Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Implementing an outpatient rTMS service for chronic stroke rehabilitation: The Tübingen Framework

Anne Lieb

anne.lieb@uni-tuebingen.de

Universitätsklinikum Tübingen

Brigitte Zrenner

Temerty Centre for Therapeutic Brain Intervention

Christoph Zrenner

Temerty Centre for Therapeutic Brain Intervention

Claudia Resch

Universitätsklinikum Tübingen

Christina Kohlmann Dell'Acqua

Universitätsklinikum Tübingen

Dania Humaidan

Universitätsklinikum Tübingen

Andreas Jooß

Universitätsklinikum Tübingen

Leidy Reyes Jimenez

Universitätsklinikum Tübingen

Gabor Kozák

Universitätsklinikum Tübingen

Joachim Liepert

Kliniken Schmieder Allensbach

Ulf Ziemann

Universitätsklinikum Tübingen

Research Article

Keywords: Stroke rehabilitation, repetitive transcranial magnetic stimulation, motor recovery, aphasia, outpatient care

Posted Date: August 20th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10622756/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Background.

Low-frequency repetitive transcranial magnetic stimulation (rTMS) of the contralesional hemisphere is recommended by current European guidelines for upper-limb motor recovery after stroke and for chronic non-fluent post-stroke aphasia. Nevertheless, structured outpatient delivery models embedded in routine care remain rare.

Objective.

To describe the implementation framework of a dedicated outpatient rTMS service for chronic stroke rehabilitation, established in 2019 at a German tertiary care center, including patient selection, the stimulation protocol, treatment pathways, and linkage to rehabilitation.

Methods.

We report a framework description derived from clinical and organizational experience of an rTMS outpatient clinic (2019–2025), with retrospective observations from routine chronic stroke care in 112 patients with upper-limb paresis and 19 patients with motor aphasia. Neuronavigated low-frequency rTMS (1 Hz, 1200 pulses, 120% resting motor threshold) was paired immediately with task-specific occupational or speech therapy across two delivery formats: intensive multidisciplinary rehabilitation (15 sessions over 3 weeks) or a serial outpatient model (18 sessions over 6 weeks).

Results.

The service has operated continuously since 2019, and both delivery pathways have remained in routine use throughout this period. No serious adverse events occurred. Detailed clinical outcomes for both indications are reported separately in dedicated cohort analyses.

Conclusions.

Disciplined patient selection, consistent rTMS/occupational or speech therapy pairing and individual pathway flexibility allow outpatient rTMS to be delivered as a routine service for chronic stroke.

Registration

This article describes a clinical service framework and reports retrospective analyses of routine care data. Prospective study registration was not applicable.

Introduction

The therapeutic efficacy of repetitive transcranial magnetic stimulation (rTMS) has been investigated for post-stroke recovery for over two decades, and the European 2020 evidence-based guidelines grant a Level A recommendation to low-frequency contralesional rTMS for post-acute upper-limb motor stroke, with Level C evidence in the chronic stage and a Level B recommendation for low-frequency rTMS of the right-hemispheric inferior frontal gyrus in chronic non-fluent post-stroke aphasia (1). Despite this, structured outpatient rTMS services for chronic stroke remain rare in routine European care. Most published evidence comes from controlled trials or tertiary research environments, while patients in the chronic phase typically face fragmented aftercare with limited access to specialized neuromodulation (2). The translational gap concerns service design as much as efficacy data. Open questions are how patients should be selected, how stimulation should be coupled with task-specific rehabilitation, and which workflows allow this to run reliably outside a research setting.

The outpatient rTMS clinic at the University Hospital Tübingen was established in 2019 to address this gap. It has treated two specific chronic-stroke target groups so far, patients with spastic upper-limb paresis and patients with motor aphasia and pairs each stimulation session with immediately following occupational or speech therapy. The principal motor cohort and a separately evaluated aphasia subgroup are included as a routine-care reference signal.

Stroke is among the neurological conditions in which clinically meaningful improvement may still be achievable in the chronic stage, provided that residual recovery potential is identified and treatment is sufficiently specific, intensive and functionally embedded (3, 4). Persistent upper-limb motor deficits, spasticity and language impairment frequently continue into the chronic phase and remain relevant determinants of disability (5–7), while access to specialized, interdisciplinary and sufficiently intensive outpatient neurorehabilitation is structurally limited (8).

The neurophysiological rationale of therapeutic rTMS rests on its capacity to induce lasting changes in synaptic efficacy and network excitability. In post-stroke rehabilitation, these effects have classically been interpreted within the framework of maladaptive interhemispheric imbalance, whereby the contralesional hemisphere may exert excessive transcallosal inhibition on residual networks of the ipsilesional hemisphere (9–11). Low-frequency (≤ 1 Hz) inhibitory rTMS of the contralesional hemisphere has accordingly been used to attenuate this imbalance (12, 13). Network-level models, including the bimodal balance-recovery framework, refine this account by integrating structural reserve and lesion topology as moderators of treatment response (14–16).

Despite the maturity of these models, the literature remains heterogeneous with regard to patient populations, lesion characteristics, stimulation targets, and intensity and timing of concomitant therapy (17–20). Recent meta-analyses report small-to-moderate motor effects in chronic stroke, with the most consistent benefits for low-frequency rTMS protocols targeting the contralesional motor cortex (21–23), and comparable benefits in chronic non-fluent aphasia with low-frequency rTMS targeting the right-hemispheric inferior frontal gyrus (24–26), while the Third Stroke Recovery and Rehabilitation

Roundtable consensus calls for explicit phenotype-based stratification and tighter integration with task-specific therapy in future trials (27). Implementation-oriented work remains underrepresented. Little has been published on how rTMS can be translated into a structured outpatient care pathway for chronic stroke, how patients should be selected in routine practice, and which organizational conditions are required for sustainable implementation.

Within these boundaries, the present article describes the conceptual rationale, clinical structure and practical implementation of a specialized outpatient rTMS clinic for chronic stroke rehabilitation, covering patient selection, pathway assignment, the stimulation protocol with its safety framework, and the immediate coupling of stimulation with task-specific therapy. We present the Tübingen model as a framework that is informed by evidence and derived from routine practice and that can serve as a structured template for other centers establishing similar services. The central question addressed here is how a guideline-supported rTMS intervention can be delivered as a routine outpatient service for chronic stroke. The article is implementation-focused and not intended as an efficacy report. The principal motor cohort (n = 112) and the aphasia cohort (n = 19) are referenced to characterize the kind of change the framework produces in routine care. Detailed inferential analyses for the motor and aphasia cohorts are reported separately in dedicated companion manuscripts.

Methods

Overall approach

This article is an implementation framework description, reported in accordance with the StaRI checklist (28) derived from clinical and organizational experience operating the service. Following the StaRI distinction, methods report two distinct components: (i) the evidence-based intervention being implemented (the rTMS protocol and its task-specific therapy pairing, summarized in Tables 1–2); and (ii) the implementation strategy delivering the intervention in routine care (specialist-led indication, two parallel pathways, immediate temporal coupling, standardized safety procedures and structured documentation; detailed in Clinical workflow, Patient selection and Practical implementation considerations). The implementation indicators reported here, comprising reach (number of patients treated per indication), treatment completion, session count and safety, were reconstructed retrospectively from routine clinical documentation. Process-level fidelity metrics that would require dedicated audit (per-session deviation logs, structured acceptability surveys, sustained adoption tracking) were not prospectively operationalized.

Literature basis and conceptual derivation

The conceptual framework was informed by a narrative literature review focusing on therapeutic rTMS in post-stroke recovery, with particular attention to upper-limb motor impairment, spasticity, and post-stroke aphasia. Priority was given to clinical trials, systematic reviews, meta-analyses, expert guidelines

and neurophysiological framework papers. Pooled evidence from randomized trials available before 2019 supported the clinical translation of this model (24, 29, 30). The interhemispheric imbalance model was adopted as an evidence-informed working framework reflecting the contemporary evidence available when the service was established (9, 14) without claiming a universal mechanistic consensus. The European therapeutic guidelines assigned a Level C recommendation to low-frequency contralesional rTMS in chronic upper-limb motor stroke and a Level B recommendation to low-frequency rTMS of the right inferior frontal gyrus in chronic non-fluent aphasia (1, 31), while the safety recommendations of the International Federation of Clinical Neurophysiology, including contraindication screening, seizure-risk assessment and dosing limits, govern eligibility and monitoring in the present service (1, 31).

Clinical setting

The clinical setting is the outpatient TMS service established in 2019 and embedded within a stroke-oriented neurological and rehabilitative environment at the University Hospital Tübingen and the associated Center of outpatient rehabilitation (ZAR). It combines neurological assessment, indication review, neuromodulatory treatment, and rehabilitation linkage within a unified ambulatory care pathway. Logistically, the rehabilitation center is in an adjacent building approximately 300 meters away, so patients must be able to cover this distance or be accompanied (e.g. by wheelchair).

Cohort and stimulation protocol

The service operates two indication-specific treatment arms, one for chronic upper-limb paresis and one for chronic motor aphasia. The patients treated in each arm to date are characterized in Tables 1a and 1b, and the corresponding numbers are reported under Clinical experience and observed outcomes. The stimulation protocol (Table 2) is applied with the same parameters across both indications, with the stimulation target determined by indication. For each patient, a structural cranial MRI is acquired on a clinical 3T scanner (T1-weighted MPRAGE, 1 mm isotropic) after the initial consultation; the volumetric dataset is imported into the neuronavigation system, on which the individual stimulation target is defined anatomically (contralesional motor cortex hand area for the motor indication; right-hemispheric Broca homologue for the aphasia indication), and used to guide coil placement during every subsequent stimulation session.

Before treatment, the resting motor threshold of the contralesional motor cortex is determined (32), which defines both the stimulation site and the intensity of the rTMS treatment protocol (120% of resting motor threshold). For the aphasia indication, the resting motor threshold is determined over the right motor cortex and applied to the right Broca homologue(31). Full procedural detail is given in the Supplementary Material 2.

Table 1

a. Cohort characteristics, principal motor indication (n = 112).

Variable	Value	Detail / range
Patients (n)	112	Treated 2019–2025
Sex	70 male / 42 female	
Age	61.2 ± 11.7 years	Range 27–87
Time since stroke	3.8 years (mean)	Range 0–21 years
Stroke type	67% ischemic / 33% hemorrhagic	
Affected hemisphere	68% right / 32% left	

Table 1

b. Cohort characteristics, motor aphasia indication (n = 19)

Variable	Value	Detail / range
Patients (n)	19	Treated 2019–2025
Sex	13 male / 6 female	
Age	58.0 ± 13.9 years	Range 29–78
Time since stroke	3.1 years (mean)	Range 0–9 years
Stroke type	79% ischemic / 11% hemorrhagic (10% not reported)	
Affected hemisphere	100% left	

Table 2
Stimulation protocol applied across both treatment pathways.

Parameter	Specification
Frequency	1 Hz (low-frequency, inhibitory)
Pulses per session	1200
Intensity	120% of resting motor threshold of the targeted contralesional motor cortex
Target - motor indication	Contralesional primary motor cortex (hand area)
Target - aphasia indication	Right-hemispheric Broca homologue (inferior frontal gyrus)
Stimulator	Clinical rTMS system with biphasic pulse configuration (technical specifications available from the corresponding author)
Coil	70-mm figure-of-eight air-cooled
Neuronavigation	stereoscopic system, individual MRI-based, displacement maintained within ~ 2 mm
Sessions per cycle	15 sessions over 3 weeks (5×/week) or 18 sessions over 6 weeks (3×/week)
Therapy pairing	Occupational therapy (motor) or speech and language therapy (aphasia), starting within ~ 15 min after stimulation
Evidence for clinical efficacy	Lefaucheur et al. (2020) European guidelines (1, 31)
Safety framework	Rossi et al. (2021) consensus safety recommendations (31)

Clinical assessment and treatment logic

Patients predominantly present to the outpatient clinic on their own initiative, either by telephone or email. Awareness of the service is generated mainly through posters and flyers on the stroke wards, complemented by occasional coverage in regional print and television media. During this initial contact, preliminary eligibility is assessed and an on-site consultation is arranged. Initial presentation includes a comprehensive neurological and rehabilitative history, review of previous reports and assessment of motor, language, neuropsychological and psychosocial aspects. Treatment options are discussed, additional diagnostics initiated where needed, and the rationale, expected effects and limitations of rTMS explained transparently. The initial consultation is a formal clinical decision point at which indication, goals, feasibility, and expectations are aligned with the patient. Patients are invited to provide a broad consent for the retrospective inclusion of their anonymized data in studies, and the service also informs patients about ongoing trials, thereby supporting entry and recruitment into prospective studies.

Treatment pathways

Both indications are delivered in one of two structured treatment formats (Fig. 1). In the first, rTMS is integrated into an intensive full-day rehabilitation setting (designated Phase D in the German neurological rehabilitation phase model (33)) with multimodal neurorehabilitation, including physiotherapy, occupational therapy, group-based treatment, neuropsychological interventions and physical treatments, with weekly physician reviews. In the second pathway, patients receive a serial outpatient treatment of three sessions per week, each comprising one rTMS session followed immediately by occupational or speech therapy. Across both models, rTMS protocols are identical and both rely on the close temporal coupling between stimulation and task-specific training, focused on the affected function and otherwise left to the treating therapist's judgement. Training begins within approximately 15 minutes of the rTMS session and typically lasts about 50 minutes (34–36).

Stimulation framework

Stimulation is neuronavigated and delivered as low-frequency (1 Hz) rTMS over the contralesional primary motor cortex for upper-limb impairment or over the right-hemispheric Broca homologue for motor aphasia. Each session lasts 20 minutes (application of 1200 TMS pulses) plus preparation time. Low-frequency contralesional stimulation reflects the interhemispheric imbalance framework (9, 10), complemented by accumulated clinical experience in which this approach has yielded the most consistent functional benefit in chronic-stage patients treated within the present service. Following the rTMS session, patients undergo occupational or speech therapy. After completion of the treatment cycle, repeated standardized evaluation and a final clinical consultation are performed.

Clinical outcome selection

In the motor domain, upper-limb performance is assessed using the Fugl-Meyer Assessment (37, 38) and spasticity using the modified Ashworth Scale (39, 40). The two instruments were chosen as established measures in stroke recovery research that are feasible to administer under routine outpatient conditions. Detailed inferential analyses, effect sizes and proportions reaching the established clinically meaningful threshold for the Fugl-Meyer Assessment (41, 42) are reported in the motor companion manuscript.

In the language domain, aphasia is assessed by the cooperating speech and language therapists using the Aphasia Check List (ACL (43)), a validated German screening battery used here as a feasible outcome instrument under routine outpatient conditions, complemented by the caregiver-rated Communicative Effectiveness Index (CETI (44)), a functional communication measure.

Patient selection

Selection for both indications is confined to the late subacute to chronic stage. Patients are considered from at least three months post-stroke, after completion of acute and early rehabilitative stages, when substantial deficits remain despite prior treatment. Chronicity is explicitly not viewed as a contraindication. To anticipate one finding reported in full in the motor companion manuscript, treatment effects on tone and motor impairment were not significantly related to time since stroke onset, reflecting the conceptual premise that clinically meaningful gains remain achievable years after the index event in selected patients (3, 36).

The eligibility criteria of the service are summarized in Tables 3A and 3B. Selection includes standard TMS safety considerations per the international safety recommendations (31). Moreover, the service aims to select patients with realistic, function-oriented goals that can be addressed through the specific combination of rTMS and occupational or speech therapy, rather than those seeking a passive technological intervention that does not require their own active participation. Expectation management is therefore part of the indication consultation, during which patients are counseled about the expected effect and prognosis. Lesion location, severity and stroke etiology are not applied as exclusion criteria; however, the treatment effect depends on the severity of the affected function, and the degree of preserved residual function informs prognosis and the goals discussed with the patient (14–16, 45). A detailed description is reported in the companion cohort manuscripts. For the motor indication, the service treats patients with moderate to severe spastic upper-limb paresis who retain residual voluntary activation of the hand, but whose everyday hand use remains substantially limited. Preserved residual voluntary function, as an index of corticospinal tract integrity, is a prerequisite for a meaningful treatment effect, consistent with the role of corticospinal reserve and lesion topology as moderators of response (14–16, 45). Clinical experience suggests that patients with marked spasticity and only moderately pronounced weakness benefit particularly, consistent with a phenotype in which reduction of maladaptive tone is likely to translate into improved use of residual motor capacity (14, 46). In patients receiving botulinum neurotoxin (BoNT-A) for spasticity, the most recent injection into the affected upper limb should date back at least three months, since its central effects on intracortical inhibition and facilitation remain detectable across this interval (47, 48), so earlier rTMS would target a pharmacologically altered cortex.

For the language indication, the service treats patients with motor aphasia who retain auditory comprehension. These eligibility criteria derive from the stimulation target. Since inhibitory stimulation is delivered to the right-hemispheric Broca homologue, eligibility is confined to the non-fluent, Broca-type phenotype. Patients with aphasia nevertheless accounted for only a small part of the service (19 of 131 patients, 14.5%), mainly because considerably fewer patients with aphasia presented to the clinic, for reasons that cannot be reconstructed retrospectively. Apraxia of speech is limited to mild forms so that a superimposed motor-speech planning deficit does not confound the language-network effects of stimulation.

Table 3

A. Eligibility criteria applying to all patients of the service, irrespective of indication. MR, magnetic resonance; rTMS, repetitive transcranial magnetic stimulation; TMS, transcranial magnetic stimulation.

Criterion	Requirement
Time since stroke	At least three months post-stroke, chronicity not a contraindication
TMS safety screening	No contraindications, no implants at risk, medical stability, per international safety recommendations (31)
Structural epilepsy	Not categorically excluded, sustained seizure freedom for at least twelve months under antiseizure medication (centre-specific precaution)
History of craniotomy or decompressive surgery	Not excluded when rTMS is delivered over the contralesional, non-operated hemisphere and implanted material is documented as MR-safe
Not applied as exclusion criteria	Lesion location, severity and stroke etiology, which inform prognosis and treatment goals discussed with the patient
Program requirements	Realistic function-oriented goals, active participation, ability to attend the outpatient schedule

Table 3

B. Indication-specific eligibility criteria. BMRC, British Medical Research Council; BoNT A, botulinum toxin type A.

Criterion	Motor indication (spastic upper-limb paresis)	Language indication (non-fluent aphasia)
Core phenotype	Moderate to severe spastic upper-limb paresis with substantially limited everyday hand use	Non-fluent, Broca-type aphasia
Preserved function required	At least minimal residual voluntary activation of the fingers (BMRC grade 1)	Auditory comprehension sufficient to engage in rehabilitation, at most mild apraxia of speech
Pharmacological timing	Most recent BoNT A injection into the affected upper limb at least three months previously	Not applicable

Clinical workflow

For many patients the initial consultation described above is their first comprehensive rehabilitative reassessment of motor and language status since the end of inpatient or early outpatient rehabilitation, often years earlier. Based on this assessment, realistically expected treatment effects and the suitable treatment pathway are identified. The working principles of rTMS, known risks and contraindications are discussed with the patient, and written informed consent for rTMS is obtained. The patient is then scheduled for the structural brain MRI used for neuronavigated targeting. MRI-specific contraindications (e.g., ferromagnetic implants, cardiac pacemakers, claustrophobia) are screened and consented separately.

In both pathways, stimulation and therapy are organized as a combined intervention, with immediate subsequent occupational therapy in upper-limb paresis or speech and language therapy in motor aphasia. One treatment cycle comprises 15 sessions over three weeks at five sessions per week (phase D rehabilitation program) or 18 sessions over six weeks at three sessions per week (serial outpatient program), followed by repeated standardized assessment and a final physician-led review. Figure 2 illustrates the temporal structure of the two programs and the organization of a representative treatment week, showing the shared core of rTMS followed immediately by occupational therapy or speech and language therapy as well as the point at which both pathways converge on an identical reassessment.

RTMS treatment protocols and neurophysiological rationale

Inhibitory low-frequency stimulation of the contralesional hemisphere is grounded in the interhemispheric imbalance model of stroke recovery (9, 11). Stroke can induce a pathologically increased inhibitory influence of the contralesional hemisphere on residual networks of the ipsilesional hemisphere, and inhibitory stimulation of the contralesional hemisphere may attenuate this maladaptive exaggerated transcallosal inhibition (13, 46). The 2020 European guidelines grant a Level C recommendation to this paradigm for chronic upper-limb motor stroke (1), extended by network-level frameworks integrating corticospinal reserve, lesion topology and individual contralesional recruitment patterns (14–16).

For spasticity in particular, current pathophysiological accounts emphasize impaired supraspinal regulation of spinal reflex circuitry and the contribution of corticoreticulospinal pathways over purely transcallosal effects (36, 49–52). The interhemispheric model is therefore retained as a clinically operational framework for protocol selection while we acknowledge that it is a simplification. The mechanisms underlying tone reduction in our cohort may involve descending pathways not directly captured by transcallosal pathways and the model may be superseded as the evidence develops.

For non-fluent aphasia, a similar rationale is transferred to language networks. Inhibitory low-frequency rTMS over the right-hemispheric Broca homologue aims to attenuate maladaptive right-hemispheric activation and to improve conditions for residual left-hemispheric engagement during language tasks (53, 54). Because responsiveness to this paradigm is heterogenous across language modalities and differs between patients (24–26), the aphasia pathway monitors change across the full ACL subdomain profile instead of targeting a single measure.

A central conceptual feature is the immediate pairing of stimulation with task-specific rehabilitation. Modulation of cortical excitability is unlikely to translate into clinical change without subsequent task-specific behavioral activation (55). The service therefore delivers rTMS as one component of activity-dependent rehabilitation and not as a stand-alone intervention. Whether the temporal coupling produces priming-type plasticity effects in this cohort was not directly tested (56, 57).

Practical implementation considerations

In our experience, three operational elements have determined whether the service runs as intended. The first is that the indication is set by a neurologist with TMS expertise. The initial consultation is not only a checklist for stimulation eligibility; it must weigh prior rehabilitation, current functional status, how much the target deficit constrains daily life, and to what extent the patient can realistically engage in the paired therapy. The second is the close temporal coupling of stimulation and task-specific therapy. The rationale for the model rests on this adjacency and realizing it in a real-world outpatient schedule is the part that most clearly separates the clinic from a standard neurology consultation. It requires fixed slots, shared diaries with the therapists, and a willingness to protect the sequence against the usual scheduling pressures. In our clinic, this is guaranteed through the cooperation with the Center for Outpatient Rehabilitation Tübingen. The third is a safety framework applied uniformly in all cases (31, 58). Although rTMS is well tolerated overall, cortical lesions, comorbidities and concomitant medication can alter the seizure threshold in this population. Contraindication screening, patient education and monitoring are therefore part of every cycle. Reimbursement and accessibility of services remain a substantial constraint in the German healthcare system. rTMS for stroke rehabilitation is currently not covered by statutory health insurance (GKV), while private insurance (PKV) may reimburse on individual application under § 4 of the standard private insurance terms (MB/KK). There is at present no EBM position for rTMS in stroke, and the procedure is not part of the G-BA benefits catalogue. Occupational and speech therapy are prescribed separately as remedies (*Heilmittel*) under § 32 SGB V. In the Tübingen service, rTMS sessions are billed directly to patients or private insurers under the German fee schedule for physicians (GOÄ). The practical consequence is that in routine care access to this service depends on private insurance status or willingness and ability to self-pay. These constraints limit scaling, equity of access, and broader dissemination of the model so far.

A formal cost-effectiveness evaluation is outside the scope of this paper, but the main resource drivers can be named. The dominant rTMS-side cost is personnel: clinic staff coordinating and delivering each cycle, plus physician time for indication and review. The occupational and speech-language therapy sessions that follow each stimulation are not billed through the rTMS clinic but reimbursed by statutory health insurance on the standard outpatient route. The phase D pathway is delivered in cooperation with the Center for Outpatient Rehabilitation Tübingen and applied through the regular outpatient rehabilitation route, so the multidisciplinary infrastructure (physiotherapy, neuropsychology, psychological care, group therapy) is funded through that pathway. Comparative health-economic data against established chronic-stroke management strategies, e.g., botulinum toxin programs for focal spasticity and intensive task-specific therapy alone, are not yet available and remain a priority for future work.

Clinical experience and observed outcomes

From an implementation perspective, the service has been continuously operational since 2019. Both pathways have been in sustained clinical use throughout, with consistent uptake and no structural barriers requiring pathway revision. Treatment numbers are provided in the Supplementary Material 2. Across the reporting period (2019–2025), 112 motor and 19 aphasia patients completed the prescribed

treatment cycle (15 or 18 sessions depending on the program, indication-specific target, and parameters per Table 2). A further eight patients were not included in the analysis, owing to premature discontinuation for intercurrent illness unrelated to rTMS or to an extended treatment course without a completed post-treatment evaluation; these are accounted for in Supplementary Material 2. No serious adverse events occurred. To be expected side effects, such as transient scalp discomfort or mild headache occurred occasionally and did not lead to treatment discontinuation. Both programs were feasible across all severity levels. No discontinuation was attributable to limited program feasibility, including the physical demand of the sessions, the intensity of the treatment schedule, or the need to traverse the distance between the treatment buildings. These operational observations constitute the principal implementation outcome reported here and demonstrate that the service is feasible and sustainable under routine outpatient conditions, including in patients with severe chronic post-stroke impairment.

Symptom-specific clinical outcomes for both cohorts are reported and interpreted in the dedicated cohort manuscripts. Because the service operates without a control condition and delivers a multicomponent intervention (rTMS combined with task-specific therapy and broader rehabilitation), these routine-care observations do not support causal inference and are not presented as efficacy data here.

Discussion

This article describes a practice-based framework for an outpatient rTMS service dedicated to chronic stroke rehabilitation. The principal contribution is to show how neuromodulation can be embedded into a clinically coherent outpatient pathway for defined target populations. The framework addresses a specific translational gap: A guideline-recommended rTMS intervention is delivered in routine outpatient care in only a small number of European centers, and published service descriptions are correspondingly rare.

The sparse implementation of such services to date likely reflects the simultaneous need for two capacities that few centers combine, dedicated rTMS expertise on the one hand and structural embedding in neurorehabilitation on the other. The Tübingen model is defined by the integration of both. TMS expertise is concentrated in the indicating and treating team, who use the technique routinely in clinical care and continue to develop it methodologically (59, 60). Neurological rehabilitation is integrated through the cooperation with the Center for Outpatient Rehabilitation, so that each stimulation session is followed by a therapy modality matched to the functional domain and is not being delivered in isolation.

A third defining element is the proximity to the academic institution, which links clinical care and clinical research within one service. The in-depth quantitative characterization, the documentation and the consent procedures described above support recruitment into prospective trials. A service organized in this way can contribute to closing the evidence gap discussed below.

The current evidence base for rTMS in chronic stroke is substantial but clinical efficacy data remain heterogeneous (20–23). The most-cited randomized counterpoint is the multicenter NICHE trial (61), in which navigated contralesional 1 Hz rTMS produced no motor benefit over goal-oriented rehabilitation alone in a heterogeneous chronic stroke cohort. Hofmeijer et al. (18) conclude that the evidence of efficacy is hampered by unexplained variability in reported effect sizes and by an insufficient understanding of the mechanisms of action, and call for identifying the factors that account for this variation rather than treating the mixed signal as settled either way. A service model that fixes protocol, narrows phenotype and standardizes outcomes reduces variance at the implementation level but cannot by itself resolve the underlying evidence question. The Third Stroke Recovery and Rehabilitation Roundtable consensus calls for standardized protocols, adequately powered trials to identify treatment-response phenotypes, and rigorous specification of the paired therapy in future trials (27). Our framework operates within this controversy without resolving it.

Meta-analyses of low-frequency rTMS over right-hemispheric language homologues report the most consistent effects on expressive language and on naming in particular (24–26). The aphasia outcomes of the present cohort, and their relationship to this literature, are reported and interpreted in the dedicated aphasia manuscript.

Rehabilitation gains observed in a structured outpatient setting cannot be attributed to non-invasive brain stimulation alone. Motivation, therapeutic engagement and the continuity of a stable interdisciplinary team plausibly contribute as well, so the intervention is multimodal in a broad sense. The Tübingen framework offers an ambulatory complement to the inpatient Japanese NEURO multicenter program (62), which combines low-frequency rTMS with intensive occupational therapy in a 15-day inpatient setting; the two differ in setting, protocol and case mix and are not directly comparable, so the parallel serves as context and not as a comparison. A recent single-center community experience from an outpatient clinic reported real-world findings in the same direction, with 70% of predominantly chronic patients improving on at least one objective measure after 1 Hz rTMS combined with physiotherapy, and with bilateral stimulation and a shorter interval between stroke and treatment emerging as predictors of response (63). From a German perspective, the framework also points to a structural problem. Despite the 2020 European guideline recommendation (1), broader adoption requires regulatory and reimbursement decisions and cannot rest on the evidence alone, as detailed above (64).

Limitations

This article is an implementation-oriented description of a care model. The conceptual framework is informed by a narrative synthesis of the literature combined with clinical and organizational experience in routine care. Implementation outcomes such as fidelity, adoption, reach and sustainability were not prospectively operationalized; descriptive proxies are reported where available. The description was also not guided by a validated implementation-science framework such as RE-AIM or CFIR (65, 66), and acceptability and adoption were not assessed with standardized measures.

The framework rests on the experience of a single specialized center and on a deliberately narrow clinical spectrum. Both choices strengthen internal consistency, yet may limit transferability. Moreover, rTMS for stroke rehabilitation is not routinely reimbursed by statutory health insurance in Germany or many other healthcare systems, which so far complicates feasibility, restricts accessibility and introduces socio-economic selection effects.

Outcome-oriented observations derive from routine care and were recorded retrospectively across the reporting period without a prospective standardized data-collection protocol. Durability of the observed changes also remains uncertain, as outcomes were assessed within the treatment cycle and no systematic longer-term follow-up at the patient level was available. The observations reported here carry the limitations of uncontrolled routine care. There was no control condition, and clinical assessments were performed unblinded in routine care. The two treatment pathways also differed in their rehabilitation co-interventions, and pathway allocation followed referral source and insurance or self-payment status, introducing selection bias and limiting generalizability. Generating confirmatory effectiveness data for this service therefore requires a dedicated controlled trial design. The same applies to the economic case for the service. No prospective cost-effectiveness or budget-impact analysis was performed, and demonstrating economic viability would require a dedicated prospective health-economic evaluation.

Conclusion

Delivering rTMS as a routine outpatient service in chronic stroke depends above all on embedding the stimulation technique within a functioning rehabilitation service, with the scheduling and reimbursement structures that this requires. This article has described a practice-based framework built on that principle. Its defining feature is the combination of dedicated rTMS expertise with structural embedding in neurorehabilitation, so that each stimulation session is followed immediately by a therapy modality matched to the targeted functional domain. The service has been continuously operational since 2019 and has treated two clearly defined post-stroke populations, patients with residual motor capacity and marked spasticity and patients with chronic aphasia, without serious adverse events. Its feasibility and sustainability under routine outpatient conditions are the principal implementation observations reported here. The framework does not settle the evidence question surrounding rTMS in chronic stroke and is not offered as proof of efficacy, which is examined in dedicated cohort analyses. Instead, it narrows protocol, phenotype and outcome selection to reduce variance at the point of delivery and to make a guideline-recommended intervention available within a coherent clinical pathway for a severely affected population with few established therapeutic alternatives. Wider adoption requires further efficacy evidence and to the same degree the structural conditions outlined above; in particular a reliable reimbursement pathway, which is still lacking in the German statutory health system. Sham-controlled prospective trials, multicenter replication and dedicated health-economic evaluation remain the priorities for establishing the comparative efficacy, durability and economic viability of the model.

Abbreviations

ACL
Aphasia Check List
BMRC
British Medical Research Council (scale of muscle strength)
BoNT
botulinum toxin (BoNT-A, botulinum toxin type A)
CETI
Communicative Effectiveness Index
CFIR
Consolidated Framework for Implementation Research
EBM
Einheitlicher Bewertungsmaßstab (uniform value scale for outpatient statutory physician reimbursement)
G-BA
Gemeinsamer Bundesausschuss (Federal Joint Committee)
GKV
gesetzliche Krankenversicherung (statutory health insurance)
GOÄ
Gebührenordnung für Ärzte (German scale of fees for physicians)
M1
primary motor cortex
MB/KK
Musterbedingungen für die Krankheitskosten- und Krankenhaustagegeldversicherung (model terms for private health insurance)
MPRAGE
magnetization-prepared rapid gradient-echo
MR
magnetic resonance
MRI
magnetic resonance imaging
OT
occupational therapy
PKV
private Krankenversicherung (private health insurance)
RE-AIM
Reach, Effectiveness, Adoption, Implementation, Maintenance
rTMS
repetitive transcranial magnetic stimulation

SGB V
Fünftes Buch Sozialgesetzbuch (Social Code Book V)
SLT
speech and language therapy
StaRI
Standards for Reporting Implementation Studies
TMS
transcranial magnetic stimulation
UL
upper limb
ZAR
Zentrum für ambulante Rehabilitation (Center for Outpatient Rehabilitation)

Declarations

Ethics approval

The retrospective analysis of routine clinical data reported in this article was approved by the Ethics Committee of the University of Tübingen (reference 2026-0203) and was conducted in accordance with the 1964 Declaration of Helsinki and its later amendments.

Consent to participate

All patients gave written informed consent for treatment and, separately, for the use of their clinical data for research purposes. Additional study-specific consent for the retrospective analysis reported here was waived by the ethics committee, because only anonymized routine data were analysed.

Consent to publish

Not applicable. This article does not include individual patient data, images or any identifying information.

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

Funding

No funding was received to assist with the preparation of this manuscript. The outpatient rTMS service described in this article is part of routine clinical care at the University Hospital Tübingen.

Data availability

The aggregate data supporting the findings of this study, including patient numbers by indication and year, are available within the article and its Supplementary Information (Supplementary Table 2). The underlying individual patient-level clinical data were collected in routine clinical care, contain potentially identifying information and are therefore not deposited in a public repository, in accordance with data-protection requirements. De-identified data are available from the corresponding author on reasonable request, subject to a data-sharing agreement and the applicable data-protection regulations and ethics approval governing the study.

Registration

This article describes a clinical service framework and reports retrospective analyses of routine care data. Prospective study registration was not applicable.

Authors' contributions

BZ, CZ, AL: conceptualization, clinical framework implementation. AL data collection, data analysis, writing - original draft, writing - review and editing. CR, CK: clinical assessment and outcome documentation, data curation. DH, AJ, GK and LR: data collection, review and editing. JL: senior advisory input, writing - review and editing. UZ: project supervision, conceptual oversight, writing - review and editing. All authors read and approved the final manuscript.

Supplementary material

Supplementary Material 1. Completed StaRI checklist (28), mapped to the corresponding sections of the present manuscript.

Supplementary Material 2. Number of patients regarding indication and year.

References

1. Lefaucheur, J. P., Aleman, A., Baeken, C., Benninger, D. H., Brunelin, J., & Di Lazzaro, V. (2020). u. a. Evidence-based guidelines on the therapeutic use of repetitive transcranial magnetic stimulation (rTMS): An update (2014–2018). *Clin Neurophysiol Februar*, *131*(2), 474–528. 10.1016/j.clinph.2019.11.002

2. Kaendler, S., Ritter, M., Sander, D., Elstner, M., Schwarzbach, C., & Wagner, M. (2022). u. a. Positionspapier Schlaganfallnachsorge der Deutschen Schlaganfall-Gesellschaft – Teil 1: Nachsorge nach einem Schlaganfall: Status quo der Versorgungsrealität und Versorgungsdefizite in Deutschland. *Nervenarzt 1 April*, *93*(4), 368–376. 10.1007/s00115-021-01231-9
3. Ward, N. S. (2017). Restoring brain function after stroke - bridging the gap between animals and humans. *Nat Rev Neurol April*, *13*(4), 244–255. 10.1038/nrneurol.2017.34
4. Krakauer, J. W., Carmichael, S. T., Corbett, D., & Wittenberg, G. F. (2012). Getting neurorehabilitation right: what can be learned from animal models? *Neurorehabil Neural Repair Oktober*, *26*(8), 923–931. doi:10.1177/1545968312440745 PubMed Central PMCID: PMC4554531.
5. Coupar, F., Pollock, A., Rowe, P., Weir, C., & Langhorne, P. (2012). Predictors of upper limb recovery after stroke: a systematic review and meta-analysis. *Clinical Rehabilitation*, *26*(4), 291–313. 10.1177/0269215511420305
6. Pundik, S., McCabe, J., Skelly, M., Tatsuoka, C., & Daly, J. J. (2019). Association of spasticity and motor dysfunction in chronic stroke. *Ann Phys Rehabil Med 1 November*, *62*(6), 397–402. https://doi.org/10.1016/j.rehab.2018.07.006
7. Zeng, H., Chen, J., Guo, Y., & Tan, S. (2021). Prevalence and Risk Factors for Spasticity After Stroke: A Systematic Review and Meta-Analysis. *Front Neurol Januar*, 11–2020. 10.3389/fneur.2020.616097
8. Hotter, B., Ikenberg, B., Kaendler, S., Knispel, P., Ritter, M., & Sander, D. (2022). u. a. Positionspapier Schlaganfallnachsorge der Deutschen Schlaganfall-Gesellschaft–Teil 2: Konzept für eine umfassende Schlaganfallnachsorge. *Der Nervenarzt*, *93*(4), 377–384.
9. Murase, N., Duque, J., Mazzocchio, R., & Cohen, L. G. (2004). Influence of interhemispheric interactions on motor function in chronic stroke. *Ann Neurol Off J Am Neurol Assoc Child Neurol Soc*, *55*(3), 400–409. 10.1002/ana.10848
10. Nowak, D. A., Grefkes, C., Ameli, M., & Fink, G. R. (2009). Interhemispheric Competition After Stroke: Brain Stimulation to Enhance Recovery of Function of the Affected Hand. *Neurorehabil Neural Repair September*, *23*(7), 641–656. 10.1177/1545968309336661
11. Grefkes, C., & Ward, N. S. (2014). Cortical reorganization after stroke: how much and how functional? *Neuroscientist Februar*, *20*(1), 56–70. 10.1177/1073858413491147
12. Takeuchi, N., & Izumi, S. (2012). Noninvasive brain stimulation for motor recovery after stroke: mechanisms and future views. *Stroke Res Treat*, *2012*, 584727. 10.1155/2012/584727 PubMed Central PMCID: PMC3463193.
13. Yuan, X., Yang, Y., Cao, N., & Jiang, C. (2020). Promotion of Poststroke Motor-Function Recovery with Repetitive Transcranial Magnetic Stimulation by Regulating the Interhemispheric Imbalance. *Brain Sci 18 September*, *10*(9). 10.3390/brainsci10090648 PubMed Central PMCID: PMC7563987.
14. Di Pino, G., Pellegrino, G., Assenza, G., Capone, F., Ferreri, F., & Formica, D. (2014). u. a. Modulation of brain plasticity in stroke: a novel model for neurorehabilitation. *Nat Rev Neurol Oktober*, *10*(10), 597–608. 10.1038/nrneurol.2014.162

15. Lin, Y. L., Potter-Baker, K. A., Cunningham, D. A., Li, M., Sankarasubramanian, V., & Lee, J. (2020). u. a. Stratifying chronic stroke patients based on the influence of contralesional motor cortices: an inter-hemispheric inhibition study. *Clinical Neurophysiology*, *131*(10), 2516–2525.
16. Mustin, M., Hensel, L., Fink, G. R., Grefkes, C., & Tscherpel, C. (2024). Individual contralesional recruitment in the context of structural reserve in early motor reorganization after stroke. *Neuroimage*, *300*, 120828.
17. Fisicaro, F., Lanza, G., Grasso, A. A., Pennisi, G., Bella, R., & Paulus, W. (2019). u. a. Repetitive transcranial magnetic stimulation in stroke rehabilitation: review of the current evidence and pitfalls. *Therapeutic Advances In Neurological Disorders*, *12*, 1756286419878317. 101177/1756286419878317 PubMed Central PMCID: PMC6763938.
18. Hofmeijer, J., Ham, F., & Kwakkel, G. (2023). Evidence of rTMS for Motor or Cognitive Stroke Recovery: Hype or Hope? Stroke. *1 Oktober*, *54*(10), 2500–2511. 10.1161/STROKEAHA.123.043159
19. Aderinto, N., Olatunji, G., Kokori, E., Agbo, C. E., Babalola, A. E., & Aboje, J. E. (2025). u. a. Clinical Applications of Non-Invasive Brain Stimulation in Stroke Recovery: A Review of Current Evidence and Therapeutic Strategies. *Curr Treat Options Neurol 13 Januar*, *27*(1), 8. 10.1007/s11940-024-00823-5
20. Xie, G., Wang, T., Deng, L., Zhou, L., Zheng, X., & Zhao, C. (2025). u. a. Repetitive transcranial magnetic stimulation for motor function in stroke: a systematic review and meta-analysis of randomized controlled studies. *Syst Rev 24 Februar*, *14*(1), 47. 10.1186/s13643-025-02794-3
21. Chen, G., Lin, T., Wu, M., Cai, G., Ding, Q., & Xu, J. (2022). u. a. Effects of repetitive transcranial magnetic stimulation on upper-limb and finger function in stroke patients: A systematic review and meta-analysis of randomized controlled trials. *Frontiers In Neurology*, *13*, 940467. 10.3389/fneur.2022.940467 PubMed Central PMCID: PMC9372362.
22. Xia, Y., Xu, Y., Li, Y., Lu, Y., & Wang, Z. Comparative Efficacy of Different Repetitive Transcranial Magnetic Stimulation Protocols for Stroke: A Network Meta-Analysis. *Front Neurol Juni 2022;Volume* 13–2022. 10.3389/fneur.2022.918786
23. Lee, H. Y., & Ryu, B. (2025). Effects of Repetitive Transcranial Magnetic Stimulation on Upper and Lower Limb Motor Function and Spasticity After Stroke: A Meta-Analysis. *Brain Neurorehabil*. ;18(2).
24. Ren, C. L., Zhang, G. F., Xia, N., Jin, C. H., Zhang, X. H., & Hao, J. F. (2014). u. a. Effect of Low-Frequency rTMS on Aphasia in Stroke Patients: A Meta-Analysis of Randomized Controlled Trials. Avenanti A, Herausgeber. *PLoS ONE 18 Juli*, *9*(7), e102557. 10.1371/journal.pone.0102557
25. Hong, Z., Zheng, H., Luo, J., Yin, M., Ai, Y., & Deng, B. (2021). u. a. Effects of Low-Frequency Repetitive Transcranial Magnetic Stimulation on Language Recovery in Poststroke Survivors With Aphasia: An Updated Meta-analysis. *Neurorehabil Neural Repair August*, *35*(8), 680–691. 10.1177/15459683211011230
26. Zhang, J., Zhong, D., Xiao, X., Yuan, L., Li, Y., & Zheng, Y. (2021). u. a. Effects of repetitive transcranial magnetic stimulation (rTMS) on aphasia in stroke patients: A systematic review and meta-analysis. *Clin Rehabil August*, *35*(8), 1103–1116. 10.1177/0269215521999554

27. Edwards, J. D., Dominguez-Vargas, A. U., Rosso, C., Branscheidt, M., Sheehy, L., & Quandt, F. (2024). u. a. A translational roadmap for transcranial magnetic and direct current stimulation in stroke rehabilitation: Consensus-based core recommendations from the third stroke recovery and rehabilitation roundtable. *International Journal Of Stroke : Official Journal Of The International Stroke Society*, *19*(2), 145–157. 10.1177/17474930231203982
28. Pinnock, H., Barwick, M., Carpenter, C. R., Eldridge, S., Grandes, G., & Griffiths, C. J. (2017). März, u. a. Standards for Reporting Implementation Studies (StaRI) Statement. BMJ. 6. ;i6795. 10.1136/bmj.i6795
29. Hsu, W. Y., Cheng, C. H., Liao, K. K., Lee, I. H., & Lin, Y. Y. (2012). Effects of Repetitive Transcranial Magnetic Stimulation on Motor Functions in Patients With Stroke: A Meta-Analysis. *Stroke Juli*, *43*(7), 1849–1857. 10.1161/STROKEAHA.111.649756
30. Zhang, L., Xing, G., Shuai, S., Guo, Z., Chen, H., & McClure, M. A. (2017). u. a. Low-Frequency Repetitive Transcranial Magnetic Stimulation for Stroke-Induced Upper Limb Motor Deficit: A Meta-Analysis. *Neural Plasticity*, *2017*, 2758097. 10.1155/2017/2758097 PubMed Central PMCID: PMC5756908.
31. Rossi, S., Antal, A., Bestmann, S., Bikson, M., Brewer, C., & Brockmöller, J. (2021). u. a. Safety and recommendations for TMS use in healthy subjects and patient populations, with updates on training, ethical and regulatory issues: Expert Guidelines. *Clin Neurophysiol Januar*, *132*(1), 269–306. 10.1016/j.clinph.2020.10.003
32. Rossini, P. M., Burke, D., Chen, R., Cohen, L. G., Daskalakis, Z., & Di Iorio, R. (2015). u. a. 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 Juni*, *126*(6), 1071–1107. 10.1016/j.clinph.2015.02.001
33. Schupp, W. (1995). [Concept for a functional status and handicap-adjustment treatment and rehabilitation service chain in neurologic and neurosurgical management in Germany („phase model)]. *Nervenarzt Dezember*, *66*(12), 907–914. PubMed PMID: 8584075.
34. Avenanti, A., Coccia, M., Ladavas, E., Provinciali, L., & Ceravolo, M. G. (2012). Low-frequency rTMS promotes use-dependent motor plasticity in chronic stroke: a randomized trial. *NEUROLOGY 24 Januar*, *78*(4), 256–264. 10.1212/WNL.0b013e3182436558
35. Cha, T. H., & Hwang, H. S. (2022). Rehabilitation Interventions Combined with Noninvasive Brain Stimulation on Upper Limb Motor Function in Stroke Patients. *Brain Sci 27 Juli*, *12*(8). 10.3390/brainsci12080994 PubMed Central PMCID: PMC9332761.
36. Mahmoud, W., Hultborn, H., Zuluaga, J., Zrenner, C., Zrenner, B., & Ziemann, U. (2023). u. a. Testing spasticity mechanisms in chronic stroke before and after intervention with contralesional motor cortex 1 Hz rTMS and physiotherapy. *J Neuroeng Rehabil 8 November*, *20*(1), 150. 10.1186/s12984-023-01275-9 PubMed Central PMCID: PMC10631065.
37. Fugl-Meyer, A. R., Jaasko, L., Leyman, I., Olsson, S., & Steglind, S. (1975). The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. *Scandinavian Journal Of Rehabilitation*

Medicine, *7*(1), 13–31. 10.2340/1650197771331

38. Platz, T., Pinkowski, C., van Wijck, F., Kim, I. H., di Bella, P., & Johnson, G. (2005). Reliability and validity of arm function assessment with standardized guidelines for the Fugl-Meyer Test, Action Research Arm Test and Box and Block Test: a multicentre study. *Clin Rehabil Juni*, *19*(4), 404–411. 10.1191/0269215505cr832oa
39. Ashworth, B., PRELIMINARY TRIAL OF, & CARISOPRODOL IN MULTIPLE SCLEROSIS. (1964). *Practitioner April* ;192:540–542. doi:10.1001/jama.1963.03700110141121.
40. Bohannon, R. W., & Smith, M. B. (1987). Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther Februar*, *67*(2), 206–207. 10.1093/ptj/67.2.206
41. Page, S. J., Fulk, G. D., & Boyne, P. (2012). Clinically important differences for the upper-extremity Fugl-Meyer Scale in people with minimal to moderate impairment due to chronic stroke. *Phys Ther Juni*, *92*(6), 791–798. 10.2522/ptj.20110009
42. Narayan Arya, K., Verma, R., & Garg, R. K. (2011). Estimating the Minimal Clinically Important Difference of an Upper Extremity Recovery Measure in Subacute Stroke Patients. *Top Stroke Rehabil 1 Oktober*, *18*(sup1), 599–610. 10.1310/tsr18s01-599
43. Kalbe, E., Reinhold, N., Brand, M., Markowitsch, H. J., & Kessler, J. (2005). A New Test Battery to Assess Aphasic Disturbances and Associated Cognitive Dysfunctions — German Normative Data on the Aphasia Check List. *J Clin Exp Neuropsychol Oktober*, *27*(7), 779–794. 10.1080/13803390490918273
44. Lomas, J., Pickard, L., Bester, S., Elbard, H., Finlayson, A., & Zoghaib, C. (1989). The Communicative Effectiveness Index: Development and Psychometric Evaluation of a Functional Communication Measure for Adult Aphasia. *J Speech Hear Disord Februar*, *54*(1), 113–124. 10.1044/jshd.5401.113
45. Stinear, C. M., Barber, P. A., Petoe, M., Anwar, S., & Byblow, W. D. (2012). The PREP algorithm predicts potential for upper limb recovery after stroke. *Brain*, *135*(8), 2527–2535. 10.1093/brain/aws146
46. Boddington, L. J., & Reynolds, J. N. J. (2017). Targeting interhemispheric inhibition with neuromodulation to enhance stroke rehabilitation. *Brain Stimul Basic Transl Clin Res Neuromodulation*, *10*(2), 214–222. 10.1016/j.brs.2017.01.006
47. Kim, D. Y., Oh, B. M., Paik, N. J., & CENTRAL EFFECT OF BOTULINUM TOXIN (2006). TYPE A IN HUMANS. *Int J Neurosci Januar*, *116*(6), 667–680. 10.1080/00207450600674525
48. Veverka, T., Hok, P., Otruba, P., Zapletalová, J., Kukolová, B., & Tüdös, Z. (2019). u. a. Botulinum Toxin Modulates Posterior Parietal Cortex Activation in Post-stroke Spasticity of the Upper Limb. *Front Neurol 9 Mai*, *10*, 495. 10.3389/fneur.2019.00495
49. Li, S. (2017). Spasticity, motor recovery, and neural plasticity after stroke. *Frontiers In Neurology*, *8*, 120.
50. Li, S., Chen, Y. T., Francisco, G. E., Zhou, P., & Rymer, W. Z. (2019). A Unifying Pathophysiological Account for Post-stroke Spasticity and Disordered Motor Control. *Frontiers In Neurology*, *10*, 468. 10.3389/fneur.2019.00468 PubMed Central PMCID: PMC6524557.

51. Mooney, A. R., Anaya, A. M., Stilling, M. J., & Celnik, A. P. (2025). Heightened Reticulospinal Excitability after Severe Corticospinal Damage in Chronic Stroke. *Ann Neurol 10 Oktober*, *97*(1), 163–174. 10.1002/ana.27103
52. Schading-Sassenhausen, S., Dietz, V., & Freund, P. (2025). Effect of corticospinal and reticulospinal tract damage on spastic muscle tone and mobility: a retrospective observational MRI study. *EBioMedicine*, *118*. 10.1016/j.ebiom.2025.105824
53. Naeser, M., Martin, P., Nicholas, M., Baker, E., Seekins, H., & Kobayashi, M. (2005). u. a. Improved picture naming in chronic aphasia after TMS to part of right Broca?s area: An open-protocol study. *Brain Lang April*, *93*(1), 95–105. 10.1016/j.bandl.2004.08.004
54. Hamilton, R. H., Chrysikou, E. G., & Coslett, B. (2011). Mechanisms of aphasia recovery after stroke and the role of noninvasive brain stimulation. *Brain Lang Juli*, *118*(1–2), 40–50. 10.1016/j.bandl.2011.02.005
55. Kleim, J. A., & Jones, T. A. (2008). Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. *J Speech Lang Hear Res JSLHR Februar*, *51*(1), S225–239. 10.1044/1092-4388(2008/018) PubMed PMID: 18230848.
56. Stinear, C. M., Barber, P. A., Coxon, J. P., Fleming, M. K., & Byblow, W. D. (2008). Priming the motor system enhances the effects of upper limb therapy in chronic stroke. *Brain Mai*, *131*(5), 1381–1390. 10.1093/brain/awn051
57. Ackerley, S. J., Byblow, W. D., Barber, P. A., MacDonald, H., McIntyre-Robinson, A., & Stinear, C. M. (2016). Primed Physical Therapy Enhances Recovery of Upper Limb Function in Chronic Stroke Patients. *Neurorehabil Neural Repair Mai*, *30*(4), 339–348. 10.1177/1545968315595285
58. Kim, W. S., & Paik, N. J. (2021). Safety review for clinical application of repetitive transcranial magnetic stimulation. *Brain Neurorehabilitation*, *14*(1), e6.
59. Ziemann, U., Romani, G. L., & Ilmoniemi, R. J. (2019). „ConnectToBrain: Synergy-Projekt zur Closed-loop-Stimulationstherapie von Netzwerkerkrankungen des Gehirns. *Nervenarzt August*, *90*(8), 804–808. 10.1007/s00115-019-0747-x
60. Lieb, A., Zrenner, B., Zrenner, C., Kozak, G., Martus, P., & Grefkes, C. (2023). u. a. Brain-oscillation-synchronized stimulation to enhance motor recovery in early subacute stroke: a randomized controlled double-blind three- arm parallel-group exploratory trial comparing personalized, non-personalized and sham repetitive transcranial magnetic stimulation (Acronym: BOSS-STROKE). *BMC Neurol 25 Mai*, *23*(1), 204. 10.1186/s12883-023-03235-1 PubMed Central PMCID: PMC10210305.
61. Harvey, R. L., Edwards, D., Dunning, K., Fregni, F., Stein, J., & Laine, J. (2018). u. a. Randomized Sham-Controlled Trial of Navigated Repetitive Transcranial Magnetic Stimulation for Motor Recovery in Stroke. *Stroke September*, *49*(9), 2138–2146. 10.1161/strokeaha.117.020607
62. Kakuda, W., Abo, M., Shimizu, M., Sasanuma, J., Okamoto, T., & Yokoi, A. (2012). u. a. A multi-center study on low-frequency rTMS combined with intensive occupational therapy for upper limb hemiparesis in post-stroke patients. *J NeuroEngineering Rehabil*, *9*(1), 4.

63. Jacques, F. H., Acosta Diaz, J., Deschenes, E., Rabia, N., & Apedaile, B. E. (2026). Repetitive transcranial magnetic stimulation for post stroke rehabilitation-a single center community experience. *Frontiers In Neurology*. 10.3389/fneur.2026.1792409 PubMed PMID: 41929600.
64. Smith, M. C., & Stinear, C. M. (2016). Transcranial magnetic stimulation (TMS) in stroke: Ready for clinical practice? *J Clin Neurosci September*, *31*, 10–14. 10.1016/j.jocn.2016.01.034
65. Damschroder, L. J., Aron, D. C., Keith, R. E., Kirsh, S. R., Alexander, J. A., & Lowery, J. C. (2009). Fostering implementation of health services research findings into practice: a consolidated framework for advancing implementation science. *Implement Sci Dezember*, *4*(1), 50. 10.1186/1748-5908-4-50
66. Glasgow, R. E., Vogt, T. M., & Boles, S. M. (1999). Evaluating the public health impact of health promotion interventions: the RE-AIM framework. *Am J Public Health September*, *89*(9), 1322–1327. 10.2105/AJPH.89.9.1322

Figures

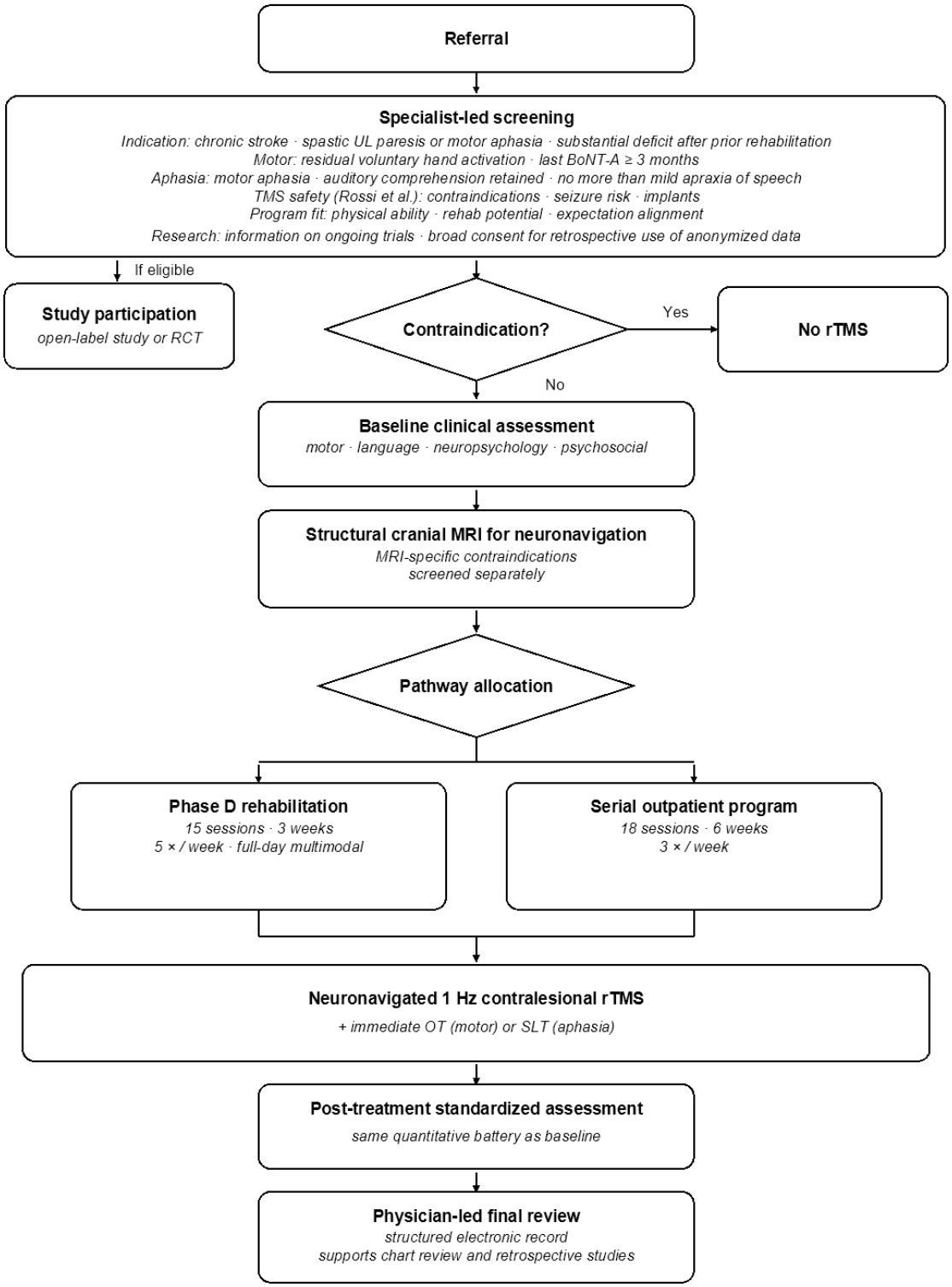


Figure 1

Flow diagram illustrating the structured patient pathway of the outpatient rTMS service. BoNT-A, botulinum toxin type A; MRI, magnetic resonance imaging; OT, occupational therapy; Phase D, full-day multimodal rehabilitation stage of the German neurological rehabilitation phase model; rTMS, repetitive transcranial magnetic stimulation; SLT, speech and language therapy; TMS, transcranial magnetic stimulation; UL, upper limb.

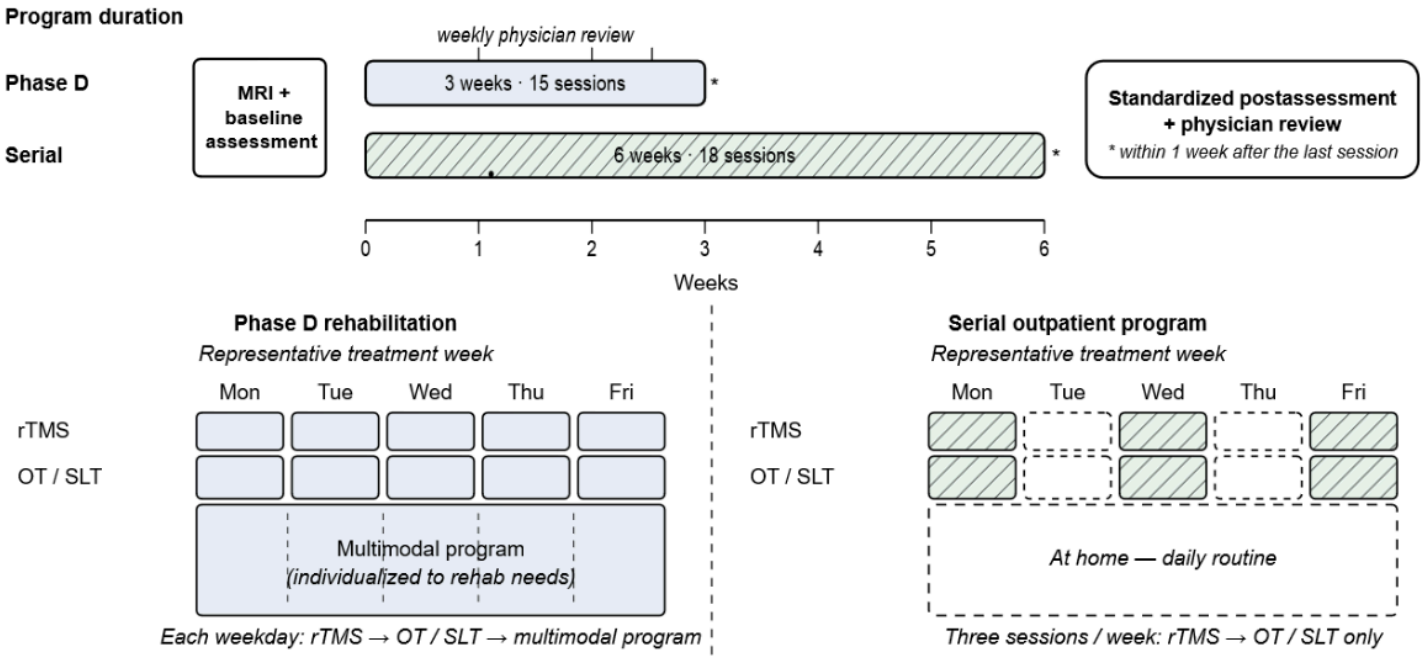


Figure 2

The program-duration timeline (top) shows Phase D over 3 weeks (15 sessions, weekly physician review) vs Serial over 6 weeks (18 sessions), both converging on an identical reassessment within at least 1 week after the last session. The representative week (below) shows the shared core, rTMS then OT / SLT, running daily in Phase D ahead of an individualized multimodal program, versus Serial's core on three days per week with home days otherwise. Abbreviations used in the figure are as follows. MRI, magnetic resonance imaging; OT, occupational therapy; Phase D, full-day multimodal rehabilitation stage of the German neurological rehabilitation phase model; rTMS, repetitive transcranial magnetic stimulation; SLT, speech and language therapy.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- FrameworkSupplementaryMaterial.docx