Swallowing Neuro-rehabilitation: From the research laboratory to routine clinical application

Abstract

The recent application of neuro-stimulation techniques to enhance the understanding of swallowing neural plasticity has expanded the focus of rehabilitation research from manipulation of swallowing biomechanics to manipulation of underlying neural systems. Neuromodulatory strategies that promote the brain's ability to reorganize its neural connections have been shown to hold promising potential to aid the recovery of impaired swallowing function. These techniques include those applied to the brain through the intact skull, for example, transcranial magnetic stimulation or transcranial direct current stimulation, or those applied to the sensorimotor system in the periphery, such as neuromuscular electrical stimulation. Recent research has demonstrated that each of these techniques, either by themselves or in combination with these and other treatments, can, under certain circumstances, modify the excitability of motor representations of muscles involved in swallowing. In some studies, experimentally induced plastic changes have been shown to have functional relevance for swallowing biomechanics. However, the transition of novel, neuromodulatory brain stimulation techniques from the research laboratory to routine clinical practice is accompanied by a number of ethical, organizational and clinical implications that impact professions concerned with the treatment of swallowing rehabilitation. In this paper, we provide a brief overview of the neuromodulatory strategies that may hold potential to aid the recovery of swallowing function, and raise a number of issues which we believe the clinical professions involved in the rehabilitation of swallowing disorders must confront as these novel brain stimulation techniques emerge into clinical practice.

Keywords

Rehabilitation, neuroplasticity, deglutition, transcranial magnetic stimulation, electric stimulation

Abbreviations

NMES: neuromuscular electrical stimulation; MEP: motor evoked potential; PAS: paired associative stimulation; PES: pharyngeal electrical stimulation; TMS: transcranial magnetic stimulation; rTMS: repetitive transcranial magnetic stimulation; tDCS: transcranial direct current stimulation;

Traditionally, behavioral interventions for swallowing impairment, such as compensatory swallowing maneuvers or active motor exercises, have focused on restoring safe and effective swallowing through *functional* modification of swallowing biomechanics. Compensatory maneuvers, including head positioning, food/fluid texture modifications and other techniques, can have immediate beneficial effects by facilitating safer bolus transfer; however, these effects are not considered to persist in the longer-term when the maneuver is not performed. For longer-term, cumulative rehabilitation of swallowing function, active motor exercises are available that are aimed primarily at strengthening the oropharyngeal musculature for effective pharyngeal bolus clearance and optimal airway protection. The effortful swallow, the tongue-hold swallow (1) and the headlift exercise (2) are all examples of this type of rehabilitation approach. The immediate effects of these interventions on biomechanical measures of swallowing function have been examined using a variety of functional swallowing assessment tools, including clinical rating scales (3), videofluoroscopic swallowing study (4), video-endoscopy (5), surface electromyography (eg, 6, 7) or pharyngeal manometry (eg, 8, 9, 10, 11, 12). These exercises have been hypothesized to engender long term rehabilitative change in a many patients through predominantly case series reports or small trials, which reported on cumulative effects of a mix of treatment approaches (eg, 13, 14, 15), as well as a small number of more recent, controlled trials on the headlift exercise in particular (16). However, there is a paucity of research on the cumulative rehabilitative effects of these approaches.

Perhaps in part as a response to this limited research base, recent advances in neuro-stimulation techniques are expanding the focus from traditional, exercise-based swallowing rehabilitation toward the development of novel swallowing rehabilitation approaches that modulate the neuronal circuitries involved in swallowing motor control. Driven by increased understanding of the neurophysiological underpinnings of swallowing sensorimotor control, the changes induced in these networks by neurotrauma, and the functional improvements brought about by swallowing rehabilitation interventions, speech pathologists increasingly find themselves in the role of "neurorehabilitationists", with the focus of treatment shifting from manipulation of peripheral swallowing biomechanics to manipulation of underlying neural systems.

Neuro-modulatory techniques in swallowing rehabilitation

The last decade in particular has seen the emergence of neuromuscular electrical stimulation (NMES) protocols in rehabilitation medicine. In general, NMES employs the application of pulsed electrical currents to muscles, nerves or neuromuscular junctions with the therapeutic benefits thought to arise from improvements in muscle strength, stamina and reaction time (17). Based on these general concepts, a number of differing protocols for applying NMES as a swallowing rehabilitation intervention have been developed. In order to assist readability and clarity, the term NMES will be used from here onwards as an umbrella term for any technique employing an electrical stimulus to muscles involved in swallowing. The various subtypes [Vitalstim, pharyngeal electrical stimulation (PES), and other forms of experimental electrical stimulation] will be briefly outlined. However, for detailed information about the existing research evaluating these NMES approaches in healthy research subjects and swallowing impaired patients, the reader is referred to several comprehensive reviews (18, 19, 20, 21).

Vitalstim

Perhaps the most commercially recognized electrical stimulation protocol is that advocated by Freed and colleagues, referred to as Vitalstim. This protocol was based on a randomized controlled trial of 99 patients with dysphagia (22), in which electrical stimulation is provided by means of surface electrodes applied overlying the floor of mouth and laryngeal musculature. Research on this particular protocol reports contradictory functional outcomes which have been widely discussed (for reviews, see 18, 19, 20, 21). It is noteworthy that the emergence of this particular NMES modality has impacted the profession of speech pathology beyond the rehabilitative potential of the intervention. Since its commercial availability, significant controversy surrounding the clinical application of the Vitalstim protocol for swallowing rehabilitation has highlighted a number of professional issues. One of the main points of discussion relates to the wide-spread, routine clinical application of this form of NMES prior to the establishment of a thorough, evidence-based research foundation. In particular, the ramifications of providing a more invasive, non-behavioural treatment, which is administered by the clinician, rather than being performed by the patient, are not yet precisely understood. Further, provision of this form of NMES to patients presenting with a vast variety of underlying impairments and issues surrounding the training of clinicians have sparked extensive discussions within the profession (23). Although this technique may hold rehabilitative potential for some patient groups under certain conditions, wide-spread use of this technique does not imply that it is synonymous with a universally effective rehabilitation approach for impaired swallowing.

Pharyngeal electrical stimulation

A very different electrical stimulation technique has been carefully investigated over the last decade by Hamdy and colleagues (24). Pharyngeal electrical stimulation is applied to the pharyngeal mucosa via surface electrodes mounted on an intraluminal catheter. In a number of studies, these researchers have demonstrated that PES primarily affects swallowing function through changes in the excitability of the pharyngeal representation in the primary motor cortex (24, 25). For example, PES using certain stimulus parameters can increase corticobulbar excitability in healthy research subjects and patients with dysphagia and, importantly, improve dysphagic symptoms, including aspiration score and pharyngeal transit times (24). Recently, this group demonstrated improvement in functional outcomes (the severity of swallowing impairment, feeding status and duration of hospitalization) following PES applied for three consecutive days in a placebo controlled trial involving 28 swallowing impaired acute stroke patients (25).

Experimental electrical stimulation paradigms

Other experimental NMES paradigms targeting orofacial muscle groups have been tested in the last decade. Power and colleagues demonstrated in healthy research subjects that NMES applied to the muscles underlying the faucial pillar mucosa had frequency-specific effects on corticobulbar motor excitability (26). Interestingly, inhibitory faucial pillar NMES resulted in a lengthened swallow response time, whereas facilitatory faucial pillar NMES did not affect swallowing function. Similarly, a subsequent sham controlled study of 16 acute stroke patients showed no changes in swallowing function following facilitatory faucial pillar NMES (27).

Doeltgen and colleagues systematically investigated the effects of swallowing-triggered NMES applied to the floor of mouth musculature in healthy research subjects (28). Cortical effects were frequency-specific, and were only observed following NMES triggered by volitional swallowing, and not when applied at rest (28). Interestingly, although PES, faucial pillar NMES and swallowing-triggered NMES all induced frequency-specific changes in corticobulbar excitability, inhibitory and facilitatory frequencies differed across the different modalities and stimulated muscle groups. This suggests that NMES-induced effects are not only dependent on the stimulus frequency employed, but also depend on the stimulated muscle group. In light of the apparent relationship between increased corticobulbar excitability and enhanced swallowing function following facilitatory PES (24), and the prolongation of swallowing response time following inhibitory faucial pillar NMES (26), the results of these studies underscore the necessity and importance of carefully evaluating optimal stimulus parameters for each NMES modality and target muscle group.

The clinical application of NMES marks the emergence of techniques that can be classified as "neuro-modulatory"; this also includes techniques such as TMS and transcranial direct current stimulation (tDCS). These techniques can, under certain circumstances, affect neural mechanisms underlying motor function. A large body of research has investigated the effects of neuro-modulatory techniques in the corticospinal motor system controlling the muscles of the limbs and torso. Many of these studies have demonstrated that experimentally induced changes in corticospinal excitability can be functionally relevant in health and disease (eg, 29, 30, 31). A small number of studies evaluating the effects in the head and neck musculature controlled by the corticobulbar motor system have recently demonstrated a similar functional relevance for swallowing. For example, changes in cortical synaptic connectivity subserving the pharyngeal musculature affect peripheral swallowing biomechanics (24, 32). This finding has significant clinical ramifications. If it were possible to modify and interact with the brain's capability of undergoing change, then induction of neural plasticity might provide a very useful therapeutic tool for the recovery of impaired swallowing function. Even if the application of neuromodulatory brain stimulation did not, in the long term, prove to be an effective therapeutic approach *per se,* recent studies in the area of physical rehabilitation medicine provide preliminary data to support the notion that a combination of neuromodulatory brain stimulation and "traditional" behavioural exercise may result in more beneficial therapeutic effects than either type of intervention alone (33, 34).

The intent of this article is not to provide an in-depth review of studies that have documented the potential of neuromodulatory brain stimulation techniques for the rehabilitation of swallowing disorders. There are excellent recent reviews provided by Martin (35) and Barritt and Smithard (36). Instead, we first provide a general overview of the currently available brain stimulation techniques and the emerging evidence of their potential to enhance and inhibit the recovery of lost swallowing function. Then we raise a number of relevant questions, which we believe the clinical professions involved in the rehabilitation of swallowing disorders must confront as these novel brain stimulation techniques emerge into clinical swallowing neuro-rehabilitation.

Experimental transcranial brain stimulation and swallowing rehabilitation

TMS and tDCS are the most common transcranial brain stimulation techniques, which stimulate neuronal networks within the brain through the intact skull with little or no discomfort. Both techniques are currently only used in experimental and clinical dysphagia research settings. TMS is based on concepts of electromagnetism, and can be applied either as single magnetic pulses (single or paired pulse TMS) or trains of magnetic pulses (repetitive TMS, rTMS). Single-pulse TMS is used diagnostically to assess the excitability of corticobulbar or corticospinal motor projections, mapping cortical motor representations of certain muscles or groups of muscles, or studying central motor conduction time. Specifically, a short-lasting magnetic field is generated by a strong electric current that passes through a coil of wires placed over the head. If a sufficiently strong magnetic pulse is generated over the primary motor cortex, it passes through the scalp nearly unimpeded and trans-synaptically activates interneurons that project onto descending motor output neurons.

The resulting descending current, known as the motor evoked potential (MEP), can be measured in the target muscle using surface electromyography. The amplitude and latency of the MEP provide important information about the excitability of the stimulated neural pathway.

Paired-pulse TMS employs application of two magnetic stimuli, a sub-threshold conditioning stimulus and a supra-threshold test stimulus, in close temporal sequence. This TMS paradigm provides important information about the excitability of intracortical inhibitory or facilitatory motor networks, by selectively activating facilitatory or inhibitory interneuronal networks. Interestingly, some disease conditions are characterized by imbalances of intracortical facilitation and inhibition (37).

In contrast to single-pulse and paired-pulse TMS, which only produce short lasting responses, eg, momentary activation of motor output cells, repeated application of trains of magnetic stimuli (rTMS) has longer lasting effects on the stimulated neuronal networks, often outlasting the stimulation period by 30-60 minutes (eg, 38, 39). The nature of these effects is highly dependent on the pattern of stimulation, including the overall number, frequency and intensity of the train of stimuli applied. For example, research in the corticospinal system identifies that low stimulation frequencies generally inhibit corticospinal excitability, whereas high stimulation frequencies (> 1Hz) facilitate corticospinal excitability. Safety limits have been established for rTMS parameters, as rTMS is thought to be associated with a number of potential side effects; these include mild effects on hearing, local pain and discomfort and, under certain circumstances, the induction of seizures (40).

A small number of studies have explored the potential of rTMS to modulate the excitability of cortical motor representations of muscles involved in swallowing and have investigated the functional relevance of motor plasticity induced by rTMS. For example, 1 Hz rTMS applied to the cortical hemisphere with dominant pharyngeal motor representation of healthy research subjects has been shown to induce a reduction of excitability of corticobulbar motor projections to pharyngeal musculature, as reflected in smaller pharyngeal MEPs (32). This effect was accompanied by a reduction in swallowing reaction time of normal and fast swallows, as assessed by a swallowing reaction time task (32). This finding may be particularly relevant for the rehabilitation of patients who present with dysphagia characterized by delayed pharyngeal onset of swallowing. Clinical studies are warranted to test this hypothesis. It is noteworthy that there may be differences in the corticobulbar processing of swallowing onset between the swallowing reaction time task employed (based on visual cue to trigger swallow) and the initiation of a swallow in a deglutitive context. The findings of this study further raise questions regarding the role of pharyngeal cortical motor circuits in the initiation of swallowing. One may hypothesize that pharyngeal cortical motor circuits exert an inhibitory influence on swallowing pattern generators at least in the pharyngeal phase of the mainly brainstem driven swallowing response, which is temporarily released by rTMS induced inhibition of these motor networks. Interestingly, the inhibitory effects induced by 1 Hz rTMS could be reversed by high-frequency (facilitatory) 5 Hz rTMS applied to the contralateral, “non-lesioned” hemisphere, which was associated with a restoration of swallowing function (41).

The technique of paired-associative stimulation (PAS) consists of repeated applications of a single electrical stimulus applied over a peripheral muscle paired with a single pulse of TMS over the corresponding motor cortex (38). When this technique is applied over the pharyngeal mucosa and the cortical region associated with the pharynx, an increase of the excitability of pharyngeal motor representation was evident for two hours following stimulation. This change was associated with a reduction in glutamate concentration in the stimulated hemisphere, suggesting that mechanisms consistent with long-term potentiation underlie the PAS-induced plastic changes in pharyngeal motor representation (42). The relevance of PAS-induced increases in corticobulbar excitability for swallowing function are unknown; however, emerging evidence in the corticospinal motor system suggests that PAS-induced plasticity may have functional relevance and may, therefore, be therapeutically useful (43).

Transcranial direct current stimulation employs low-intensity electrical direct currents that modify neuronal activation in the stimulated brain areas. The nature of effects induced by tDCS is dependent on the direction of current flow. Anodal stimulation of the motor cortex generally produces facilitation of motor cortical excitability, whereas cathodal stimulation reduces it. Functionally, anodal tDCS of the primary motor cortex has been shown to improve the performance of healthy research subjects in a choice reaction-time task (31). When applied to the region of pharyngeal motor representation for 10 min with an intensity of 1.5mA and a cathodal current direction, tDCS has been shown to reduce corticobulbar excitability. In contrast, 10 min of 1.5 mA and 20 min of 1mA anodal stimulation increased corticobulbar excitability (44). The functional correlates of tDCS-induced plasticity in regard to swallowing are currently being investigated. For example, it has been shown in the corticospinal motor system that anodal tDCS facilitates the effects of unilateral motor training following stroke (45) and enhances motor function in young (46) and older (47) healthy research subjects. Furthermore, tDCS has been shown to facilitate motor learning when applied over the human motor cortex (48) and has the potential to enhance the retention of declarative memory (49). In a recent pilot study of 14 subacute stroke patients with dysphagia, application of anodal tDCS over the unaffected hemisphere on five consecutive days, in combination with an effortful swallowing exercise and lemon taste exposure, resulted in greater improvement of swallowing function than sham tDCS paired with exercise (50).

As outlined above, the plastic effects induced by neuro-modulatory stimulation techniques hold the potential for improving motor function in healthy individuals and aiding the recovery of impaired motor function after damage to the central nervous system. Importantly, the plastic changes induced in the motor cortex critically depend on the stimulus parameters employed. For example, the stimulus frequency and stimulation pattern of rTMS determine whether corticospinal excitability is facilitated or inhibited. Evidence is emerging that this is also true for the corticobulbar motor system. Interestingly, for NMES of the corticobulbar motor system, facilitatory and inhibitory parameters appear to depend also on the muscle group stimulated, with high frequency NMES being facilitatory for the floor of mouth muscle representation (28) and low frequency NMES facilitating the excitability of the pharyngeal muscle representation (24).

In the context of optimal stimulation parameters and paradigms, the question arises whether the combined administration of behavioural swallowing exercise and neuro-modulatory brain stimulation may be the most promising approach. In fact, one might wonder whether the duration of the after-effects induced by experimental brain stimulation, which generally outlast the stimulation period by around 30-60 minutes, could on its own ever be sufficient to be therapeutically beneficial. As Ridding and Rothwell have outlined in their review of the therapeutic potential of TMS (51), if one assumes that experimental brain stimulation can "repair" imbalanced brain function caused by insult or disease, then the relatively short-lived nature of the effects induced by currently available paradigms would critically limit the therapeutic potential of these interventions. In fact, if experimental brain stimulation induced permanent changes in cortical circuits, it would ethically be highly problematic to explore the effects of the techniques in healthy individuals. In contrast, perhaps the more effective strategy to improve function may be to promote the brain's intrinsic neural repair mechanisms by providing conventional rehabilitative training during a period of experimentally enhanced cortical excitability. Therefore, providing a 1 hour "therapeutic window" would be sufficient for most training protocols. Indeed, there is evidence in the corticospinal motor system for the efficacy of this combined approach in both healthy research subjects and stroke patients (34, 35). In addition, application of sensory stimulation of peripheral nerves and muscles involved in swallowing, or performance of a motor task, combined with transcranial brain stimulation may provide a promising approach that holds greater effects than the sum of its parts. One such approach, PAS, has been shown to be capable of bidirectionally modifying the excitability of corticospinal (38) and corticobulbar motor projections (52). Similarly, short intervals of NMES triggered by volitional swallows provide a promising approach toward optimizing the potential of this rehabilitative intervention (28).

The observation that the spontaneous recovery of swallowing function following unilateral stroke is associated with natural reorganization of cortical motor circuits in the contralateral hemisphere (53) further underscores the notion that experimentally induced plasticity in cortical muscle representations may have a promising potential to assist in the recovery of swallowing function. Taken together, the above mentioned studies provide promising support for the notion that experimental brain stimulation techniques may one day play an important role in the rehabilitation of swallowing disorders. However, larger clinical trials are needed to confirm these findings and provide a strong evidence base. In addition, a number of experimental challenges will need to be overcome before these techniques can be applied routinely in clinical practice. For example, optimal placement of the stimulation coil or electrodes over the relevant oropharyngeal motor representations is arguably more difficult than, for example, for the limb musculature and requires extensive expertise in the use of these techniques. The risk for the induction of seizures following rTMS is recognized (40) and in and of itself requires either formal medical training of the treating clinician, or availability of an emergency response team. In addition, incorrect application of tDCS holds the risk for burns of the scalp surface (54). Clinical professions concerned with the care of those affected by swallowing disorders, in particular speech pathologists, will, therefore, face a number of critical questions regarding the provision of these services. We raise a number of questions, which we believe require consideration if experimental brain stimulation techniques were to be established in routine clinical practice.

Provision of experimental brain stimulation services in clinical dysphagia rehabilitation

Although rTMS is already being tested in large-scale clinical trials as a treatment for other health conditions (eg, treatment-resistant depression and tinnitus), brain stimulation for the purpose of swallowing rehabilitation is currently only used by trained researchers conducting carefully monitored experimental protocols in a few research centres across the world. As more data are collected and if outcomes support the viability of neuro-stimulation protocols, the natural progression will be a transfer of these techniques to clinical practice. Given that speech pathologists traditionally have provided swallowing rehabilitation services in most countries, can it be assumed that the eventual provision of interventional brain stimulation will also fall to that profession? If speech pathologists were indeed the most likely providers of these novel rehabilitation techniques, how can our profession prepare for these impending new challenges? What qualifications would be necessary to ensure that experimental brain stimulation is applied in a safe and effective manner? Given that these techniques are powerful enough to temporarily alter the synaptic connections in the stimulated tissues of the human brain, and have successfully been used to alter the psychological state of patients (eg, those with depression), appropriate training of how to apply which kind of intervention to which area of the brain is critical. This is particularly vital as various dysphagic presentations can result from a variety of underlying pathophysiologies (eg, flaccidity, spasticity, dyscoordination), each of which may respond differentially to specific stimulation protocols.

A consensus group of international experts comments on issues of professional responsibility in the most recently updated TMS safety guidelines (40). The authors list a number of potential research settings in which TMS/rTMS may be applied on clinical populations. Most relevant for the application of rTMS in swallowing rehabilitation are the categories referred to as Class 3 ("indirect benefit, low risk") and Class 2 ("indirect benefit, moderate risk") research studies on "normal subjects and patients with stable medical conditions (p. 2033) and Class 1 studies ("direct benefit, potential high risk") as "treatment for any medical condition" (p.2033). For Class 3 and Class 2 studies, the authors recommend that any form of TMS may be carried out by "trained professionals", who may include "MDs, Technicians, Psychologists, Physicists, Physiotherapists, Engineers". In this scenario, speech pathologists may likely be considered qualified to perform rTMS in studies of stable, dysphagic patients and healthy control subjects, if adequately trained. For Class 1 studies, the consensus group states that "it is advisable that a licensed physician…closely supervises the rTMS application" (p. 2033), with medical staff trained in the diagnosis and emergency management of seizures available at all times (40). These guidelines were issued in relation to research studies employing rTMS in healthy research subjects and clinical populations. It appears likely that similar recommendations would apply for the eventual routine use of rTMS in clinical rehabilitation settings. Although probably most of the dysphagic patients treated in in- and outpatient clinics are medically stable, and may therefore not present with a directly increased medical risk for rTMS/tDCS-induced side effects, the consensus statement raises several important questions. Which patients can safely receive rTMS/tDCS and who will decide whether or not these interventions will be administered? Will neuro-modulatory interventions be prescribed by a physician and administered by a speech pathologist, or will the speech pathologist decide who does and does not receive rTMS (-assisted) therapy? As importantly, what constitutes “adequate training” of rTMS/tDCS operators, which ensures safe and effective application of neuro-modulatory techniques in a variety of clinical populations? Consideration of these questions is imperative and will require consultation and consensus of various professional groups involved in the care of patients with dysphagia before neuro-modulatory stimulation techniques can be safely and effectively implemented in routine clinical practice. It is noteworthy that these questions not only pertain to novel transcranial brain stimulation techniques, but should also have been carefully considered for NMES techniques that are already commonly used in dysphagia rehabilitation settings. Research is further warranted to evaluate optimal treatment frequencies and intensities and to develop standardized outcome measures for the assessment of clinical effects of all of these interventions.

Professional training – Guidelines for ensuring optimal patient care

The development of reliable and standardized brain stimulation protocols for routine clinical use should be accompanied by the development of guidelines for the training and application of these paradigms in clinical practice. To date, no international or national guidelines have been established that outline the training requirements for experimental brain stimulation. The International Federation of Clinical Neurophysiology is currently in the process of developing such guidelines (40). Although (Neuro)-physiology and (Neuro)-anatomy courses form part of the majority of speech pathology undergraduate training programmes, a multifaceted curriculum does not always allow in-depth coverage of these topics. However, a thorough understanding of the neurophysiological underpinnings of neural plasticity, and the induction thereof, should be a critical objective of competency training. Neuro-rehabilitation training for swallowing (and probably also speech and language) should include basic information about the physics of electromagnetism and its interaction with human neural systems, as well as an introduction to the various stimulation paradigms and their mechanisms of action. In addition, academic preparation in the rationales underlying selection of paradigms for application to specific clinical presentations would be necessary, as well as an introduction to current safety recommendations. It would appear sensible that basic first aid training should also form part of training for the application of neuro-modulatory techniques. Given the complexity of these requirements, the question arises whether undergraduate or graduate clinical speech pathology programmes can provide such specialized training. Alternatively, it may be that postgraduate professional development courses could provide the necessary training, for example in the form postgraduate training courses offered by academic institutions. National legal regulations may vary across countries, and may provide a legal framework for such training. Whatever the optimal or most practical format, the objective of specialized training programs should be to convey a thorough understanding of the precise neural mechanisms by which neuro-modulatory techniques interact with the human nervous system, and ultimately motor function. Providing simplified treatment protocols without provision of in-depth neurophysiological education is undesirable and may pose a risk to both clinicians and patients.

Access to stimulation equipment – practical considerations

Unlike NMES devices, which are relatively inexpensive, and can be operated by a patient or carer using clinician defined protocols, experimental brain stimulation tools, especially rTMS, are expensive (in excess of ten thousand U.S. dollars) and cannot be patient-operated.

Therefore, patients will be required to attend the swallowing rehabilitation service providers' clinics to receive treatment. This may be clinically optimal, since paired application of brain stimulation with conventional swallowing rehabilitation exercises may prove an ideal combination of treatments (as outlined above). For example, patients may attend a brain stimulation session, which is followed by a "conventional" swallowing rehabilitation session, although basic research is yet to establish optimal treatment protocols. In the planning of individual rehabilitation programmes, consideration will need to be given to the fact that having to attend a clinic for treatment, possibly on a daily basis, would be more demanding of patients and carers than, for example, home-based exercises programmes that are monitored by less frequent therapy sessions. One could argue that home-based programmes are not optimal for any rehabilitative approach, but for brain stimulation techniques, they would be impossible.

Conclusion

We conclude that the currently available research evidence suggests that experimental brain stimulation holds the potential for (i) inducing changes in the motor cortical areas that are involved in swallowing, which outlast the stimulation period, and importantly, (ii) that such experimentally induced plastic changes can under certain circumstances be relevant for swallowing function. Given the promising potential that these novel rehabilitation techniques hold for improving the health, safety and quality of life of patients living with dysphagia, further research and development of safe and effective treatment paradigms is warranted. Before tested treatment paradigms can be applied in routine clinical practice, it will be necessary to develop a strategic plan that will allow the profession of speech pathology, as well as others, to move forward to meet the academic, clinical and ethical challenges that accompany the advent of these novel interventions. Large scale clinical trials will be needed to confirm the safety and efficacy of brain stimulation protocols that are often developed in healthy populations, or small patient subgroups. Trials of this nature should evaluate (i) the functional benefits of novel modulatory interventions, and, as importantly, (ii) determine changes in the impact of the disability perceived by the patient (55). A coordinated international effort would likely speed up the development of a thorough clinical evidence base. Consensus groups involving experts from a variety of medical and therapeutic backgrounds may provide answers to some of the questions raised in this article and facilitate the transfer of these emerging techniques from the research laboratory to clinical practice. In light of the recent discussion around the efficacy of rTMS in the treatment of depression (eg, 51), or the by some perceived premature use of NMES in swallowing rehabilitation, which overshadows the theoretical potential of this technique to improve swallowing function, patience will be necessary before widespread clinical use of neuro-modulatory brain stimulation techniques can be implemented in routine clinical swallowing rehabilitation practice.

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