1016/j.jpsychires.2018.08.022.
9. Turco CV, Nelson AJ. Transcranial magnetic stimulation to assess exercise-induced neuroplasticity. Front Neuroergonomics. 2021;2: 679033. https://doi.org/10.3389/fnrgo.2021.679033.
10. Rösler KM. Transcranial magnetic brain stimulation: a tool to investigate central motor pathways. News Physiol Sci. 2001;16:297–302. https://doi.org/10.1152/physiologyonline.2001.16.6.297.
11. Voitenkov VB, Klimkin AV, Skripchenko NV, Pulman NF, Ivanova MV. Diagnostic transcranial magnetic stimulation as a prognostic tool in children with acute transverse myelitis. Spinal Cord. 2016;54:226–8. https://doi.org/10.1038/sc.2015.129.
12. Gan H, Zhu J, Zhuo K, Zhang J, Tang Y, Qian Z, et al. High frequency repetitive transcranial magnetic stimulation of dorsomedial prefrontal cortex for negative symptoms in patients with schizophrenia: a double-blind, randomized controlled trial. Psychiatry Res. 2021;299: 113876. https://doi.org/10.1016/j.psychres.2021.113876.
13. Antczak JM. Transcranial magnetic stimulation as a diagnostic and therapeutic tool in cerebral palsy. Postep Psychiatr Neurol. 2021;30:203–12. https://doi.org/10.5114/ppn.2021.110796.
14. Oroz R, Kung S, Croarkin PE, Cheung J. Transcranial magnetic stimulation therapeutic applications on sleep and insomnia: a review. Sleep Sci Pract. 2021;5:3. https://doi.org/10.1186/s41606-020-00057-9.
15. de Sauvage RC, Beuter A, Lagroye I, Veyret B. Design and construction of a portable transcranial magnetic stimulation (TMS) apparatus for migraine treatment. J Med Devices. 2010;4: 015002. https://doi.org/10.1115/1.4000616.

16. Rossi S, Ferro M, Cincotta M, Ulivelli M, Bartalini S, Miniussi C, et al. A real electro-magnetic placebo (REMP) device for sham transcranial magnetic stimulation (TMS) Clin. Neurophysiol. 2007;118:709–16. https://doi.org/10.1016/j.clinph.2006.11.005.
17. Klomjai W, Katz R, Lackmy-Vallée A. Basic principles of transcranial magnetic stimulation (TMS) and repetitive TMS (rTMS) Ann. Phys Rehabil Med. 2015;58:208–13. https://doi.org/10.1016/j.rehab.2015.05.005.
18. Chung SW, Hoy KE, Fitzgerald PB. Theta-burst stimulation: a new form of tms treatment for depression? Depress Anxiety. 2015;32:182–92. https://doi.org/10.1002/da.22335.
19. Kricheldorff J, Göke K, Kiebs M, Kasten FH, Herrmann CS, Witt K, et al. Brain sciences evidence of neuroplastic changes after transcranial magnetic, electric, and deep brain stimulation. Brain Sci. 2022. https://doi.org/10.3390/brainsci12070929.
20. McAllister CJ, Rönnqvist KC, Stanford IM, Woodhall GL, Furlong PL, Hall SD. Oscillatory beta activity mediates neuroplastic effects of motor cortex stimulation in humans. J Neurosci. 2013;33:7919–27. https://doi.org/10.1523/JNEUROSCI.5624-12.2013.
21. Noh NA, Fuggetta G, Manganotti P. Theta-burst transcranial magnetic stimulation alters the functional topography of the cortical motor network. Malays J Med Sci. 2015;22:35–43.
22. Jung JY, Lambon Ralph MA. The immediate impact of transcranial magnetic stimulation on brain structure: short-term neuroplasticity following one session of cTBS. Neuroimaging. 2021;240: 118375. https://doi.org/10.1016/j.neuroimage.2021.118375.
23. Gutierrez MI, Poblete-Naredo I, Mercado-Gutierrez JA, Toledo-Peral CL, Quinzaños-Fresnedo J, Yanez-Suarez O, et al. Devices and technology in transcranial magnetic stimulation: a systematic review. Brain Sci. 2022;12(9):1218. https://doi.org/10.3390/brainsci12091218.
24. Dionísio A, Carvalho S, Castelhano J. Editorial: TMS application in both health and disease. Front Hum Neurosci. 2023;16:1110274. https://doi.org/10.3389/fnhum.2022.1110274.
25. Riddle J, Scimeca JM, Pagnotta MF, Inglis B, Sheltraw D, Muse-Fisher C, D'Esposito M. A guide for concurrent TMS-fMRI to investigate functional brain networks. Front Hum Neurosci. 2022;16:1050605. https://doi.org/10.3389/fnhum.2022.1050605.
26. Koch G, Casula EP, Bonnì S, Borghi I, Assogna M, Minei M, et al. Precuneus magnetic stimulation for Alzheimer's disease: a randomized, sham-controlled trial. Brain. 2022;145(11):3776–86. https://doi.org/10.1093/brain/awac285.
27. Cummings J, Lee G, Nahed P, Kambar MEZN, Zhong K, Fonseca J, et al. Alzheimer's disease drug development pipeline: 2022. Alzheimers Dement (N Y). 2022;8(1): e12295. https://doi.org/10.1002/trc2.12295.
28. d'Andrea G, Mancusi G, Santovito MC, Marrangone C, Martino F, Santorelli M, et al. Investigating the role of maintenance TMS protocols for major depression: systematic review and future perspectives for personalized interventions. J Pers Med. 2023;13(4):697. https://doi.org/10.3390/jpm13040697.
29. Elsayed OH, Ercis M, Pahwa M, Singh B. Treatment-resistant bipolar depression: therapeutic trends, challenges and future directions. Neuropsychiatr Dis Treat. 2022;18:2927–43. https://doi.org/10.2147/NDT.S273503.
30. Holland E, Holbert R. Repetitive TMS for refractory depression in a patient with a seizure disorder. Brain Stimul. 2022;15(6):1335–6. https://doi.org/10.1016/j.brs.2022.10.002.
31. Sigrist C, Vöckel J, MacMaster FP, Farzan F, Croarkin PE, Galletly C, et al. Transcranial magnetic stimulation in the treatment of adolescent depression: a systematic review and meta-analysis of aggregated and individual-patient data from uncontrolled studies. Eur Child Adolesc Psychiatry. 2022;31(10):1501–25. https://doi.org/10.1007/s00787-022-02021-7.
32. van Rooij SJH, Arulpragasam AR, McDonald WM, Philip NS. Accelerated TMS—moving quickly into the future of depression treatment. Neuropsychopharmacology. 2023. https://doi.org/10.1038/s41386-023-01599-z.
33. Fitzgerald PB, Sritharan A, Benitez J, Daskalakis ZJ, Jackson G, Kulkarni J, et al. A preliminary fMRI study of the effects on cortical activation of the treatment of refractory auditory hallucinations with rTMS. Psychiatry Res. 2007;155:83–8. https://doi.org/10.1016/j.pscychresns.2006.12.011.
34. Kindler J, Homan P, Jann K, Federspiel A, Flury R, Hauf M, et al. Reduced neuronal activity in language-related regions after transcranial magnetic stimulation therapy for auditory verbal hallucinations. Biol Psychiatry. 2013;73:518–24. https://doi.org/10.1016/j.biopsych.2012.06.019.
35. Palm U, Keeser D, Hasan A, Kupka MJ, Blautzik J, Sarubin N, et al. Prefrontal transcranial direct current stimulation for treatment of schizophrenia with predominant negative symptoms: a double-blind, sham-controlled proof-of-concept study. Schizophr Bull. 2016;42:1253–61. https://doi.org/10.1093/schbul/sbw041.
36. Kammen A, Cavaleri J, Lam J, Frank AC, Mason X, Choi W, et al. Neuromodulation of OCD: a review of invasive and non-invasive methods. Front Neurol. 2022;13: 909264. https://doi.org/10.3389/fneur.2022.909264.
37. Liu K, Yin M, Cai Z. Research and application advances in rehabilitation assessment of stroke. J Zhejiang Univ Sci B. 2022;23(8):625–41. https://doi.org/10.1631/jzus.B2100999.
38. Li Y, Chen K, Wang J, Lu H, Li X, Yang L, et al. Research progress on transcranial magnetic stimulation for post-stroke dysphagia. Front Behav Neurosci. 2022;16: 995614. https://doi.org/10.3389/fnbeh.2022.995614.
39. Ntemou E, Svaldi C, Jonkers R, Picht T, Rofes A. Verb and sentence processing with TMS: a systematic review and meta-analysis. Cortex. 2023;162:38–55. https://doi.org/10.1016/j.cortex.2023.01.005.
40. Arrington CN, Ossowski AE, Baig H, Persichetti E, Morris R. The impact of transcranial magnetic stimulation on reading processes: a systematic review. Neuropsychol Rev. 2023;33(1):255–77. https://doi.org/10.1007/s11065-022-09534-7.
41. Gersner R, Barnea-Ygael N, Tendler A. Moderators of the response to deep TMS for smoking addiction. Front Psychiatry. 2023;13:1079138. https://doi.org/10.3389/fpsyt.2022.1079138.
42. Zhou X, Li K, Chen S, Zhou W, Li J, Huang Q, et al. Clinical application of transcranial magnetic stimulation in multiple sclerosis. Front Immunol. 2022;13: 902658. https://doi.org/10.3389/fimmu.2022.902658.
43. Šoda J, Pavelin S, Vujović I, Rogić VM. Assessment of motor evoked potentials in multiple sclerosis. Sensors (Basel). 2023;23(1):497. https://doi.org/10.3390/s23010497.
44. Arora T, Desai N, Kirshblum S, Chen R. Utility of transcranial magnetic stimulation in the assessment of spinal cord injury: current status and future directions. Front Rehabil Sci. 2022;3:1005111. https://doi.org/10.3389/fresc.2022.1005111.
45. Lanza G, Fisicaro F, Dubbioso R, Ranieri F, Chistyakov AV, Cantone M, et al. A comprehensive review of transcranial magnetic stimulation in secondary dementia. Front Aging Neurosci. 2022;14: 995000. https://doi.org/10.3389/fnagi.2022.995000.
46. Julkunen P, Kimiskidis VK, Belardinelli P. Bridging the gap: TMS-EEG from lab to clinic. J Neurosci Methods. 2022;369: 109482. https://doi.org/10.1016/j.jneumeth.2022.109482.
47. Gefferie SR, Jiménez-Jiménez D, Visser GH, Helling RM, Sander JW, Balestrini S, et al. Transcranial magnetic stimulation-evoked electroencephalography responses as biomarkers for epilepsy: a review of study design and outcomes. Hum Brain Mapp. 2023;44(8):3446–60. https://doi.org/10.1002/hbm.26260.
48. Dong Q, Wang Y, Gu P, Shao R, Zhao L, Liu X, et al. The neuroprotective mechanism of low-frequency rTMS on nigral dopaminergic neurons of Parkinson's disease model mice. Parkinsons Dis. 2015. https://doi.org/10.1155/2015/564095.
49. Lozeron P, Poujois A, Richard A, Masmoudi S, Meppiel E, Woimant F, et al. Contribution of TMS and rTMS in the understanding of the pathophysiology and in the treatment of dystonia. Front Neural Circ. 2016;10:90. https://doi.org/10.3389/fncir.2016.00090.
50. Salatino A, Momo E, Nobili M, Berti A, Ricci R. Awareness of symptoms amelioration following low-frequency repetitive transcranial magnetic stimulation in a patient with Tourette syndrome and comorbid obsessive-compulsive disorder. Brain Stimul. 2014;7:341–3. https://doi.org/10.1016/j.brs.2014.01.002.
51. Jose L, Martins LB, Cordeiro TM, Lee K, Diaz AP, Ahn H, et al. Non-invasive neuromodulation methods to alleviate symptoms of Huntington's disease: a systematic review of the literature. J Clin Med. 2023;12(5):2002. https://doi.org/10.3390/jcm12052002.
52. Shiga Y, Tsuda T, Itoyama Y, Shimizu H, Miyazawa K, Jin K, et al. Transcranial magnetic stimulation alleviates truncal ataxia in spinocerebellar degeneration. J Neurol Neurosurg Psychiatry. 2002;72:124–6. https://doi.org/10.1136/jnnp.72.1.124.
53. Chen YH, Yang J, Wu H, Beier KT, Sawan M. Challenges and future trends in wearable closed-loop neuromodulation to efficiently treat methamphetamine addiction. Front Psychiatry. 2023;14:1085036. https://doi.org/10.3389/fpsyt.2023.1085036.

54. Belgers M, Van Eijndhoven P, Markus W, Schene AH, Schellekens A. rTMS reduces craving and alcohol use in patients with alcohol use disorder: results of a randomized, sham-controlled clinical trial. J Clin Med. 2022;11(4):951. https://doi.org/10.3390/jcm11040951.
55. Ziesel D, Nowakowska M, Scheruebel S, Kornmueller K, Schäfer U, Schindl R, et al. Electrical stimulation methods and protocols for the treatment of traumatic brain injury: a critical review of preclinical research. J Neuroeng Rehabil. 2023;20(1):51. https://doi.org/10.1186/s12984-023-01159-y.
56. Passera B, Chauvin A, Raffin E, Bougerol T, David O, Harquel S. Exploring the spatial resolution of TMS-EEG coupling on the sensorimotor region. Neuroimage. 2022;259: 119419. https://doi.org/10.1016/j.neuroimage.2022.119419.
57. Liu Y, Li Z, Bai Y. Frontal and parietal lobes play crucial roles in understanding the disorder of consciousness: a perspective from electroencephalogram studies. Front Neurosci. 2023;16:1024278. https://doi.org/10.3389/fnins.2022.1024278.
58. Hernandez-Pavon JC, Veniero D, Bergmann TO, Belardinelli P, Bortoletto M, Casarotto S, et al. TMS combined with EEG: recommendations and open issues for data collection and analysis. Brain Stimul. 2023;16(2):567–93. https://doi.org/10.1016/j.brs.2023.02.009.
59. Tăuţan AM, Casula EP, Pellicciari MC, Borghi I, Maiella M, Bonni S, et al. TMS-EEG perturbation biomarkers for Alzheimer's disease patients' classification. Sci Rep. 2023;13(1):7667. https://doi.org/10.1038/s41598-022-22978-4.
60. Simpson KN, Welch MJ, Kozel FA, Demitrack MA, Nahas Z. Cost-effectiveness of transcranial magnetic stimulation in the treatment of major depression: a health economics analysis. Adv Ther. 2009;26(3):346–68. https://doi.org/10.1007/s12325-009-0013-x.
61. Zis P, Shafique F, Hadjivassiliou M, Blackburn D, Venneri A, Iliodromiti S, et al. Safety, TOLERABILITY, and nocebo phenomena during transcranial magnetic stimulation: a systematic review and meta-analysis of placebo-controlled clinical trials. Neuromodulation. 2020;23(3):291–300. https://doi.org/10.1111/ner.12946.
62. Chen R, Spencer DC, Weston J, Nolan SJ. Transcranial magnetic stimulation for the treatment of epilepsy. Cochr Database Syst Rev. 2016. https://doi.org/10.1002/14651858.CD011025.pub2.
63. Loo CK, McFarquhar TF, Mitchell PB. A review of the safety of repetitive transcranial magnetic stimulation as a clinical treatment for depression. Int J Neuropsychopharmacol. 2008;11:131–47. https://doi.org/10.1017/S1461145707007717.
64. Cohen SL, Bikson M, Badran BW, George MS. A visual and narrative timeline of US FDA milestones for transcranial magnetic stimulation (TMS) devices. Brain Stimul. 2022;15(1):73–5. https://doi.org/10.1016/j.brs.2021.11.010.
65. Shah MR, Jampa A, Kaur M, Robert CA, Patel RS. Transcranial magnetic stimulation for major depressive disorder in pregnancy: a literature review. Cureus. 2019;11(8): e5431. https://doi.org/10.7759/cureus.5431.

Publisher's Note