Special Review

Transcranial Magnetic Stimulation and its Imaging Features in Patients With Depression, Post-traumatic Stress Disorder, and Traumatic Brain Injury

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Transcranial magnetic stimulation (TMS) is a type of noninvasive neurostimulation used increasingly often in clinical medicine. While most studies to date have focused on TMS's ability to treat major depressive disorder, it has shown promise in several other conditions including post-traumatic stress disorder (PTSD) and traumatic brain injury (TBI). As different treatment protocols are often used across studies, the ability to predict patient outcomes and evaluate immediate and long-term changes using imaging becomes increasingly important. Several imaging features, such as thickness, connectedness, and baseline activity of a variety of cortical and subcortical areas, have been found to be correlated with a greater response to TMS therapy. Intrastimulation imaging can reveal in real time how TMS applied to superficial areas activates or inhibits activity in deeper brain regions. Functional imaging performed weeks to months after treatment can offer an understanding of how long-term effects on brain activity relate to clinical improvement. Further work should be done to expand our knowledge of imaging features relevant to TMS therapy and how they vary across patients with different neurological and psychiatric conditions.

Key Words: transcranial magnetic stimulation; depression; post-traumatic stress disorder; traumatic brain injury; neuroimaging.

Abbreviations: **TMS** transcranial magnetic stimulation, **PTSD** post-traumatic stress disorder, **TBI** traumatic brain injury, **OCD** obsessive-compulsive disorder, **rTMS** repetitive TMS, **EEG** electroencephalogram, **fMRI** functional magnetic resonance imaging, **PET** positron emission tomography, **DTI** diffusion tensor imaging, **DLPFC** dorsolateral prefrontal cortex, **ACC** anterior cingulate cortex, **rACC** rostral anterior cingulate cortex, **sgACC** subgenual anterior cingulate cortex, **DMN** default mode network, **vmPFC** ventromedial prefrontal cortex, **SPECT** single-photon emission computed tomography, **HF-rTMS** high-frequency repetitive transcranial magnetic stimulation, **GMV** gray matter volume, **rCMRGlu** regional cerebral glucose metabolic rate, **rCBF** regional cerebral blood flow

BACKGROUND

Non-invasive neurostimulation refers to a set of technologies and techniques that use externally applied electrical or magnetic fields to modulate neuronal excitability (1,2). Transcranial magnetic stimulation (TMS)—the most commonly used noninvasive neurostimulation method—employs a generator which produces brief, high-intensity currents that travel through a wire coil positioned over the head to create a magnetic field perpendicular to the coil (3). This rapid change in the magnetic field induces an electrical current that travels into and through subjacent brain tissue (Fig 1) (4). As detailed in the following section, using different stimulation frequencies can potentiate or attenuate neuronal excitability and thus modulate neural network activity on a broad scale (5).

Although TMS has been FDA-approved only for treatment of major depression, obsessive-compulsive disorder (OCD), migraine with aura, anxiety with comorbid depression, and smoking cessation in the United States, it is under investigation for many other disorders, including post-traumatic stress disorder (PTSD), traumatic brain injury (TBI), and their sequelae (Table 1) (6–8). As TMS becomes used

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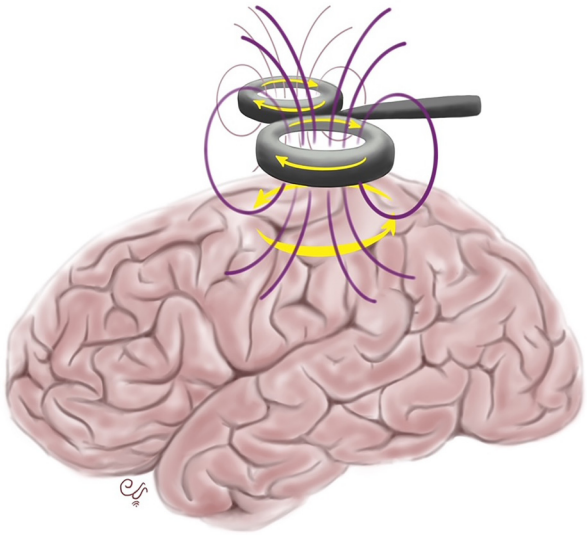

Fig 1. A current (yellow arrows, superior) runs through the TMS coil to generate a magnetic field (purple lines) perpendicular to the coil. This rapidly changing magnetic field creates an electric current (yellow arrows, inferior) that travels into subjacent brain tissue, changing neuronal excitability. Stimulation of different surface structures modulates neuronal excitability in a variety of deeper brain structures. (Color version of figure is available online.)

increasingly in the clinical realm, neuroradiologists may be in a unique position to investigate and interpret the pre-, intra-, and post-stimulation structural and functional findings of TMS in patients with neuropsychiatric disorders. Evaluation of the imaging correlates of TMS could help clinicians and patients predict treatment outcomes including long-term effects on brain function (9,10). Our goals in this review are to: (1) provide a brief explanation of TMS technology to the radiology community; (2) update readers on the current state of TMS therapy in the clinical realm; and (3) explore the role of imaging in TMS therapy. We hope to extend radiologists' understanding of the role they may play in TMS's continued development, growth, and implementation.

DEVICES AND TECHNIQUES USED IN TMS

Coils used in TMS have evolved from their initial large, circular shape that stimulated a large, ill-defined area of cortex to new sizes and shapes such as figure-eight, double cone, and Hesed coils (Fig 2), optimized to narrowly target deeper brain structures (11–13). The generated pulse that produces the magnetic field may be monophasic, with a short, fast first phase and a long, slow second phase, or biphasic, with two equal phases of opposite polarity (14). Biphasic pulses are used often clinically in what is referred to as repetitive TMS (rTMS). (15,16) This type of TMS relies on repeated low-frequency (≤1 Hz) neuronal stimulation to effect long-term depression of activity (17). At high frequencies (≥5 Hz), rTMS may result in long-term potentiation of neuronal activity (18). When repeated over days to weeks, such stimulation at low or high frequency can have durable effects and be effective in treating motor, mood, behavioral, and cognitive disorders (19). Other types of TMS, such as paired-pulse TMS (20,21, theta burst stimulation (22), and the triple

TABLE 1. Disorders and Associated Anatomical Areas Targeted by TMS

Type of Disorder	Condition	Superficial Brain Region(s) Stimulated
Psychiatric	Major depressive disorder* (40)	DLPFC
	Post-traumatic stress disorder (102)	DLPFC, M1
	Obsessive-compulsive disorder* (103)	DLPFC
	Anxiety with comorbid major depressive disorder* (104)	DLPFC
Movement	Parkinson's disease (105)	DLPFC, M1
	Multiple sclerosis (106)	M1
	Amyotrophic lateral sclerosis (24)	M1
	Spasticity (107)	M1
Brain damage and neurorehabilitation	Aphasia (66)	Right Broca's area homolog
	Paralysis (67)	M1
	Consciousness disturbance (68)	Right DLPFC
Other	Headache (108)	Left M1
	Migraine with aura* (109)	Occipital lobe
	Alzheimer's dementia (110)	DLPFC, Broca's area, Wernicke's area, somatosensory association cortices
	Dizziness (111)	Left DLPFC
	Spinal cord injury (112)	M1, thoracic spine (T8), premotor cortex
	Epilepsy (113)	Epileptogenic foci (variable)
	Tinnitus (114)	Auditory cortex
	Chronic pain (115)	M1
	Smoking cessation* (116)	Left DLPFC

* Only FDA-approved conditions treated by TMS in the USA as of 2022.

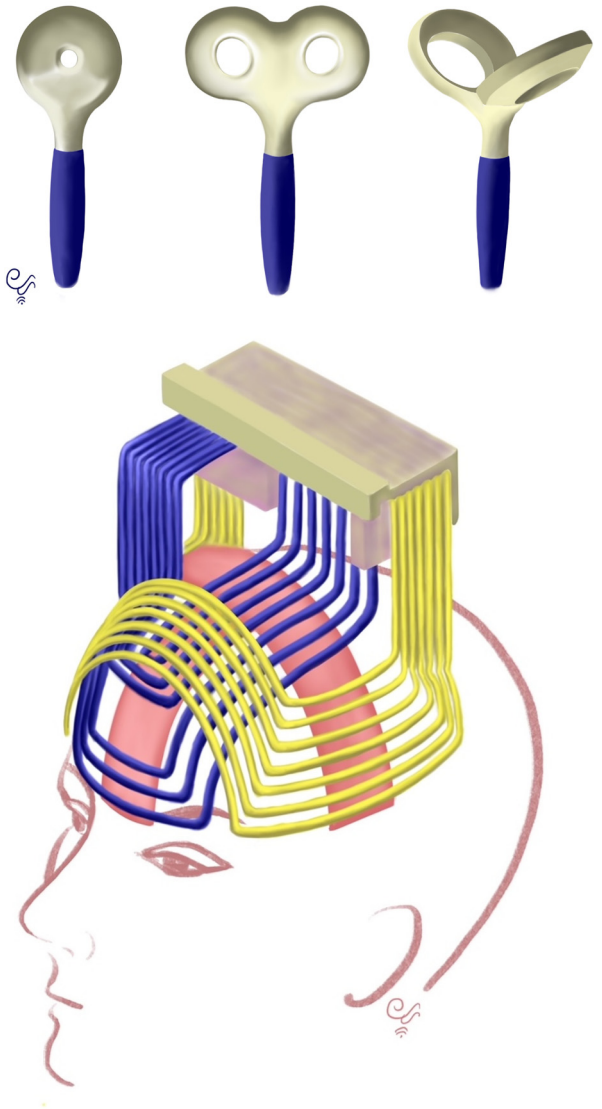

Fig 2. Multiple coil types have been used for TMS, including the original circular coil (top left), the figure-of-eight coil (top middle), double cone coils (top right), and Hesed (H) coils (bottom). H coils are larger than previous coil types, contour the shape of the skull, and are used most often today to target deeper brain structures. (Color version of figure is available online.)

stimulation technique (23) can be used to investigate interhemispheric effects of stimulation, reduce conditioning time for treatment, and diagnose upper motor neuron or lower motor neuron defects, such as in amyotrophic lateral sclerosis (24).

Accurate and precise localization of brain areas for stimulation is critical for TMS therapy to be effective. TMS target sites have routinely been determined according to specific distances measured along the scalp or by electroencephalogram (EEG) electrode location (25,26). Subsequent studies, however, have demonstrated the advantage of image-guided navigation techniques in terms of accuracy and reproducibility of coil placement and consequently cortical stimulation (27,28). The use of these techniques presents an opportunity for radiologists to contribute to the expanding role of TMS. Currently clinically available neuro-navigation systems use either a patient's own MRI information for real-time dynamic navigation of the magnet or a template brain such as the Montreal Neurological Institute (MNI) template to estimate target location (29,30). Once the optimal target has been identified via neuroimaging, fiducial markers can be applied to the scalp to locate the point that overlies the previously identified cortical target. Alternatively, various cranial landmarks (e.g., nasion, inion vertex, tragus) can be used to calculate the distances between each landmark and the cortical target (31).

Other methods such as functional MRI (fMRI), positron emission tomography (PET), diffusion tensor imaging (DTI), and frameless stereotactic systems have also shown promise in improving reproducibility of coil placement and should be further investigated to optimize treatment outcomes (31–35). A frameless stereotactic system is a state-of-the-art apparatus that involves 3D reconstruction of neuroanatomy to visualize the location and orientation of the TMS coil over the head while also allowing for real-time visualization of electric field density within the cortex during TMS therapy. While technologically advanced, this navigational procedure performs better than standard procedures at replicating conditions across TMS treatment sessions and, as such, should be encouraged for use if possible (36).

CLINICAL EFFICACY OF TMS

As major depressive disorder is one of the only FDA-approved conditions approved to be treated with TMS, most studies have focused on the efficacy of TMS related to depressive symptoms, although some have also included effects on other aspects of neuropsychiatric health and have included patients with PTSD and TBI (37). When considering the effects of TMS on patients with depression, it is important to also include patients with PTSD and TBI-related deficits, as these conditions often co-occur with depression. Depressed patients without comorbid PTSD or TBI may respond to TMS differently and have different imaging findings compared to depressed patients who do have these conditions. As such, our understanding of the effectiveness of TMS and its imaging features would be boosted by a more nuanced approach that incorporates patients who have multiple comorbid neuropsychiatric conditions.

Studies examining the efficacy of TMS have found variable results, likely in part due to the heterogeneity of patient populations, treatment design, and outcome measures. Several studies have found insignificant effects of TMS on depression in PTSD and TBI, self-reported PTSD symptoms, and suicidal thinking (38–41). Other studies, however, have found that TMS significantly improves symptoms of TBI and PTSD. In patients with TBI, TMS has been found to significantly reduce headache and symptoms of depression and to improve visual attention, task switching, and executive functioning (39,42,43). TMS in patients with PTSD has been

shown to improve fear and anxiety responses (44), social and occupational function (38), core PTSD symptoms (45), anxiety (46), avoidance (47), somatization (48), re-experiencing, and hyperarousal (49), while reducing clinical relapse (50). A few studies have also found that combining TMS with other therapies such as exposure therapy (51) or cognitive processing therapy (52) is safe, feasible, and likely augments the effectiveness of TMS.

While TMS shows promising results for many patients with TBI-related depression, PTSD, and other neuropsychiatric conditions, its effect in many cases appears to be variable, dependent on the measures used to evaluate symptoms, or on the patient population. The emphasis in future studies will be determining for which patient populations and neuropsychiatric disorders TMS is most effective. Radiologists may play a pivotal role in these studies by helping to customize treatment protocols based on imaging findings.

IMAGING FINDINGS IN TMS THERAPY

Imaging the brain before, during, and after TMS is essential for investigators' and clinicians' understanding of how preexisting features, immediate activity changes, and long-term neuronal alterations influence patient response to treatment. While most studies have focused on how TMS affects imaging features in patients with depression, a few recent ones have expanded the patient population to include people with TBI, PTSD, and related disorders.

Prestimulation findings

Performing imaging before beginning TMS therapy can help radiologists and clinicians predict for which patients TMS may be most helpful. Analysis of structural MRI, for example, may reveal certain morphological characteristics that predict improved response. In 2018, Boes et al. treated depressed patients with rTMS and found that the thickness of the left rostral anterior cingulate cortex (rACC) is inversely related to clinical improvement, i.e., a thinner ACC (commonly reported in depressed patients (53,54) is associated with greater responsiveness to TMS (Supplemental Table 1) (55).

In addition to structural features of the ACC, its functional connectivity has also been implicated in response to TMS therapy in depressed patients. A higher baseline connectivity between the rACC and left lateral parietal cortex is associated with better long-term response to TMS. Together, these data suggest that patients with a thinner rACC that has more robust connectivity to the lateral parietal cortex respond better to TMS therapy.

In patients with comorbid PTSD and depression, clinical response may be predicted by baseline inverse correlation between the subgenual ACC (sgACC) and default mode network (DMN), anticorrelation of cross-network activity, positive connectivity within the DMN, and positive connectivity between the ventromedial prefrontal cortex (vmPFC) and amygdala (38,50,56).

Connectivity of the sgACC and dorsolateral prefrontal cortex (DLPFC) may also be related to response to TMS, but the current evidence is controversial. Some studies have found that hypoconnectivity between the sgACC and the DLPFC stimulation site predicts improvements in depressive symptoms following TMS (57−61), whereas others have found that sgACC and DLPFC hyperconnectivity predicts better long-term outcomes (62,63). Apart from the ACC, other authors have found that higher functional connectivity between the DLPFC and deeper brain structures such as the striatum (64) and caudate (65) may also predict responsiveness to TMS in treatment-resistant depression.

Considering patients with TBI, routine MR imaging typically shows areas of gliosis, encephalomalacia, residual hemosiderin, and focal volume loss. The impact of these factors on the effectiveness of TMS has not been thoroughly evaluated and may explain some of TMS's variable efficacy in TBI sequelae such as aphasia (66), paralysis (67), consciousness disturbances (68), and motor weakness (69,70).

Apart from structural and functional MRI, other metabolic imaging (e.g., PET, single-photon emission computed tomography [SPECT]) may provide further evidence of features most predictive of a clinical response. In depressed patients compared to controls, baseline imaging typically shows metabolic alterations of prefrontal, cingulate, and temporal cortices as well as several limbic and subcortical regions (71,72). Patients with medication-resistant depression who respond to TMS may have a significantly higher baseline metabolism in the bilateral medial PFC and rACC and a lower metabolism in limbic structures (left parahippocampal and fusiform gyri) versus nonresponders (73). A positive correlation between FDG PET activity in the ACC has also been noted among responders, whereas lack of response to TMS has been associated with a lower glucose uptake in the left DLPFC and bilateral insula along with a higher uptake in the left amygdala and uncus. The hypometabolism in the left DLPFC and bilateral insula noted in nonresponders, however, could be partially explained by decreased gray matter volume (74). A later study further implicated the ACC, finding that metabolic activity of the sgACC predicted clinical outcomes to high-frequency rTMS (HF-rTMS), with higher baseline activity predicting a better response (75).

Although cerebral activity may provide clues as to which patients may improve from TMS, it is imperative that the TMS protocol be accounted for. In fact, patients who improve on one protocol may worsen on another; (76) patients with baseline hypoperfusion have been shown to worsen clinically when low-frequency (1 Hz) TMS was applied and to improve when high-frequency (20 Hz) TMS was applied, and vice-versa for patients with hypermetabolic brains (77). Apart from frequency used, the site to which TMS is applied likely also influences physiological and clinical response (78). As exemplified by patients with large structural changes poststroke, TMS protocols should be modified for individual patients according to their underlying brain physiology and health (79).

Overall, while several studies have implicated baseline functional connectivity in eventual treatment outcome, it remains unclear exactly which imaging features best predict clinical response and how strongly response to TMS depends on the treatment regimen used. Many of the regions implicated in TMS-treated depression, including the medial prefrontal, temporal, and dorsolateral prefrontal cortices; cerebellum; and amygdala are altered at rest in patients with PTSD (80–82). Given that the brains of patients with PTSD or TBI differ from patients without these conditions, it is plausible that the imaging features which predict their clinical response to TMS differ as well. Future studies should investigate which features of these patients' unique underlying brain states best predict response to TMS.

Intra- and peri-stimulation findings

Simultaneous TMS and neuroimaging allows clinicians and investigators an opportunity to observe changes in brain activity that occur during and immediately after stimulation. As long-term structural or functional changes may not represent the short-term changes in brain activity following neurostimulation, investigators have sought to understand both the initial changes in brain circuitry following TMS and how they develop into lasting alterations in neurophysiology (83).

Despite the technical difficulties inherent in concurrent stimulation and imaging (84,85), several studies have been able to shed light on the immediate changes in the brains of depressed patients undergoing TMS. One such study found that low-frequency TMS applied over the left prefrontal cortex immediately increases activity (measured by BOLD fMRI) at the stimulation site and at several associated limbic structures while decreasing activity in the right ventromedial prefrontal cortex (86). Patients with more severe depression were also found to have higher BOLD activity in the right insula during stimulation.

Concurrent TMS-fMRI imaging studies performed with healthy, non-depressed patients have also been used to better understand the relation between TMS and depression. As discussed earlier, the sgACC is linked to depression (87), and its baseline connectivity and activity may predict response to TMS. Until recently, however, it was unclear how TMS affected the sgACC. In 2018, Vink et al. used TMS-fMRI to show that stimulation of the DLPFC propagates to the sgACC in some (but not all) healthy patients, possibly explaining part of TMS's effectiveness in treating depression (Fig 3) (88). Furthermore, the authors suggested that a lack of such propagation from the DLPFC to the sgACC may predict a poor long-term response to treatment in patients with depression.

Beyond the link between DLPFC and sgACC, stimulation of the DLPFC with different frequencies has also been found to produce different downstream effects during therapy. High-frequency stimulation increases blood flow to the posterior cingulate cortex as well as the inferior frontal cortices, right dorsomedial frontal cortex, and the parahippocampal region, whereas low-frequency stimulation increases blood flow to the right ACC, bilateral parietal cortices, bilateral insula, and the left cerebellum (89). This relationship between stimulation frequency and blood flow to different brain areas in depressed patients may be crucial for understanding treatment response.

Post-stimulation findings

Structural imaging

After TMS, a variety of structural changes can be appreciated on brain imaging. Gray matter volume (GMV) may serve as one important indicator of treatment efficacy. In patients with depression, rTMS applied to the DLPFC over 4–7 weeks has been found to increase GMV in several brain areas including the left ACC as well as the left middle temporal gyrus, left insula, and the right angular gyrus (55,90). Only GMV change in the ACC, however, was found to correlate positively with the clinical depression score. Although very few studies have examined structural changes following TMS in depressed patients (including TBI- and PTSD-related depression), such changes have been shown to occur in patients with tinnitus (decreased thickness of the rACC and temporal lobe and increased thickness of frontal lobe) (91), schizophrenia (increased GMV of the hippocampal, parahippocampal, and precuneal cortices) (92), and Parkinson's disease (increased GMV of the left globus pallidus) (93).

Functional imaging

While TMS may produce some gross structural changes, its efficacy more likely lies in its ability to induce long-term changes in functional connectivity and activity of the brain, resulting in clinical effects that last greater than one year for many patients (94). This is true especially for depression, given the shift towards the idea that symptoms result from perturbations of large-scale brain networks rather than dysfunction of a single structure (95).

Investigators have recently gained better insight into the changes induced by TMS by employing a variety of functional imaging techniques (e.g., DTI, fMRI, PET, SPECT). As mentioned previously, baseline connectivity of the DLPFC and ACC predicts response to TMS. Following TMS treatment in patients with TBI-related depression, sgACC-DLPFC connectivity (via resting-state fMRI) has been found to decrease with concomitant improvement in symptoms of depression (59). This decreased sgACC-DLPFC connectivity and resulting symptom improvement, however, may be mediated by connectivity between the sgACC and left occipitotemporal region (fusiform gyrus) (57).

Considering PET findings, patients with treatment-resistant depression who respond to TMS experienced a reduction in the hypermetabolism of the left middle temporal cortex and the fusiform gyrus in weeks to months following

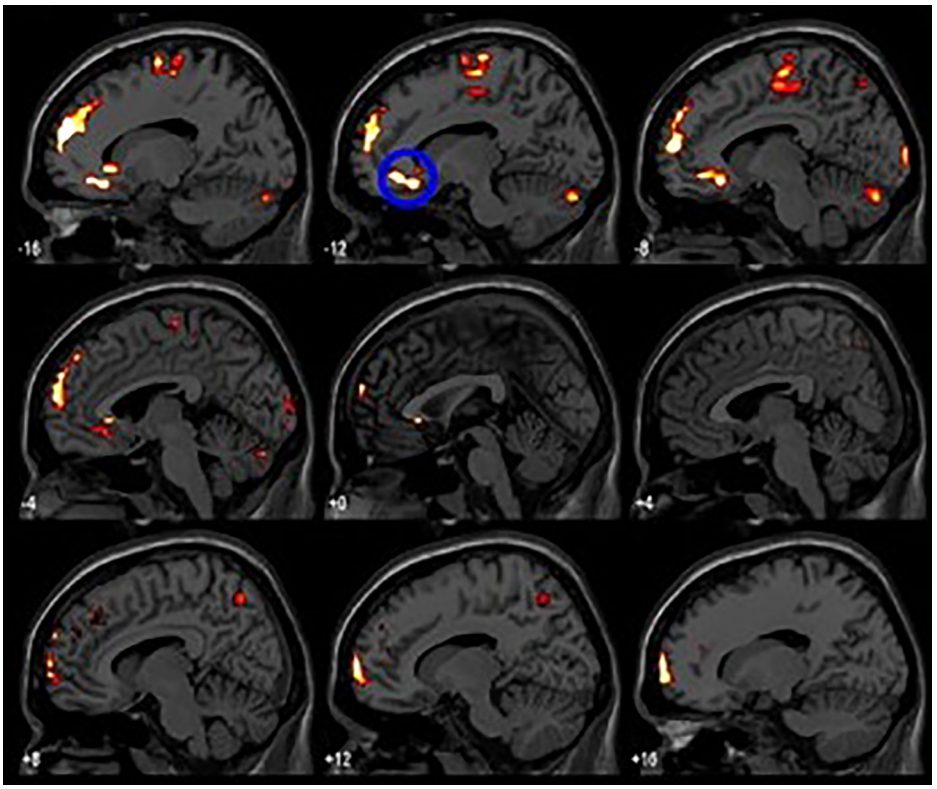

Fig 3. TMS pulses over the DLPFC at 115% of resting motor threshold interleaved with pulses at 60% of resting motor threshold in one patient (first row, second column) induce activity in the sgACC (blue circle) as seen on T1-weighted images with overlaid BOLD activity. A lack of propagation from the DLPFC to sgACC may be an important predictor of response to TMS therapy in depressed patients. (Reproduced from Vink et al. (88)) (Color version of figure is available online.)

treatment; the opposite response occurred in nonresponders (73,96). Also in responders, metabolism in the middle cingulum, bilateral somatosensory areas, and precuneus increased significantly. But despite treatment, the metabolic profile of responders' brains did not return to that of healthy controls. In a depressed patient who underwent TMS therapy, decreased metabolism in several areas of the frontal lobe was reversed following treatment (Fig 4).

Several studies have used SPECT imaging to investigate the changes in brain connectivity and activity post-TMS.

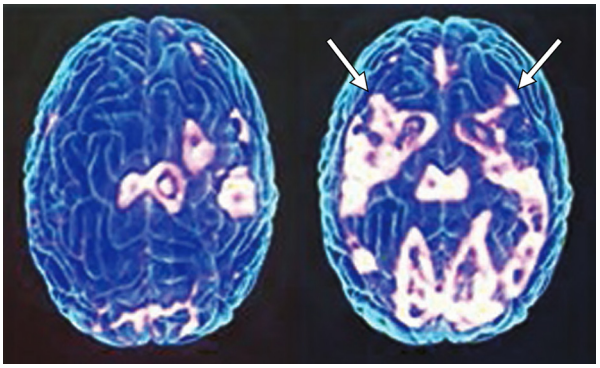

Fig 4. In a single patient with depression, 18-FDG PET scans at rest before (left) and after (right) TMS therapy reveal a reversal in hypometabolism of several areas (arrows) of the frontal lobe. (Color version of figure is available online.)

Authors in one study observed changes in regional cerebral glucose metabolic rate (rCMRGlu) with ^{18}F-FDG and regional ^{99m}Tc HMPAO uptake rate (regional cerebral blood flow, rCBF) after two weeks of low-frequency rTMS (97). For both rCMRGlu and rCBF, dorsal frontal regions bilaterally experienced increased uptake rates, and the left orbitofrontal cortex experienced decreased uptake rates. A predominant right-sided increase in uptake rates of rCBF but not rCMRGlu was also observed.

Alterations in rCBF have been implicated in depression remission in several other studies with mixed results. Interestingly, both high and low-frequency TMS have been found to improve symptoms of depression through different alterations in blood flow to the cingulate cortex. With low-frequency TMS, symptom improvement was associated with *decreased* rCBF in the right sgACC, bilateral prefrontal and orbitofrontal cortices, anterior insula, and left parietal cortex (98). Improved symptoms with high-frequency TMS was associated with *increased* rCBF in the left sgACC, anterior insula, right putamen, and the left DLPFC, VLPFC, and right orbitofrontal cortex (99). These contrasting findings may be explained by the different TMS frequencies used in the studies or the timing of post-treatment imaging, as short-term changes in brain activity may not reflect the long-term changes. Finally, an earlier study by Teneback et al. found that depressed patients who responded to two weeks of TMS

treatment experienced increased SPECT activity in the cingulate cortex and bilateral inferior frontal lobes relative to baseline (100).

FUTURE DIRECTIONS OF TMS

TMS and its derivatives have entered the clinical realm. While FDA-approved for only a few conditions, TMS has shown promise in treating symptoms of depression, PTSD, TBI, and myriad other disorders. Despite studies detailing its clinical impact, many questions remain about the most appropriate stimulation sites, frequency, and duration to achieve the desired outcome. The variability in these factors inevitably obscures attempts to measure outcomes, including imaging studies that attempt to predict and quantify clinical response according to differences in brain structure and activity. While additional studies are being performed that attempt to untangle these questions of best use practices, simultaneous exploration of novel TMS-related avenues such as better navigation techniques for coil placement and continued investigation into TMS-specific imaging features can accelerate the development of more effective treatment options.

TMS may also benefit from more frequent imaging investigations throughout the course of treatment. As the majority of studies imaged participants before and at one time point after therapy, it is largely unclear what changes in neuronal connectivity and/or brain morphology occur in response to stimulation. Serial investigations following therapy may better elucidate the processes the brain undergoes in responders versus non-responders, and would be especially helpful in understanding neural changes during remission, relapse, and long-term resolution.

The full potential of TMS may be realized as an adjunctive therapy. Given that the effects of psychopharmacological treatment can lead to changes in (functional) neuroimaging, it would be beneficial to know to what extent TMS influences drug-based treatment and how the interplay of these two treatments affects brain structure and function. There are currently few studies that investigate the effects of psychiatric medications on TMS outcomes.

Finally, as discussed in Philip et al., standardized reporting of TMS imaging outcomes will be important for the therapy's future (101). Currently, many studies use unclear terms such as "anticorrelation" when comparing changes in brain activity, which could refer to a reduction in correlation (i.e., nearer to zero) or a stronger negative correlation. While other examples exist, imaging professionals should strive to adopt a clear set of terms when describing connectivity or correlation changes effected by TMS; specifically, changes in degree of correlation should be stated in addition to the positivity or negativity of correlation. More straightforward reporting would allow easier synthesis of findings across different studies using different protocols.

Role of the radiologist

Radiologists can spearhead TMS advancements as both imaging experts and data curators. There is currently a dearth of data on pre-, intra-, and post-treatment imaging features in patients who receive TMS therapy, especially for patients with conditions other than depression. As TMS usage expands to include other conditions, radiologists are well-suited to determine the structural and circuit-level changes that occur in relation to the patient's underlying brain state. Finally, TMS is likely to benefit from the general technical advancements in radiology. Pre-treatment personalized planning can be enhanced by more precise localization techniques such as 3D-MRI, event-related optical signals, and diffuse optical imaging. By continuing to promote advancements in imaging techniques including "on-line" methods such as fMRI-TMS or PET-TMS, radiologists can also help better characterize the immediate effects of TMS on the brain.

CONCLUSION

Although to date TMS has mostly been used for treatment of depression, its clinical use is rapidly expanding to include many other psychiatric and neurological conditions. This growth may be especially helpful for patients with PTSD or TBI, as these patients often suffer from several symptoms or other conditions concurrently. Imaging studies so far have identified some features that predict treatment response, intra-therapy effects of TMS, and connectivity changes post-treatment. While MRI localization techniques may be an effective method to target specific sites for TMS, further investigation is needed to determine whether its increased accuracy and precision is worth the increased cost relative to localization via EEG or scalp measurements. Radiologists can play a central role in this emerging therapeutic tool by using their imaging knowledge and technical expertise to help clinicians accurately target therapy, identify which patients are the best candidates for TMS therapy, and measure the long-term impact of TMS on patients' brain structure and function.

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REFERENCES

1. Rossini PM, Burke D, Chen R, et al. Non-invasive electrical and magnetic stimulation of the brain, spinal cord, roots and peripheral nerves: Basic principles and procedures for routine clinical and research

application. An updated report from an I.F.C.N. Committee. Clin Neurophysiol Off J Int Fed Clin Neurophysiol 2015; 126(6):1071–1107. doi:10.1016/j.clinph.2015.02.001.
2. Valero-Cabré A, Amengual JL, Stengel C, et al. Transcranial magnetic stimulation in basic and clinical neuroscience: a comprehensive review of fundamental principles and novel insights. Neurosci Biobehav Rev 2017; 83:381–404. doi:10.1016/j.neubiorev.2017.10.006.
3. Nollet H, Van Ham L, Deprez P, et al. Transcranial magnetic stimulation: review of the technique, basic principles and applications. Vet J Lond Engl 1997; 166(1):28–42. doi:10.1016/s1090-0233(03)00025-x. 2003.
4. Klomjai W, Katz R, Lackmy-Vallée A. Basic principles of transcranial magnetic stimulation (TMS) and repetitive TMS (rTMS). Ann Phys Rehabil Med 2015; 58(4):208–213. doi:10.1016/j.rehab.2015.05.005.
5. Ahmed Z, Wieraszko A. Modulation of learning and hippocampal, neuronal plasticity by repetitive transcranial magnetic stimulation (rTMS). Bioelectromagnetics 2006; 27(4):288–294. doi:10.1002/bem.20211.
6. Namgung E, Kim M, Yoon S. Repetitive transcranial magnetic stimulation in trauma-related conditions. Neuropsychiatr Dis Treat 2019; 15:701–712. doi:10.2147/NDT.S189498.
7. Burke MJ, Fried PJ, Pascual-Leone A. Transcranial magnetic stimulation: Neurophysiological and clinical applications. Handb Clin Neurol 2019; 163:73–92. doi:10.1016/B978-0-12-804281-6.00005-7.
8. Cohen SL, Bikson M, Badran BW, et al. A visual and narrative timeline of US FDA milestones for Transcranial Magnetic Stimulation (TMS) devices. Brain Stimulat 2022; 15(1):73–75. doi:10.1016/j.brs.2021.11.010.
9. Luber BM, Davis S, Bernhardt E, et al. Using neuroimaging to individualize TMS treatment for depression: toward a new paradigm for imaging-guided intervention. NeuroImage 2017; 148:1–7. doi:10.1016/j.neuroimage.2016.12.083.
10. Esposito R, Bortoletto M, Miniussi C. Integrating TMS, EEG, and MRI as an approach for studying brain connectivity. Neurosci Rev J Bringing Neurobiol Neurol Psychiatry 2020; 26(5-6):471–486. doi:10.1177/1073858420916452.
11. 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(10):5862–5864. doi:10.1063/1.342181.
12. Deng ZD, Lisanby SH, Peterchev AV. Coil design considerations for deep transcranial magnetic stimulation. Clin Neurophysiol Off J Int Fed Clin Neurophysiol 2014; 125(6):1202–1212. doi:10.1016/j.clinph.2013.11.038.
13. Zangen A, Roth Y, Voller B, et al. Transcranial magnetic stimulation of deep brain regions: evidence for efficacy of the H-coil. Clin Neurophysiol Off J Int Fed Clin Neurophysiol 2005; 116(4):775–779. doi:10.1016/j.clinph.2004.11.008.
14. Salvador R, Silva S, Basser PJ, et al. Determining which mechanisms lead to activation in the motor cortex: a modeling study of transcranial magnetic stimulation using realistic stimulus waveforms and sulcal geometry. Clin Neurophysiol Off J Int Fed Clin Neurophysiol 2011; 122(4):748–758. doi:10.1016/j.clinph.2010.09.022.
15. Sommer M, Ciocca M, Chieffo R, et al. TMS of primary motor cortex with a biphasic pulse activates two independent sets of excitable neurones. Brain Stimulat 2018; 11(3):558–565. doi:10.1016/j.brs.2018.01.001.
16. Arai N, Okabe S, Furubayashi T, et al. Comparison between short train, monophasic and biphasic repetitive transcranial magnetic stimulation (rTMS) of the human motor cortex. Clin Neurophysiol Off J Int Fed Clin Neurophysiol 2005; 116(3):605–613. doi:10.1016/j.clinph.2004.09.020.
17. Chen R, Classen J, Gerloff C, et al. Depression of motor cortex excitability by low-frequency transcranial magnetic stimulation. Neurology 1997; 48(5):1398–1403. doi:10.1212/wnl.48.5.1398.
18. Pascual-Leone A, Valls-Solé J, Wassermann EM, et al. Responses to rapid-rate transcranial magnetic stimulation of the human motor cortex. Brain J Neurol 1994; 117(Pt 4):847–858. doi:10.1093/brain/117.4.847.
19. Lefaucheur JP, André-Obadia N, Antal A, et al. Evidence-based guidelines on the therapeutic use of repetitive transcranial magnetic stimulation (rTMS). Clin Neurophysiol Off J Int Fed Clin Neurophysiol 2014; 125(11):2150–2206. doi:10.1016/j.clinph.2014.05.021.
20. Valls-Solé J, Pascual-Leone A, Wassermann EM, et al. Human motor evoked responses to paired transcranial magnetic stimuli. Electroencephalogr Clin Neurophysiol 1992; 85(6). doi:10.1016/0168-5597(92)90048-g.
21. Ferbert A, Priori A, Rothwell JC, et al. Interhemispheric inhibition of the human motor cortex. J Physiol 1992; 453:525–546. doi:10.1113/jphysiol.1992.sp019243.
22. Huang YZ, Sommer M, Thickbroom G, et al. Consensus: New methodologies for brain stimulation. Brain Stimulat 2009; 2(1):2–13. doi:10.1016/j.brs.2008.09.007.
23. Magistris MR, Rösler KM, Truffert A, et al. Transcranial stimulation excites virtually all motor neurons supplying the target muscle. A demonstration and a method improving the study of motor evoked potentials. Brain J Neurol 1998; 121(Pt 3):437–450. doi:10.1093/brain/121.3.437.
24. Rösler KM, Truffert A, Hess CW, et al. Quantification of upper motor neuron loss in amyotrophic lateral sclerosis. Clin Neurophysiol Off J Int Fed Clin Neurophysiol 2000; 111(12):2208–2218. doi:10.1016/s1388-2457(00)00481-8.
25. Conforto AB, Z'Graggen WJ, Kohl AS, et al. Impact of coil position and electrophysiological monitoring on determination of motor thresholds to transcranial magnetic stimulation. Clin Neurophysiol Off J Int Fed Clin Neurophysiol 2004; 115(4):812–819. doi:10.1016/j.clinph.2003.11.010.
26. Beam W, Borckardt JJ, Reeves ST, et al. An efficient and accurate new method for locating the F3 position for prefrontal TMS applications. Brain Stimulat 2009; 2(1):50–54. doi:10.1016/j.brs.2008.09.006.
27. Sparing R, Buelte D, Meister IG, et al. Transcranial magnetic stimulation and the challenge of coil placement: a comparison of conventional and stereotaxic neuronavigational strategies. Hum Brain Mapp 2008; 29(1):82–96. doi:10.1002/hbm.20360.
28. Wall CA, Croarkin PE, Maroney-Smith MJ, et al. Magnetic resonance imaging-guided, open-label, high-frequency repetitive transcranial magnetic stimulation for adolescents with major depressive disorder. J Child Adolesc Psychopharmacol 2016; 26(7):582–589. doi:10.1089/cap.2015.0217.
29. Fox MD, Liu H, Pascual-Leone A. Identification of reproducible individualized targets for treatment of depression with TMS based on intrinsic connectivity. NeuroImage 2013; 66:151–160. doi:10.1016/j.neuroimage.2012.10.082.
30. Cash RFH, Weigand A, Zalesky A, et al. Using brain imaging to improve spatial targeting of transcranial magnetic stimulation for depression. Biol Psychiatry 2021; 90(10):689–700. doi:10.1016/j.biopsych.2020.05.033.
31. Lefaucheur JP. Why image-guided navigation becomes essential in the practice of transcranial magnetic stimulation. Neurophysiol Clin Neurophysiol 2010; 40(1):1–5. doi:10.1016/j.neucli.2009.10.004.
32. Ahdab R, Ayache SS, Brugières P, et al. Comparison of "standard" and "navigated" procedures of TMS coil positioning over motor, premotor and prefrontal targets in patients with chronic pain and depression. Neurophysiol Clin Clin Neurophysiol 2010; 40(1):27–36. doi:10.1016/j.neucli.2010.01.001.
33. Herwig U, Padberg F, Unger J, et al. Transcranial magnetic stimulation in therapy studies: examination of the reliability of "standard" coil positioning by neuronavigation. Biol Psychiatry 2001; 50(1):58–61. doi:10.1016/s0006-3223(01)01153-2.
34. Neggers SFW, Langerak TR, Schutter DJLG, et al. A stereotactic method for image-guided transcranial magnetic stimulation validated with fMRI and motor-evoked potentials. NeuroImage 2004; 21(4):1805–1817. doi:10.1016/j.neuroimage.2003.12.006.
35. Quesada C, Pommier B, Fauchon C, et al. Robot-guided neuronavigated repetitive Transcranial Magnetic Stimulation (rTMS) in central neuropathic pain. Arch Phys Med Rehabil 2018; 99(11):2203–2215. doi:10.1016/j.apmr.2018.04.013. e1.
36. Schönfeldt-Lecuona C, Lefaucheur JP, Cardenas-Morales L, et al. The value of neuronavigated rTMS for the treatment of depression. Neurophysiol Clin Clin Neurophysiol 2010; 40(1):37–43. doi:10.1016/j.neucli.2009.06.004.
37. Perera T, George MS, Grammer G, et al. The clinical TMS society consensus review and treatment recommendations for TMS therapy for major depressive disorder. Brain Stimulat 2016; 9(3):336–346. doi:10.1016/j.brs.2016.03.010.
38. Philip NS, Barredo J, Aiken E, et al. Theta-Burst Transcranial Magnetic Stimulation for Posttraumatic Stress Disorder. Am J Psychiatry 2019; 176(11):939–948. doi:10.1176/appi.ajp.2019.18101160.
39. Hoy KE, McQueen S, Elliot D, et al. A pilot investigation of repetitive transcranial magnetic stimulation for post-traumatic brain injury depression: safety, tolerability, and efficacy. J Neurotrauma 2019; 36(13):2092–2098. doi:10.1089/neu.2018.6097.
40. Rao V, Bechtold K, McCann U, et al. Low-frequency right repetitive transcranial magnetic stimulation for the treatment of depression after traumatic brain injury: a randomized sham-controlled pilot study. J

Neuropsychiatry Clin Neurosci 2019; 31(4):306–318. doi:10.1176/appi.neuropsych.17110338.
41. George MS, Raman R, Benedek DM, et al. A two-site pilot randomized 3 day trial of high dose left prefrontal repetitive transcranial magnetic stimulation (rTMS) for suicidal inpatients. Brain Stimulat 2014; 7(3):421–431. doi:10.1016/j.brs.2014.03.006.
42. Leung A, Shukla S, Fallah A, et al. Repetitive transcranial magnetic stimulation in managing mild traumatic brain injury-related headaches. Neuromodulation J Int Neuromodulation Soc 2016; 19(2):133–141. doi:10.1111/ner.12364.
43. Meek BP, Hill S, Modirrousta M. Accelerated repetitive transcranial magnetic stimulation in the treatment of post-concussion symptoms due to mild traumatic brain injury: a pilot study. Brain Inj 2021; 35(1):48–58. doi:10.1080/02699052.2020.1857837.
44. Balderston NL, Beydler EM, Goodwin M, et al. Low-frequency parietal repetitive transcranial magnetic stimulation reduces fear and anxiety. Transl Psychiatry 2020; 10(1):68. doi:10.1038/s41398-020-0751-8.
45. Cohen H, Kaplan Z, Kotler M, et al. Repetitive transcranial magnetic stimulation of the right dorsolateral prefrontal cortex in posttraumatic stress disorder: a double-blind, placebo-controlled study. Am J Psychiatry 2004; 161(3):515–524. doi:10.1176/appi.ajp.161.3.515.
46. Rosenberg PB, Mehndiratta RB, Mehndiratta YP, et al. Repetitive transcranial magnetic stimulation treatment of comorbid posttraumatic stress disorder and major depression. J Neuropsychiatry Clin Neurosci 2002; 14(3):270–276. doi:10.1176/jnp.14.3.270.
47. Nam DH, Pae CU, Chae JH. Low-frequency, repetitive transcranial magnetic stimulation for the treatment of patients with posttraumatic stress disorder: a double-blind, sham-controlled study. Clin Psychopharmacol Neurosci 2013; 11(2):96–102. doi:10.9758/cpn.2013.11.2.96.
48. Grisaru N, Amir M, Cohen H, et al. Effect of transcranial magnetic stimulation in posttraumatic stress disorder: a preliminary study. Biol Psychiatry 1998; 44(1):52–55. doi:10.1016/S0006-3223(98)00016-X.
49. Oznur T, Akarsu S, Celik C, et al. Is transcranial magnetic stimulation effective in treatment-resistant combat related posttraumatic stress disorder? Neurosci Riyadh Saudi Arab 2014; 19(1):29–32.
50. Petrosino NJ, Wout-Frank M van 't, Aiken E, et al. One-year clinical outcomes following theta burst stimulation for post-traumatic stress disorder. Neuropsychopharmacol Off Publ Am Coll Neuropsychopharmacol 2020; 45(6):940–946. doi:10.1038/s41386-019-0584-4.
51. Fryml LD, Pelic CG, Acierno R, et al. Exposure therapy and simultaneous repetitive transcranial magnetic stimulation: a controlled pilot trial for the treatment of posttraumatic stress disorder. J ECT 2019; 35(1):53–60. doi:10.1097/YCT.0000000000000505.
52. Kozel FA, Motes MA, Didehbani N, et al. Repetitive TMS to augment cognitive processing therapy in combat veterans of recent conflicts with PTSD: a randomized clinical trial. J Affect Disord 2018; 229:506–514. doi:10.1016/j.jad.2017.12.046.
53. Schmaal L, Hibar DP, Sämann PG, et al. Cortical abnormalities in adults and adolescents with major depression based on brain scans from 20 cohorts worldwide in the ENIGMA Major Depressive Disorder Working Group. Mol Psychiatry 2017; 22(6):900–909. doi:10.1038/mp.2016.60.
54. Boes AD, McCormick LM, Coryell WH, et al. Rostral anterior cingulate cortex volume correlates with depressed mood in normal healthy children. Biol Psychiatry 2008; 63(4):391–397. doi:10.1016/j.biopsych.2007.07.018.
55. Boes AD, Uitermarkt BD, Albazron FM, et al. Rostral anterior cingulate cortex is a structural correlate of repetitive TMS treatment response in depression. Brain Stimulat 2018; 11(3):575–581. doi:10.1016/j.brs.2018.01.029.
56. Philip NS, Barredo J, van 't Wout-Frank M, et al. Network mechanisms of clinical response to transcranial magnetic stimulation in posttraumatic stress disorder and major depressive disorder. Biol Psychiatry 2018; 83(3):263–272. doi:10.1016/j.biopsych.2017.07.021.
57. Ge R, Downar J, Blumberger DM, et al. Functional connectivity of the anterior cingulate cortex predicts treatment outcome for rTMS in treatment-resistant depression at 3-month follow-up. Brain Stimulat 2020; 13(1):206–214. doi:10.1016/j.brs.2019.10.012.
58. Fox MD, Buckner RL, White MP, et al. Efficacy of transcranial magnetic stimulation targets for depression is related to intrinsic functional connectivity with the subgenual cingulate. Biol Psychiatry 2012; 72(7):595–603. doi:10.1016/j.biopsych.2012.04.028.
59. Siddiqi SH, Trapp NT, Hacker CD, et al. Repetitive transcranial magnetic stimulation with resting-state network targeting for treatment-resistant depression in traumatic brain injury: a randomized, controlled, double-blinded pilot study. J Neurotrauma 2019; 36(8):1361–1374. doi:10.1089/neu.2018.5889.
60. Jing Y, Zhao N, Deng XP, et al. Pregenual or subgenual anterior cingulate cortex as potential effective region for brain stimulation of depression. Brain Behav 2020; 10(4):e01591. doi:10.1002/brb3.1591.
61. Weigand A, Horn A, Caballero R, et al. Prospective validation that subgenual connectivity predicts antidepressant efficacy of transcranial magnetic stimulation sites. Biol Psychiatry 2018; 84(1):28–37. doi:10.1016/j.biopsych.2017.10.028.
62. Liston C, Chen AC, Zebley BD, et al. Default mode network mechanisms of transcranial magnetic stimulation in depression. Biol Psychiatry 2014; 76(7):517–526. doi:10.1016/j.biopsych.2014.01.023.
63. Salomons TV, Dunlop K, Kennedy SH, et al. Resting-state cortico-thalamic-striatal connectivity predicts response to dorsomedial prefrontal rTMS in major depressive disorder. Neuropsychopharmacol Off Publ Am Coll Neuropsychopharmacol 2014; 39(2):488–498. doi:10.1038/npp.2013.222.
64. Avissar M, Powell F, Ilieva I, et al. Functional connectivity of the left DLPFC to striatum predicts treatment response of depression to TMS. Brain Stimulat 2017; 10(5):919–925. doi:10.1016/j.brs.2017.07.002.
65. Kang JI, Lee H, Jhung K, et al. Frontostriatal connectivity changes in major depressive disorder after repetitive transcranial magnetic stimulation: a randomized sham-controlled study. J Clin Psychiatry 2016; 77(9):e1137–e1143. doi:10.4088/JCP.15m10110.
66. Hu XY, Zhang T, Rajah GB, et al. Effects of different frequencies of repetitive transcranial magnetic stimulation in stroke patients with non-fluent aphasia: a randomized, sham-controlled study. Neurol Res 2018; 40(6):459–465. doi:10.1080/01616412.2018.1453980.
67. Du J, Yang F, Hu J, et al. Effects of high- and low-frequency repetitive transcranial magnetic stimulation on motor recovery in early stroke patients: Evidence from a randomized controlled trial with clinical, neurophysiological and functional imaging assessments. NeuroImage Clin 2019; 21. doi:10.1016/j.nicl.2018.101620.
68. Xie Y, Zhang T. Repetitive transcranial magnetic stimulation improves consciousness disturbance in stroke patients: a quantitative electroencephalography spectral power analysis. Neural Regen Res 2012; 7(31):2465–2472. doi:10.3969/j.issn.1673-5374.2012.31.008.
69. Valero-Cabré A, Pascual-Leone A. Impact of TMS on the primary motor cortex and associated spinal systems. IEEE Eng Med Biol Mag Q Mag Eng Med Biol Soc 2005; 24(1):29–35. doi:10.1109/memb.2005.1384097.
70. Demirtas-Tatlidede A, Vahabzadeh-Hagh AM, Bernabeu M, et al. Non-invasive brain stimulation in traumatic brain injury. J Head Trauma Rehabil 2012; 27(4):274–292. doi:10.1097/HTR.0b013e318217df55.
71. Konarski JZ, Kennedy SH, McIntyre RS, et al. Relationship between regional brain metabolism, illness severity and age in depressed subjects. Psychiatry Res 2007; 155(3):203–210. doi:10.1016/j.pscychresns.2007.02.001.
72. Kennedy SH, Javanmard M, Vaccarino FJ. A review of functional neuroimaging in mood disorders: positron emission tomography and depression. Can J Psychiatry 1997; 42(5):467–475. doi:10.1177/070674379704200502.
73. Li CT, Wang SJ, Hirvonen J, et al. Antidepressant mechanism of add-on repetitive transcranial magnetic stimulation in medication-resistant depression using cerebral glucose metabolism. J Affect Disord 2010; 127(1-3):219–229. doi:10.1016/j.jad.2010.05.028.
74. Paillère Martinot ML, Martinot JL, Ringuenet D, et al. Baseline brain metabolism in resistant depression and response to transcranial magnetic stimulation. Neuropsychopharmacol Off Publ Am Coll Neuropsychopharmacol 2011; 36(13):2710–2719. doi:10.1038/npp.2011.161.
75. Baeken C, Marinazzo D, Everaert H, et al. The impact of accelerated HF-rTMS on the subgenual anterior cingulate cortex in refractory unipolar major depression: insights from 18FDG PET brain imaging. Brain Stimulat 2015; 8(4):808–815. doi:10.1016/j.brs.2015.01.415.
76. Kimbrell TA, Little JT, Dunn RT, et al. Frequency dependence of antidepressant response to left prefrontal repetitive transcranial magnetic stimulation (rTMS) as a function of baseline cerebral glucose metabolism. Biol Psychiatry 1999; 46(12):1603–1613. doi:10.1016/S0006-3223(99)00195-X.
77. Speer AM, Benson BE, Kimbrell TK, et al. Opposite effects of high and low frequency rTMS on mood in depressed patients: relationship to baseline cerebral activity on PET. J Affect Disord 2009; 115(3):386–394. doi:10.1016/j.jad.2008.10.006.
78. Pascual-Leone A, Rubio B, Pallardó F, et al. Rapid-rate transcranial magnetic stimulation of left dorsolateral prefrontal cortex in drug-resistant depression. Lancet Lond Engl 1996; 348(9022):233–237. doi:10.1016/s0140-6736(96)01219-6.

79. Minjoli S, Saturnino GB, Blicher JU, et al. The impact of large structural brain changes in chronic stroke patients on the electric field caused by transcranial brain stimulation. NeuroImage Clin 2017; 15:106–117. doi:10.1016/j.nicl.2017.04.014.
80. Bonne O, Gilboa A, Louzoun Y, et al. Resting regional cerebral perfusion in recent posttraumatic stress disorder. Biol Psychiatry 2003; 54 (10):1077–1086. doi:10.1016/s0006-3223(03)00525-0.
81. Chung YA, Kim SH, Chung SK, et al. Alterations in cerebral perfusion in posttraumatic stress disorder patients without re-exposure to accident-related stimuli. Clin Neurophysiol Off J Int Fed Clin Neurophysiol 2006; 117(3):637–642. doi:10.1016/j.clinph.2005.10.020.
82. Bremner JD, Innis RB, Ng CK, et al. Positron emission tomography measurement of cerebral metabolic correlates of yohimbine administration in combat-related posttraumatic stress disorder. Arch Gen Psychiatry 1997; 54(3):246–254. doi:10.1001/archpsyc.1997.01830150070011.
83. Bestmann S, Ruff CC, Blankenburg F, Weiskopf N, Driver J, Rothwell JC. Mapping causal interregional influences with concurrent TMS–fMRI. Exp Brain Res 2008; 191(4):383–402. doi:10.1007/s00221-008-1601-8.
84. Caparelli EC, Zhai T, Yang Y. Simultaneous transcranial magnetic stimulation and functional magnetic resonance imaging: aspects of technical implementation. Front Neurosci 2020; 14:554714doi:10.3389/fnins.2020.554714.
85. Bohning D, Shastri A, McConnell K, et al. A combined TMS/fMRI study of intensity-dependent TMS over motor cortex. Biol Psychiatry 1999; 45(4):385–394. doi:10.1016/S0006-3223(98)00368-0.
86. Li X, Nahas Z, Kozel FA, et al. Acute left prefrontal transcranial magnetic stimulation in depressed patients is associated with immediately increased activity in prefrontal cortical as well as subcortical regions. Biol Psychiatry 2004; 55(9):882–890. doi:10.1016/j.biopsych.2004.01.017.
87. Drevets WC, Savitz J, Trimble M. The subgenual anterior cingulate cortex in mood disorders. CNS Spectr 2008; 13(8):663–681. doi:10.1017/s1092852900013754.
88. Vink JJT, Mandija S, Petrov PI, et al. A novel concurrent TMS-fMRI method to reveal propagation patterns of prefrontal magnetic brain stimulation. Hum Brain Mapp 2018; 39(11):4580–4592. doi:10.1002/hbm.24307.
89. Loo CK, Sachdev PS, Haindl W, et al. High (15 Hz) and low (1 Hz) frequency transcranial magnetic stimulation have different acute effects on regional cerebral blood flow in depressed patients. Psychol Med 2003; 33(6):997–1006. doi:10.1017/s0033291703007955.
90. Lan MJ, Chhetry BT, Liston C, et al. Transcranial magnetic stimulation of left dorsolateral prefrontal cortex induces brain morphological changes in regions associated with a treatment resistant major depressive episode: an exploratory analysis. Brain Stimulat 2016; 9(4):577–583. doi:10.1016/j.brs.2016.02.011.
91. Stubbeman W, Ramones A, Nable M, et al. Cortical thickness changes following sound paired 20 Hz theta burst TMS therapy for tinnitus. Brain Stimulat 2019; 12(2):513. doi:10.1016/j.brs.2018.12.683.
92. Hasan A, Wobrock T, Guse B, et al. Structural brain changes are associated with response of negative symptoms to prefrontal repetitive transcranial magnetic stimulation in patients with schizophrenia. Mol Psychiatry 2017; 22(6):857–864. doi:10.1038/mp.2016.161.
93. Ji G, Liu T, Li Y, et al. Structural correlates underlying accelerated magnetic stimulation in Parkinson's disease. Hum Brain Mapp 2020. doi:10.1002/hbm.25319. Published online December 14hbm.25319.
94. Demitrack M, Dunner D, Carpenter L, et al. A multisite, longitudinal, naturalistic observational study of transcranial magnetic stimulation (TMS) for major depression in clinical practice (NR12-5). In: American Psychological Association. .
95. Kaiser RH, Andrews-Hanna JR, Wager TD, et al. Large-scale network dysfunction in major depressive disorder: a meta-analysis of resting-state functional connectivity. JAMA Psychiatry 2015; 72(6):603. doi:10.1001/jamapsychiatry.2015.0071.
96. Tastevin M, Richieri R, Boyer L, et al. Brain PET metabolic substrate of TMS response in pharmaco-resistant depression. Brain Stimulat 2020; 13(3):683–685. doi:10.1016/j.brs.2020.02.014.
97. Conca A, Peschina W, König P, et al. Effect of chronic repetitive transcranial magnetic stimulation on regional cerebral blood flow and regional cerebral glucose uptake in drug treatment-resistant depressives. A brief report. Neuropsychobiology 2002; 45(1):27–31. doi:10.1159/000048669.
98. Kito S, Fujita K, Koga Y. Regional cerebral blood flow changes after low-frequency transcranial magnetic stimulation of the right dorsolateral prefrontal cortex in treatment-resistant depression. Neuropsychobiology 2008; 58(1):29–36. doi:10.1159/000154477.
99. Kito S, Fujita K, Koga Y. Changes in regional cerebral blood flow after repetitive transcranial magnetic stimulation of the left dorsolateral prefrontal cortex in treatment-resistant depression. J Neuropsychiatry Clin Neurosci 2008; 20(1):74–80. doi:10.1176/jnp.2008.20.1.74.
100. Teneback CC, Nahas Z, Speer AM, et al. Changes in prefrontal cortex and paralimbic activity in depression following two weeks of daily left prefrontal TMS. J Neuropsychiatry Clin Neurosci 1999; 11(4):426–435. doi:10.1176/jnp.11.4.426.
101. Philip NS, Barredo J, Aiken E, et al. Neuroimaging mechanisms of therapeutic transcranial magnetic stimulation for major depressive disorder. Biol Psychiatry Cogn Neurosci Neuroimaging 2018; 3(3):211–222. doi:10.1016/j.bpsc.2017.10.007.
102. Cirillo P, Gold AK, Nardi AE, et al. Transcranial magnetic stimulation in anxiety and trauma-related disorders: A systematic review and meta-analysis. Brain Behav 2019; 9(6). doi:10.1002/brb3.1284.
103. Trevizol AP, Shiozawa P, Cook IA, et al. Transcranial magnetic stimulation for obsessive-compulsive disorder: an updated systematic review and meta-analysis. J ECT 2016; 32(4):262–266. doi:10.1097/YCT.0000000000000335.
104. Pell GS, Harmelech T, Zibman S, et al. Efficacy of deep TMS with the H1 coil for anxious depression. J Clin Med 2022; 11(4):1015. doi:10.3390/jcm11041015.
105. Aftanas LI, Gevorgyan MM, Zhanaeva SY, et al. therapeutic effects of repetitive transcranial magnetic stimulation (rTMS) on neuroinflammation and neuroplasticity in patients with Parkinson's disease: a placebo-controlled study. Bull Exp Biol Med 2018; 165(2):195–199. doi:10.1007/s10517-018-4128-4.
106. Elzamarany E, Afifi L, El-Fayoumy NM, et al. Motor cortex rTMS improves dexterity in relapsing-remitting and secondary progressive multiple sclerosis. Acta Neurol Belg 2016; 116(2):145–150. doi:10.1007/s13760-015-0540-y.
107. Mori F, Koch G, Foti C, et al. The use of repetitive transcranial magnetic stimulation (rTMS) for the treatment of spasticity. Prog Brain Res 2009; 175:429–439. doi:10.1016/S0079-6123(09)17528-3.
108. Leung A, Fallah A, Shukla S, et al. rTMS in alleviating mild TBI related headaches–a case series. Pain Physician 2016; 19(2):E347–E354.
109. Lipton RB, Dodick DW, Silberstein SD, et al. Single-pulse transcranial magnetic stimulation for acute treatment of migraine with aura: a randomised, double-blind, parallel-group, sham-controlled trial. Lancet Neurol 2010; 9(4):373–380. doi:10.1016/S1474-4422(10)70054-5.
110. Weiler M, Stieger KC, Long JM, et al. Transcranial magnetic stimulation in Alzheimer's disease: are we ready? eNeuro 2020; 7(1). doi:10.1523/ENEURO.0235-19.2019.
111. Paxman E, Stilling J, Mercier L, et al. Repetitive transcranial magnetic stimulation (rTMS) as a treatment for chronic dizziness following mild traumatic brain injury. BMJ Case Rep 2018. doi:10.1136/bcr-2018-226698. Published online November 5bcr-2018-226698.
112. Korzhova J, Sinitsyn D, Chervyakov A, et al. Transcranial and spinal cord magnetic stimulation in treatment of spasticity: a literature review and meta-analysis. Eur J Phys Rehabil Med 2018; 54(1):75–84. doi:10.23736/S1973-9087.16.04433-6.
113. Kimiskidis VK, Valentin A, Kälviäinen R. Transcranial magnetic stimulation for the diagnosis and treatment of epilepsy. Curr Opin Neurol 2014; 27(2):236–241. doi:10.1097/WCO.0000000000000071.
114. Frank E, Schecklmann M, Landgrebe M, et al. Treatment of chronic tinnitus with repeated sessions of prefrontal transcranial direct current stimulation: outcomes from an open-label pilot study. J Neurol 2012; 259(2):327–333. doi:10.1007/s00415-011-6189-4.
115. Leung A, Donohue M, Xu R, et al. rTMS for suppressing neuropathic pain: a meta-analysis. J Pain 2009; 10(12):1205–1216. doi:10.1016/j.jpain.2009.03.010.
116. Li X, Hartwell KJ, Henderson S, et al. Two weeks of image-guided left dorsolateral prefrontal cortex repetitive transcranial magnetic stimulation improves smoking cessation: a double-blind, sham-controlled, randomized clinical trial. Brain Stimulat 2020; 13(5):1271–1279. doi:10.1016/j.brs.2020.06.007.

SUPPLEMENTARY MATERIALS

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