British Journal of Hospital Medicine

Br. J. Hosp. Med. (Lond) **2026**; 87(10): 52794
https://doi.org/10.31083/BJHM52794

Systematic Review

Effects of Different Stimulation Parameters on the Efficacy of Transcranial Direct Current Stimulation for Post-Stroke Dysphagia: An Updated Systematic Review and Meta-Analysis of Randomized Controlled Trials

Cheng Gong[1,2,†], Runqi Zhong[1,3,†], Na Zhao[1,2], Wei Shuai[1], Yaoshan Dun[1,3,4,*], Yuan Lin[1,3,4,*]

[1]Department of Physical Medicine & Rehabilitation, Xiangya Hospital, Central South University, Jiangxi (National Regional Center for Neurological Diseases), 330038 Nanchang, Jiangxi, China
[2]Department of Rehabilitation Medicine, Jiangxi Provincial People's Hospital, 330006 Nanchang, Jiangxi, China
[3]Department of Physical Medicine & Rehabilitation, Xiangya Hospital, Central South University, 410008 Changsha, Hunan, China
[4]National Clinical Research Center for Geriatric Diseases, Xiangya Hospital, Central South University, 410008 Changsha, Hunan, China
*Correspondence: dunyaoshan@csu.edu.cn (Yaoshan Dun); liny@csu.edu.cn (Yuan Lin)
[†]These authors contributed equally.
Academic Editor: Arianna Di Stadio
Submitted: 10 April 2026 Revised: 1 August 2026 Accepted: 11 August 2026 Published: 23 October 2026

Abstract

Aims/Background: Transcranial direct current stimulation (tDCS) is a promising intervention for post-stroke dysphagia (PSD). However, no consensus has been reached regarding the optimal stimulation parameters. This study aimed to identify the optimal tDCS stimulation protocol for patients with PSD. **Methods:** Following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, we systematically searched seven databases (Web of Science, PubMed, Embase, Cochrane Library, WanFang, CNKI, and VIP) for relevant trials, covering the period from database inception to 1 January 2025. Statistical analyses were performed with Review Manager 5.40, with the choice of fixed- or random-effects model guided by I^2 values. **Results:** Overall, tDCS significantly improved swallowing function compared with control conditions for both outcome measures in which higher scores indicate better swallowing function (standardized mean difference (SMD) = 1.16, $p < 0.001$) and those in which lower scores indicate better swallowing function (SMD = −0.85, $p < 0.001$). In the subgroup analysis by stimulation intensity, 1.4 mA yielded the largest point estimate among positive-direction outcomes (SMD = 1.91, $p = 0.04$), whereas 1.8 mA yielded the largest effect estimate among negative-direction outcomes (SMD = –0.82, $p = 0.04$). Both single-session tDCS lasting 20 minutes and 30 minutes significantly improved swallowing function in patients with PSD (positive outcome indicators, 20 min: SMD = 1.18, $p < 0.001$; 30 min: SMD = 1.28, $p = 0.02$, subgroup difference: $p = 0.86$; negative outcome indicators, 20 min: SMD = –0.69, $p < 0.001$; 30 min, SMD = –0.70, $p = 0.005$, subgroup difference, $p = 0.89$). However, prolonging single-session duration to 30 minutes did not confer superior therapeutic efficacy relative to 20 minutes. tDCS was effective for both supratentorial and infratentorial lesions (positive outcome indicators, SMD = 1.57, $p < 0.001$; negative outcome indicators, SMD = –0.73, $p < 0.001$). Compared with the control group, swallowing function was improved in acute, sub-acute and chronic stroke patients treated with tDCS intervention (positive outcome indicators, Acute: SMD = 1.17, $p < 0.0001$; Subacute: SMD = 1.72, $p < 0.0001$; Chronic: SMD = 0.59, $p = 0.0004$; negative outcome indicators, Acute: SMD = –0.78, $p < 0.0001$; Sub-acute: SMD = –0.91, $p = 0.0001$; Chronic: SMD = –0.77, $p = 0.001$). tDCS significantly improved swallowing function in patients with pseudobulbar palsy (SMD = –0.86, $p = 0.001$), whereas it showed no obvious therapeutic effect on patients with bulbar palsy (SMD = –0.48, $p = 0.07$). **Conclusion:** tDCS yields favorable effects on swallowing function in patients with PSD when administered to the lesional hemisphere, the contralesional hemisphere, or bilaterally, and there are no differences in efficacy among the three stimulation modes. An intensity of 1.8 mA represents a potential optimal "sweet spot", suggesting that higher intensities (2.0 mA) do not necessarily translate to better clinical outcomes. A 20-minute session duration is sufficient for therapeutic effect. **Systematic Review Registration:** PROSPERO (CRD42022344115).

Keywords: stroke; dysphagia; transcranial direct current stimulation; meta-analysis; systematic review

Copyright: © 2026 The Author(s). Published by IMR Press.
This is an open access article under the CC BY 4.0 license.

Publisher's Note: IMR Press stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Dysphagia is a common complication following stroke, with post-stroke dysphagia (PSD) reported to affect up to 64% of survivors [1,2]. PSD frequently causes malnutrition, aspiration pneumonia, electrolyte disturbances and other adverse sequelae, which severely hinder rehabilitation progress, lower patients' quality of life, and may even threaten survival [3,4,5,6]. Current clinical management of PSD includes dietary modification [7], postural substitution [8] and swallowing sensorimotor training [9,10,11], all aimed at restoring swallowing function. However, these interventions remain suboptimal, as some PSD patients still suffer from severe dysphagia after conventional swallowing rehabilitation [5]. Accordingly, more potent therapeutic strategies are urgently required to further improve clinical outcomes in patients with PSD.

Transcranial direct current stimulation (tDCS) is a non-invasive neuromodulation technique that delivers a weak direct current to the cerebral cortex, thereby altering neuronal membrane potential: anodal stimulation increases excitability while cathodal stimulation decreases it, allowing targeted modulation of specific brain regions and their functions. Numerous randomized controlled trials (RCTs) have reported positive clinical effects of tDCS in patients with PSD [12,13,14]. Our research team previously published a meta-analysis in 2022 verifying that tDCS demonstrates significant efficacy in improving swallowing function in individuals with PSD [15]. Nevertheless, clinical application of tDCS requires the selection of stimulus intensity, duration, site and frequency, and these parameters vary across studies. For example, some investigators apply anodal tDCS to the lesioned hemisphere to enhance excitability [16], others stimulate the contralesional hemisphere [12,14], while others use bilateral stimulation [17]. Similarly, intensity and duration differ among trials [12,14], yet most report beneficial effects on swallowing. No consensus exists regarding the optimal tDCS parameters for PSD. Our previous meta-analysis [15] attempted subgroup comparisons of stimulus parameters, but the small number of eligible RCTs precluded a comprehensive analysis.

Recently, several RCTs investigating tDCS for PSD have been published. Accordingly, an updated meta-analysis focusing on the optimal tDCS stimulation parameters for patients with PSD is warranted. This updated study aims to identify the best tDCS stimulation protocol for PSD, to analyze the efficacy differences of tDCS across different stroke types and lesion locations, and to provide evidence-based recommendations for the clinical application of tDCS.

2. Methods

This study was designed and conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [18]. The PRISMA Checklist is provided in **Supplementary Material**. The systematic review was registered in the International Prospective Register of Systematic Reviews (PROSPERO) database (CRD42022344115, https://www.crd.york.ac.uk/PROSPERO/view/CRD42022344115).

2.1 Search Strategy

Literature retrieval was carried out independently by two investigators in seven databases: Web of Science (https://webofscience.com), PubMed (https://pubmed.ncbi.nlm.nih.gov/), Embase (https://www.embase.com), Cochrane Library (https://www.cochranelibrary.com), WanFang (https://www.wanfangdata.com.cn), CNKI (https://www.cnki.net), and VIP (https://www.cqvip.com), covering the period from database inception to 1 January 2025. The main search terms comprised "transcranial direct current stimulation", "stroke", and "dysphagia"; relevant subheadings were identified through these terms to broaden the search scope. Although the search strategy included broader non-invasive brain stimulation-related terms to maximize the comprehensiveness of the search, only studies investigating transcranial direct current stimulation for post-stroke dysphagia were eligible for inclusion. Studies involving other stimulation modalities, such as transcranial alternating current stimulation or transcranial random noise stimulation, were excluded during the screening process. The complete search strategy developed for PubMed is provided in Table 1 for illustrative purposes.

2.2 Inclusion and Exclusion Criteria

Literature selection was conducted according to predefined inclusion and exclusion criteria. Inclusion criteria: (1) Adult patients with clinically or radiologically confirmed stroke who developed dysphagia, with the diagnosis or severity of dysphagia assessed using Video-fluoroscopic Swallowing Study (VFSS), Fiber-optic Endoscopic Evaluation of Swallowing (FEES), Penetration–Aspiration Scale (PAS), or other validated swallowing function assessment tools; (2) Interventions consisting of tDCS plus conventional swallowing therapy for the experimental group and control group received conventional swallowing therapy with or without sham tDCS; (3) Primary outcome: swallowing function assessed before and after tDCS treatment (any validated dysphagia scale or imaging result was acceptable); (4) Publications written in Chinese or English.

Exclusion criteria: (1) Animal experiments; (2) Duplicate publications; (3) Full text unavailable; (4) Incomplete data that could not be extracted; (5) Studies in which the main intervention was a non-tDCS intervention; (6) Non-randomized controlled trials; (7) Reviews, conference abstracts, study protocols, editorials, and comments.

2.3 Literature Screening

All retrieved records were imported into EndNote 20 (Clarivate, Philadelphia, PA, USA), duplicate citations were removed using the software's "Find Duplicates" func-

Table 1. Search strategy for PubMed database.

NO.	Search items
1	Stroke [MESH]
2	(Stroke) OR (Cerebrovascular Accident) OR (Cerebral Stroke) OR (Stroke, Cerebral) OR (Cerebrovascular Apoplexy) OR (Apoplexy, Cerebrovascular) OR (Vascular Accident, Brain) OR (Brain Vascular Accident) OR (Vascular Accidents, Brain) OR (Cerebrovascular Stroke) OR (Stroke, Cerebrovascular) OR (Apoplexy) OR (CVA) OR (CVAs) OR (Cerebrovascular Accident) OR (Stroke, Acute) OR (Acute Stroke) OR (Cerebrovascular Accident, Acute) OR (Acute Cerebrovascular Accident)
3	#1 OR #2
4	Deglutition Disorders [MESH]
5	(Deglutition Disorder) OR (Disorders, Deglutition) OR (Dysphagia) OR (Swallowing Disorder) OR (Oropharyngeal Dysphagia) OR (Dysphagia, Oropharyngeal) OR (Esophageal Dysphagia) OR (Dysphagia, Esophageal)
6	#4 OR #5
7	Transcranial direct current stimulation [MESH]
8	(tDCS) OR (Anodal Stimulation Transcranial Direct Current Stimulation) OR (Anodal Stimulation tDCS) OR (Anodal Stimulation tDCSs) OR (Stimulation tDCS, Anodal) OR (Stimulation tDCSs, Anodal) OR (tDCS, Anodal Stimulation) OR (tDCSs, Anodal Stimulation) OR (Cathodal Stimulation Transcranial Direct Current Stimulation) OR (Cathodal Stimulation tDCS) OR (Cathodal Stimulation tDCSs) OR (Stimulation tDCS, Cathodal) OR (Stimulation tDCSs, Cathodal) OR (tDCS, Cathodal Stimulation) OR (tDCSs, Cathodal Stimulation) OR (Transcranial Alternating Current Stimulation) OR (Transcranial Random Noise Stimulation) OR (Repetitive Transcranial Electrical Stimulation) OR (Transcranial Electrical Stimulation) OR (Electrical Stimulations, Transcranial) OR (Electrical Stimulation, Transcranial) OR (Stimulations, Transcranial Electrical) OR (Stimulation, Transcranial Electrical) OR (Transcranial Electrical Stimulations)
9	#7 OR #8
10	#3 AND #6 AND #9

#: Previous historical search result.

OR #: Combine all literature from the two search sets.

AND #: Retrieve the overlapping literature of the two searches.

tion. Reviewers manually verified that all duplicate records had been accurately removed. Subsequently, two reviewers independently screened titles and abstracts against the predefined inclusion and exclusion criteria. For potentially eligible studies, both reviewers downloaded and read the full texts, further excluding articles that did not meet the criteria, and discussed their eligibility. Disagreements between the two reviewers during screening were first resolved through discussion to reach consensus. If consensus could not be reached, the principal investigator was consulted for final adjudication.

2.4 Data Extraction

Two reviewers independently extracted the following information from each included study: first author, year of publication, sample size, participant characteristics (sex, age, stroke type, lesion location, disease duration, adverse events, presence of true bulbar palsy or pseudobulbar palsy), intervention details (tDCS site, intensity, treatment frequency, session number, stimulation time), and outcome measures (swallowing assessment results). For stroke phase stratification: we unified the internationally accepted time thresholds: acute stroke ≤14 days, sub-acute stroke 15–90 days, and chronic stroke >90 days [19]. When data were unclear or incomplete, the reviewers attempted to contact the original authors up to three times to obtain missing information. If no response was received after three attempts, the study was classified as having missing data. Any disagreements during extraction were resolved through discussion within a research panel that included the principal investigator.

2.5 Quality Assessment

Quality appraisal was performed independently by two reviewers, with discrepancies resolved through discussion to achieve consensus. Risk-of-bias evaluation was conducted using the Cochrane Risk of Bias 1 (RoB 1) tool (Review Manager 5.40, Cochrane Collaboration, Oxford, UK) [20]. Results were plotted and color-coded: high risk (red), unclear risk (yellow), and low risk (green). Publication bias was not formally assessed using funnel plots because fewer than 10 studies were available for most individual outcomes.

In addition, separate pooled analyses were carried out for Chinese- and English-language RCTs to examine whether the study conclusions were influenced by publication language. For RCTs with a multi-arm parallel design included in this study—such as trials wherein multiple intervention groups receiving distinct tDCS parameters share a single sham stimulation/control group—multiple effect sizes derived from the same study are statistically non-independent, as they draw on shared control group data. To further verify that the pooled findings are not compromised by potential bias inherent to multi-arm trials, we adopted

the leave-one-out sensitivity analysis within the analytical software: the primary analysis was rerun iteratively following the sequential exclusion of each multi-arm trial [21]. If the direction and statistical significance of the pooled effect size exhibited no substantive shifts following exclusion, the overall results were deemed robust and free from marked bias attributable to correlated effect sizes stemming from multi-arm designs; such multi-arm trials were retained for subsequent subgroup analyses. Conversely, trials failing this robustness check were excluded from further analyses. All the above analytical procedures were conducted using Review Manager 5.40 and required repeated manual sequential operations.

The certainty of evidence for each outcome was evaluated using the GRADE (Grading of Recommendations Assessment, Development and Evaluation) framework, which examines limitations (risk of bias), inconsistency, indirectness, imprecision, and publication bias. The certainty of evidence was categorized as high, moderate, low, or very low.

2.6 Data Analysis

Extracted data were entered into Review Manager 5.40 for statistical analysis. For meta-analysis, the appropriate effect model was selected according to heterogeneity: random-effects model if $I^2 \geq 50\%$, fixed-effects model if $I^2 < 50\%$. For continuous outcomes, between-group differences based on post-treatment scores were analyzed. The standardized mean difference (SMD) and corresponding 95% confidence intervals (CIs) were used to express the overall effect size. The magnitude is reported as I^2. $I^2 \geq 75\%$ indicates high heterogeneity; $50\% \leq I^2 < 75\%$ moderate; $I^2 < 50\%$ low; and $I^2 = 0\%$ no heterogeneity [22]. All statistical tests were two-sided, and a p value < 0.05 was considered statistically significant. In addition, to rank the therapeutic effects of different transcranial direct current stimulation parameters (e.g., current intensity and electrode configuration), we calculated the surface under the cumulative ranking curve (SUCRA) values based on the effect sizes obtained from the subgroup meta-analyses. The SUCRA values were used to provide an exploratory ranking of the probability that each parameter was the most effective. All SUCRA ranking analyses were performed using Stata version 15.0 (StataCorp LLC, College Station, TX, USA). It should be noted that this ranking method was exploratory and did not constitute a formal network meta-analysis.

3. Results

3.1 Literature Search and Screening

The initial literature search retrieved a total of 682 citations. All records were imported into EndNote 20, and 197 duplicate entries were removed using the software's built-in duplicate identification function. Two reviewers subsequently screened titles and abstracts against the predefined eligibility criteria, excluding an additional 389 irrelevant articles. Full-text manuscripts were retrieved for the remaining 96 records and independently evaluated by the same two reviewers, leading to the exclusion of 69 publications: 15 reviews, 4 case reports, 8 study protocols, 5 conference abstracts, 19 studies with ineligible interventions, 15 non-randomized investigations, and 3 studies with insufficient data (Fig. 1). Ultimately, 27 randomized controlled trials [12,13,14,16,17,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44] met all inclusion criteria and were included in the subsequent meta-analysis.

3.2 Characteristics of the Included Studies

The 27 randomized controlled trials enrolled a total of 1333 participants, with individual study samples ranging from 14 to 150 subjects. Except for the study by Sawan et al. (2020) [26], which did not report the sex distribution of participants, the remaining 27 trials included a total of 750 male and 543 female participants. Across all included studies, the absolute ages of individual patients ranged from 42 to 88 years, while the group mean ages summarized in Table 2 (Ref. [12,13,14,16,17,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44]) ranged from approximately 50.3 to 79.7 years. Stroke lesion locations included supratentorial and infratentorial regions, and disease stages spanned the acute, sub-acute and chronic phases. Outcome measures consisted of both positive and negative indicators: higher scores on positive scales denoted better swallowing function, whereas higher scores on negative scales indicated worse function. For negative indicators, five trials used the Water Swallowing Test (WST), four used the Functional Dysphagia Scale (FDS), eight used the Standard Swallowing Assessment (SSA), one used the Eating Assessment Tool-10 (EAT-10), three used the Fiberoptic Endoscopic Dysphagia Severity Scale (FEDSS), one used the Patient's Evaluation of Swallowing Outcome (PESO), five used the Penetration–Aspiration Scale (PAS), and one used the Dysphagia Severity Rating Scale (DSRS). Positive indicators were assessed with the Functional Oral Intake Scale (FOIS) in six trials, the Swallowing Severity Scale (SSS) in one, the Bedside Swallowing Assessment (BSA) in two, the Dysphagia Outcome and Severity Scale (DOSS) in six, the Video-fluoroscopic Swallowing Study (VFSS) in two, the Mann Assessment of Swallowing Ability (MASA) in one and the Modified Mann Assessment of Swallowing Ability (MMASA) in seven (Table 2).

Stimulation parameters of transcranial direct current stimulation (tDCS) varied across studies. Regarding electrode placement, ten trials targeted the contralesional hemisphere as the anodal site, another twelve targeted the ipsilesional hemisphere, and six applied bilateral anodal stimulation. Current intensities were distributed as follows: 1.0 mA in nine trials, 1.2 mA in two trials, 1.4 mA in three trials, 1.5 mA in three trials, 1.6 mA in one trial,

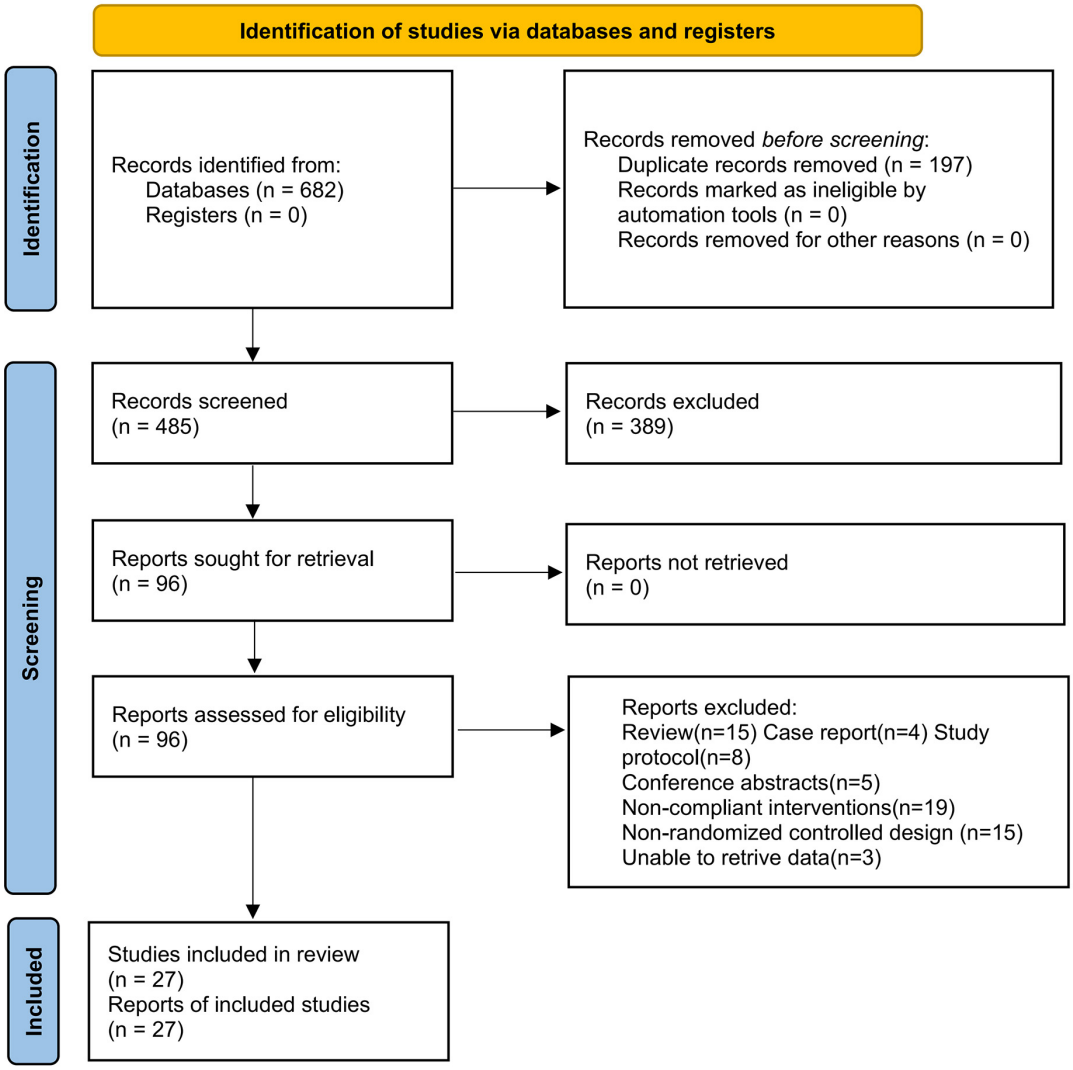


Fig. 1. PRISMA flow diagram.

1.8 mA in one trial, 2.0 mA in eight trials, and variable intensity of 1–2 mA in one trial. In addition, Chen et al. (2022) [38] set the tDCS stimulation intensity according to the patient's tolerance. Regarding the single-session duration, the duration was 20 min in twenty-one trials, 25 min in one trial, and 30 min in five trials (Table 3, Ref. [12,13,14,16,17,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44]).

3.3 Quality Assessment of the Included Studies

We evaluated the risk of bias for each included RCT with the Cochrane Risk-of-Bias tool (Review Manager 5.40). Six studies had unclear allocation concealment; five studies had unclear blinding of participants and personnel, and four had inadequate blinding; five studies had unclear blinding of outcome assessment, and two had inadequate blinding; in addition, eight studies had unclear risk for other bias. Overall, most domains were judged as having a low risk of bias, although allocation concealment was unclear in some studies and some studies had a high risk related to blinding (Fig. 2 and Fig. 3, Ref. [12,13,14,16,17,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44]). Publication bias was not formally assessed because the number of studies available for most individual outcomes was insufficient to support reliable funnel plot interpretation.

GRADE evidence profiles were constructed for each major outcome. Six instruments (EAT-10, PESO, DSRS, VFSS, BSA, and MASA) were downgraded one level for serious imprecision because their pooled sample sizes were all below 100. Additionally, the certainty of evidence for the outcome SSA was downgraded by one level due to substantial concerns related to risk of bias. As no other GRADE domains were rated as having serious limitations, these seven outcomes were classified as providing moderate-certainty evidence (Table 4). The remaining eight instruments (WST, FDS, FEDSS, PAS, FOIS, SSS, DOSS, and MMASA) demonstrated no serious limitations across

Table 2. Demographic characteristics of the included trials.

Study	Sample size (n)	Sex (M/F)	Age (years)	Stroke stage/Lesion location/true bulbar palsy or pseudobulbar palsy	Disease duration	Intervention method	Outcome	Adverse events
Li (2022) [41]	G1:15 G2:15 G3:15 G4:15	9/6 12/3 12/3 8/7	70.0 ± 10.91 72.1 ± 5.85 69.8 ± 11.61 66.6 ± 8.72	Acute stroke	5.2 ± 3.78 d 4.6 ± 3.09 d 3.8 ± 2.48 d 4.7 ± 3.35 d	ST + tDCS ST + tDCS ST + tDCS ST + sham tDCS	DOSS SSA	None
Xu et al. (2024) [44]	G1:20 G2:20 G3:20	11/9 8/12 9/11	68.87 ± 6.92 69.76 ± 7.10 70.37 ± 7.23	Chronic stroke	3.78 ± 0.83 m 3.98 ± 0.73 m 4.18 ± 0.81 m	ST + tDCS ST + tDCS ST + sham tDCS	SSA FDS EAT-10	G1: headache (1), burning (1), pruritus (1), rash (1) G2: headache (1), burning (1), pruritus (1) G3: headache (1), burning (1)
Du et al. (2020) [39]	G1:20 G2:20 G3:20	10/10 9/11 12/8	68.21 ± 1.63 72.17 ± 2.08 69.11 ± 4.88	Chronic stroke	3.58 ± 1.24 m 4.18 ± 2.35 m 5.98 ± 1.31 m	ST + tDCS ST + tDCS ST + tDCS	PAS WST SSA	NR
Sun et al. (2022) [43]	G1:14 G2:14 G3:14	7/7 6/8 6/8	62.86 ± 9.28 60.57 ± 8.34 62.00 ± 8.88	Sub-acute stroke (infratentorial)	6.64 ± 2.74 w 7.71 ± 2.34 w 7.07 ± 2.55 w	ST + tDCS ST + tDCS ST + sham tDCS	FEDSS MMASA	None
Chen and Wu (2022) [38]	G1:50 G2:50 G3:50	24/26 25/25 26/24	62.86 ± 8.87 62.89 ± 8.79 62.87 ± 8.71	Chronic stroke	98.12 ± 10.48 d 98.23 ± 10.54 d 98.14 ± 10.52 d	ST + tDCS ST + tDCS ST + sham tDCS	SSS MMASA	NR
Mao et al. (2022) [12]	G1:20 G2:20	11/9 8/12	59.8 ± 7.3 61.3 ± 8.0	Chronic stroke (infratentorial)	3.3 ± 2.2 m 3.6 ± 2.5 m	ST + tDCS ST	FDS	NR
Farpour et al. (2023) [13]	G1:22 G2:22	13/9 10/12	65.32 ± 16.34 70.68 ± 16.33	Acute/Sub-acute stroke (supratentorial/ infratentorial)	4.09 ± 3.97 d 4.50 ± 3.96 d	ST + tDCS ST + sham tDCS	FOIS MASA	G1: pruritus (3) G2: None
Sawan et al. (2020) [26]	G1:20 G2:20	NR	53.30 ± 5.04 50.30 ± 5.22	Acute/Sub-acute stroke	NR	ST + tDCS ST + sham tDCS	DOSS	NR
Yang et al. (2012) [29]	G1:9 G2:7	6/3 3/4	70.44 ± 12.59 70.57 ± 8.46	Sub-acute stroke	25.2 ± 11.5 d 26.9 ± 7.8 d	ST + tDCS ST + sham tDCS	FDS	None
Wang et al. (2020) [28]	G1:14 G2:14	11/3 10/4	61.43 ± 11.24 62.00 ± 10.46	Sub-acute stroke (infratentorial)	66.79 ± 38.62 d 67.50 ± 47.62 d	ST + tDCS ST + sham tDCS	FOIS FDS PESO	NR
Shigematsu et al. (2013) [16]	G1:10 G2:10	7/3 7/3	66.9 ± 6.3 64.7 ± 8.9	Chronic stroke (supratentorial/ infratentorial)	12.9 ± 7.8 w 12.1 ± 9.0 w	ST + tDCS ST + sham tDCS	DOSS	NR
Wang et al. (2023) [14]	G1:20 G2:20	12/8 9/11	52.7 ± 8.0 51.65 ± 9.74	Sub-acute	50.65 ± 21.82 d 50.45 ± 17.48 d	ST + tDCS ST + sham tDCS	SSA PAS	NR

Table 2. Continued.

Study	Sample size (n)	Sex (M/F)	Age (years)	Stroke stage/Lesion location/true bulbar palsy or pseudobulbar palsy	Disease duration	Intervention method	Outcome	Adverse events
Suntrup-Krueger et al. (2018) [27]	G1:29 G2:30	12/17 13/17	68.9 ± 11.5 67.2 ± 14.5	Acute stroke	116.3 ± 98.9 h 116.8 ± 64.9 h	ST + tDCS ST + sham tDCS	FEDSS DSRS	None
Ahn et al. (2017) [23]	G1:13 G2:13	9/4 6/7	61.62 ± 10.28 66.38 ± 10.67	Chronic stroke	12.27 ± 4.92 m 11.62 ± 4.56 m	ST + tDCS ST + sham tDCS	DOSS	NR
Pingue et al. (2018) [17]	G1:20 G2:20	12/8 8/12	63.5 68.5	Sub-acute stroke (supratentorial)	NA	ST + tDCS ST + sham tDCS	DOSS PAS	None
Kumar et al. (2022) [25]	G1:13 G2:14 G3:15	8/5 3/11 6/9	72 ± 13.3 68 ± 12.6 73 ± 14.1	Acute stroke	101.6 ± 32.5 h 84.1 ± 34.7 h 93.5 ± 38.8 h	ST + tDCS ST + tDCS ST + sham tDCS	PAS FOIS	None
Kumar et al. (2011) [24]	G1:7 G2:7	3/4 4/3	79.7 70	Acute stroke	80.3 h 96.71 h	ST + tDCS ST + sham tDCS	DOSS	None
Chen et al. (2019) [30]	G1:43 G2:41	25/18 23/18	54.31 ± 7.80 56.32 ± 7.81	Chronic stroke	3.22 ± 0.58 m 3.21 ± 0.67 m	ST + tDCS ST + sham tDCS	MMASA WST	None
He (2016) [31]	G1:7 G2:7 G3:8	5/2 6/1 5/3	62.29 ± 11.5 61.857 ± 8.1 60.25 ± 18.6	Sub-acute stroke	1.03 ± 0.60 m 1.80 ± 0.60 m 1.99 ± 1.66 m	ST + tDCS ST + tDCS ST + sham tDCS	MMASA WST	None
Li et al. (2020) [32]	G1:23 G2:24	15/8 15/9	62.87 ± 8.71 63.38 ± 8.41	Sub-acute stroke (infratentorial)	29.27 ± 20.22 d 34.42 ± 12.01 d	ST + tDCS ST + sham tDCS	SSA PAS VFSS	None
Liu et al. (2020) [33]	G1:25 G2:25	14/11 15/10	55.82 ± 3.74 54.92 ± 3.82	Sub-acute stroke	2–12 w	ST + tDCS ST + sham tDCS	WST VFSS	None
Wang et al. (2018) [34]	G1:12 G2:12	10/2 9/3	63.7 ± 11.2 64.1 ± 10.7	Sub-acute/Chronic stroke	2–24 w	ST + tDCS ST + sham tDCS	MMASA BSA	None
Wang et al. (2019) [35]	G1:20 G2:20	13/7 15/5	64.8 ± 7.2 60.8 ± 11.2	Sub-acute stroke (supratentorial)	51.2 ± 28.9 d 47.9 ± 21.6 d	ST + tDCS ST + sham tDCS	MMASA FOIS	None
Yang et al. (2020) [36]	G1:30 G2:30 G3:30 G4:30	23/7 26/4 24/6 21/9	54.93 ± 9.80 59.1 ± 11.24 59.7 ± 8.94 60.3 ± 11.04	Sub-acute stroke (supratentorial/ infratentorial) true bulbar palsy/ pseudobulbar palsy	40.63 ± 16.18 d 37.20 ± 13.58 d 35.77 ± 9.65 d 39.00 ± 12.50 d	ST + tDCS ST + sham tDCS ST + tDCS ST + sham tDCS	WST FOIS SSA	None
Yuan et al. (2015) [37]	G1:15 G2:15	14/1 13/2	60.7 ± 11.5 57.4 ± 7.2	Sub-acute stroke (infratentorial)	57.7 ± 25.8 d 58.5 ± 28.5 d	ST + tDCS ST + sham tDCS	MMASA BSA	None

Table 2. Continued.

Study	Sample size (n)	Sex (M/F)	Age (years)	Stroke stage/Lesion location/true bulbar palsy or pseudobulbar palsy	Disease duration	Intervention method	Outcome	Adverse events
Fu (2023) [40]	G1:15 G2:15 G3:15	10/5 11/4 10/5	58.20 ± 7.93 60.80 ± 5.65 61.60 ± 6.06	Sub-acute stroke (supratentorial)	20.20 ± 3.63 d 19.20 ± 4.71 d 20.73 ± 3.52 d	ST + tDCS ST + tDCS ST + sham tDCS	SSA FOIS	None
Luo et al. (2021) [42]	G1:30 G2:30 G3:30	14/16 13/17 16/14	62.4 ± 4.5 60.1 ± 5.9 62.3 ± 7.2	Sub-acute stroke	29.8 ± 5.6 d 27.2 ± 8.2 d 29.8 ± 9.7 d	ST + tDCS ST + tDCS ST + sham tDCS	SSA FEDSS	None

G1, group 1; G2, group 2; n, number; M, male; F, female; WST, Water Swallow Test; FDS, Functional Dysphagia Scale; SSA, Standardized Swallowing Assessment; EAT-10, Eating Assessment Tool-10; FEDSS, Fiberoptic Endoscopic Dysphagia Severity Scale; PESO, Patient's Evaluation of Swallowing Outcome; PAS, Penetration-Aspiration Scale; FOIS, Functional Oral Intake Scale; SSS, Swallow Severity Scale; DOSS, Dysphagia Outcome and Severity Scale; VFSS, Videofluoroscopic Swallowing Study; MASA, Mann Assessment of Swallowing Ability; MMASA, Modified Mann Assessment of Swallowing Ability; BSA, Bedside Swallowing Assessment; DSRS, Dysphagia Severity Rating Scale; ST, Swallowing Training; NR, not reported. Where disease duration was not reported as a specific numerical value, stroke stage was determined according to the eligibility criteria reported in the original study.

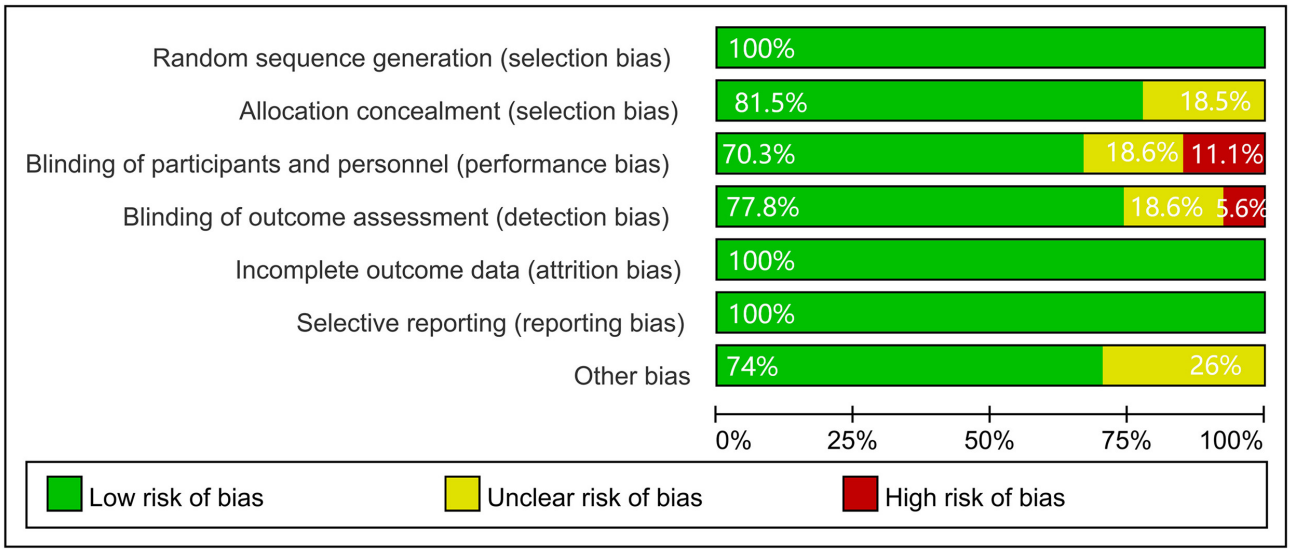


Fig. 2. Risk of bias graph: review authors' judgements about each risk of bias item presented as percentages across all included studies.

any GRADE domains and were therefore graded as high-certainty evidence.

3.4 Efficacy of tDCS for Post-Stroke Dysphagia

Meta-analysis of the positive outcome indicators showed that tDCS significantly improved swallowing function in patients with post-stroke dysphagia compared with control conditions for outcome measures in which higher scores indicate better swallowing function (SMD = 1.16, 95% CI [0.90, 1.42], $p < 0.001$; Fig. 4, Ref. [13,16,17,23,24,25,26,28,30,31,32,33,34,35,36,37,38,40,41,43]). A significant benefit was also observed for outcome measures in which lower scores indicate better swallowing function (SMD = −0.85, 95% CI [−1.02, −0.67], $p < 0.001$; Fig. 5, Ref. [12,14,17,25,27,28,29,30,31,32,33,36,38,39,40,41,42,43,44]).

Additionally, we performed separate pooled analyses of Chinese-language and English-language RCTs stratified by publication language. The results showed that when analyses were restricted to Chinese-language or English-language studies alone, the pooled effect size

Table 3. Parameters of the tDCS interventions included in trials.

Study	Electrode placement sites	Intensity (mA)	Stimulation time (min)	Treatment schedule
Li (2022) [41]	G1 Anode: the swallowing motor cortex of the affected cerebral hemisphere Cathode: the contralateral supra-orbital rim G2 Anode: the swallowing motor cortex of the unaffected cerebral hemisphere Cathode: the contralateral supra-orbital rim G3 Anode: the swallowing motor cortex of both the unaffected and affected cerebral hemispheres Cathode: the contralateral supra-orbital rim G4 Stimulation site same as G3, sham tDCS	1.5	20	once/d, 5 d/w, 2 w
Xu et al. (2024) [44]	G1 Anode: swallowing motor cortex of the affected cerebral hemisphere Cathode: Contralateral shoulder G2 Anode: swallowing motor cortex of the unaffected cerebral hemisphere Cathode: Contralateral shoulder G3 Stimulation site same as G1, sham tDCS	1.8	30	once/d, 5 d/w, 4 w
Du et al. (2020) [39]	G1/G2/G3 Anode: swallowing motor cortex of the affected cerebral hemisphere Cathode: Contralateral shoulder	G1:1.0 G2:1.5 G3:2.0	30	once/d, 5 d/w, 6 w
Sun et al. (2022) [43]	G1/G2 Anode: swallowing motor cortex of the affected cerebral hemisphere Cathode: contralateral supra-orbital rim G3 Stimulation site same as G1, sham tDCS	G1:1.0 G2:2.0	20	once/d, 5 d/w, 3 w
Chen and Wu (2022) [38]	G1 Anode: swallowing motor cortex of the unaffected cerebral hemisphere Cathode: Contralateral shoulder G2 Anode: premotor cortex of the unaffected hemisphere (Brodmann area 6) Cathode: Contralateral shoulder G3 Stimulation site same as G1, sham tDCS	Based on the patient's tolerance	20	once/d, 5 d/w, 2 w
Mao et al. (2022) [12]	G1 Anode: swallowing motor cortex of the unaffected cerebral hemisphere Cathode: Contralateral shoulder G2: No tDCS stimulation was applied	1.6	20	once/d, 6 d/w, 8 w

Table 3. Continued.

Study	Electrode placement sites	Intensity (mA)	Stimulation time (min)	Treatment schedule
Farpour et al. (2023) [13]	G1 Anode: supramarginal gyrus of the unaffected hemisphere (CP5 or CP6 of the international 10-10 EEG system) Cathode: upper part of the contralateral orbit G2 Stimulation site same as G1, sham tDCS	2.0	20	once/d, 5 d
Sawan et al. (2020) [26]	G1 Anode: swallowing motor cortex of the unaffected cerebral hemisphere Cathode: Contralateral shoulder G2 Stimulation site same as G1, sham tDCS	2.0	30	once/d, 5 d/w, 2 w
Yang et al. (2012) [29]	G1 Anode: affected cerebral hemisphere—4.6 cm anterior and 6.15 cm lateral to the vertex (for left-hemisphere stimulation: 4 cm anterior and 7.1 cm lateral to the vertex) Cathode: contralateral supraorbital margin G2 Stimulation site same as G1, sham tDCS	1.0	20	once/d, 5 d/w, 2 w
Wang et al. (2020) [28]	G1 Anode: bilateral cerebral hemispheric swallowing motor cortex Cathode: Contralateral shoulder G2 Stimulation site same as G1, sham tDCS	1.0	20	once/d, 5 d/w, 4 w
Shigematsu et al. (2013) [16]	G1 Anode: the swallowing motor cortex of the affected cerebral hemisphere Cathode: Contralateral shoulder G2 Stimulation site same as G1, sham tDCS	1.0	20	once/d, 10 d
Wang et al. (2023) [14]	G1 Anode: the swallowing motor cortex of the unaffected cerebral hemisphere Cathode: Contralateral shoulder G2 Stimulation site same as G1, sham tDCS	1.0	20	once/d, 5 d/w, 2 w
Suntrup-Krueger et al. (2018) [27]	G1 Anode: the swallowing motor cortex of the unaffected cerebral hemisphere Cathode: contralateral supraorbital margin G2 Stimulation site same as G1, sham tDCS	1.0	20	once/d, 4 d
Ahn et al. (2017) [23]	G1 Anode: bilateral cerebral hemispheric swallowing motor cortex Cathode: Contralateral shoulder G2 Stimulation site same as G1, sham tDCS	1.0	20	once/d, 5 d/w, 2 w

Table 3. Continued.

Study	Electrode placement sites	Intensity (mA)	Stimulation time (min)	Treatment schedule
Pingue et al. (2018) [17]	G1 Anode: the swallowing motor cortex of the affected cerebral hemisphere Cathode: contralateral upper orbital region G2 Stimulation site same as G1, sham tDCS	2.0	30	once/d, 10 d
Kumar et al. (2022) [25]	G1/G2 Anode: the swallowing motor cortex of the healthy cerebral hemisphere Cathode: the upper part of the contralateral orbit G3 Stimulation site same as G1, sham tDCS	2.0	20	twice/d, 4 d
Kumar et al. (2011) [24]	G1 Anode: swallowing motor cortex of the unaffected cerebral hemisphere Cathode: superior aspect of the contralateral orbit G2 Stimulation site same as G1, sham tDCS	2.0	30	once/d, 5 d
Chen et al. (2019) [30]	G1 Anode: swallowing motor cortex of the affected cerebral hemisphere Cathode: Contralateral shoulder G2 Stimulation site same as G1, sham tDCS	1.2	20	once/d, 5 d/w, 2 w
He (2016) [31]	G1/G2 Anode: bilateral cerebral hemispheric swallowing motor cortex Cathode: Contralateral shoulder G3 Stimulation site same as G1, sham tDCS	1.4	20	once/d, 5 d/w, 2 w
Li et al. (2020) [32]	G1 Anode: bilateral cerebral hemispheric swallowing motor cortex Cathode: Contralateral shoulder G2 Stimulation site same as G1, sham tDCS	1.4	20	once/d, 5 d/w, 3 w
Liu et al. (2020) [33]	G1 Anode: swallowing motor cortex of the affected cerebral hemisphere Cathode: superior orbital rim of the contralateral side G2 Stimulation site same as G1, sham tDCS	1.2	20	once/d, 5 d/w, 2 w
Wang et al. (2018) [34]	G1 Anode: swallowing motor cortex of the affected cerebral hemisphere Cathode: Contralateral shoulder G2 Stimulation site same as G1, sham tDCS	1.0	20	once/d, 20 d

Table 3. Continued.

Study	Electrode placement sites	Intensity (mA)	Stimulation time (min)	Treatment schedule
Wang et al. (2019) [35]	G1 Anode: swallowing motor cortex of the unaffected cerebral hemisphere Cathode: superior orbital rim of the contralateral side G2 Stimulation site same as G1, sham tDCS	1.5	20	once/d, 5 d/w, 2 w
Yang et al. (2020) [36]	G1 Anode: bilateral cerebral hemispheric swallowing motor cortex (true bulbar palsy) Cathode: Contralateral shoulder G2 Stimulation site same as G1, sham tDCS (true bulbar palsy) G3 Anode: bilateral cerebral hemispheric swallowing motor cortex Cathode: Contralateral shoulder (pseudobulbar palsy) G4 Stimulation site same as G3, sham tDCS (pseudobulbar palsy)	1.5	20	once/d, 6 d/w, 2 w
Yuan et al. (2015) [37]	G1 Anode: 1 cm below the inion and 3 cm lateral to the left/right Cathode: Contralateral shoulder G2 Stimulation site same as G1, sham tDCS	1	20	once/d, 20 d
Fu (2023) [40]	G1 Anode: swallowing motor cortex of the unaffected cerebral hemisphere Cathode: contralateral shoulderG2 Anode: bilateral cerebral hemispheric swallowing motor cortex Cathode: Contralateral shoulder G3 Stimulation site same as G1, sham tDCS	1.4	20	once/d, 5 d/w, 3 w
Luo et al. (2021) [42]	G1 Anode: swallowing motor cortex of the affected cerebral hemisphere Cathode: Contralateral shoulder G2 Anode: swallowing motor cortex of the unaffected cerebral hemisphere Cathode: Contralateral shoulder G3 Stimulation site same as G1, sham tDCS	2	25	once/d, 5 d/w, 2 w

The trial by Luo et al. (2021) [42] utilized a three-arm design. For the meta-analysis, data were extracted as two separate pairwise comparisons (designated as Luo 2021a and Luo 2021b) evaluating different anodal stimulation sites against a shared sham control.

changed only slightly and remained statistically significant for both Chinese-language studies and English-language studies, indicating that the original findings were not influenced by the language of publication (SMD = –0.87, 95% CI [–1.19, –0.55], $p < 0.001$, Fig. 6A, Ref. [12,14,17,25,27,28,29,30,31,32,33,36,38,39,40,41,42,43,44];

Table 4. GRADE level of evidence rating scale for indicators of consequences.

Certainty Assessment							No. of Participants				Effect
No. of Studies	Study Design	Risk of Bias	Inconsistency	Indirectness	Imprecision	Publication Bias	Experimental group	Control group	SMD [95% CI]	Size	Certainty
Level of PSD											
Outcome: WST											
5	RCT	Not serious	Not serious	Not serious	Not serious	unable to assess	n = 182	n = 182	–0.76 [–0.98, –0.54]	Moderate	⊕⊕⊕⊕ High
Outcome: FDS											
4	RCT	Not serious	Not serious	Not serious	Not serious	unable to assess	n = 83	n = 81	–0.79 [–1.17, –0.42]	Moderate	⊕⊕⊕⊕ High
Outcome: SSA											
8	RCT	Serious	Not serious	Not serious	Not serious	unable to assess	n = 318	n = 319	–0.79 [–1.08, –0.51]	Moderate	⊕⊕⊕⊖ Moderate
Outcome: EAT-10											
1	RCT	Not serious	Not serious	Not serious	Serious	unable to assess	n = 40	n = 40	–1.64 [–2.34, –0.94]	Little	⊕⊕⊕⊖ Moderate
Outcome: FEDSS											
3	RCT	Not serious	Not serious	Not serious	Not serious	unable to assess	n = 117	n = 118	–1.09 [–1.86, –0.31]	Moderate	⊕⊕⊕⊕ High
Outcome: PESO											
1	RCT	Not serious	Not serious	Not serious	Serious	unable to assess	n = 14	n = 14	–3.93 [–5.27, –2.60]	Little	⊕⊕⊕⊖ Moderate
Outcome: PAS											
5	RCT	Not serious	Not serious	Not serious	Not serious	unable to assess	n = 190	n = 194	–0.53 [–0.88, –0.18]	Moderate	⊕⊕⊕⊕ High
Outcome: DSRS											
1	RCT	Not serious	Not serious	Not serious	Serious	unable to assess	n = 29	n = 30	–1.09 [–1.64, –0.54]	Little	⊕⊕⊕⊖ Moderate
Outcome: FOIS											
6	RCT	Not serious	Not serious	Not serious	Not serious	unable to assess	n = 173	n = 176	1.20 [0.65, 1.76]	Moderate	⊕⊕⊕⊕ High
Outcome: SSS											
1	RCT	Not serious	Not serious	Not serious	Not serious	unable to assess	n = 100	n = 100	0.64 [0.34, 0.94]	Moderate	⊕⊕⊕⊕ High
Outcome: DOSS											
6	RCT	Not serious	Not serious	Not serious	Not serious	unable to assess	n = 115	n = 115	1.29 [0.72, 1.85]	Moderate	⊕⊕⊕⊕ High

Table 4. Continued.

Certainty Assessment							No. of Participants				Effect
No. of Studies	Study Design	Risk of Bias	Inconsistency	Indirectness	Imprecision	Publication Bias	Experimental group	Control group	SMD [95% CI]	Size	Certainty
Outcome: VFSS											
2	RCT	Not serious	Not serious	Not serious	Serious	unable to assess	n = 48	n = 49	3.41 [–1.93, 8.74]	Little	⊕⊕⊕⊖ Moderate
Outcome: MASA											
1	RCT	Not serious	Not serious	Not serious	Serious	unable to assess	n = 22	n = 22	0.79 [0.17, 1.40]	Little	⊕⊕⊕⊖ Moderate
Outcome: MMASA											
7	RCT	Not serious	Not serious	Not serious	Not serious	unable to assess	n = 232	n = 232	0.89 [0.57, 1.22]	Moderate	⊕⊕⊕⊕ High
Outcome: BSA											
2	RCT	Not serious	Not serious	Not serious	Serious	unable to assess	n = 27	n = 27	1.40 [0.73, 2.08]	Little	⊕⊕⊕⊖ Moderate

WST, Water Swallow Test; FDS, Functional Dysphagia Scale; SSA, Standardized Swallowing Assessment; EAT-10, Eating Assessment Tool-10; FEDSS, Fiberoptic Endoscopic Dysphagia Severity Scale; PESO, Patient's Evaluation of Swallowing Outcome; PAS, Penetration-Aspiration Scale; FOIS, Functional Oral Intake Scale; SSS, Swallow Severity Scale; DOSS, Dysphagia Outcome and Severity Scale; VFSS, Videofluoroscopic Swallowing Study; MASA, Mann Assessment of Swallowing Ability; MMASA, Modified Mann Assessment of Swallowing Ability; BSA, Bedside Swallowing Assessment; DSRS, Dysphagia Severity Rating Scale. Formal evaluation of publication bias could not be performed in this table due to the limited number of studies included in each outcome analysis.

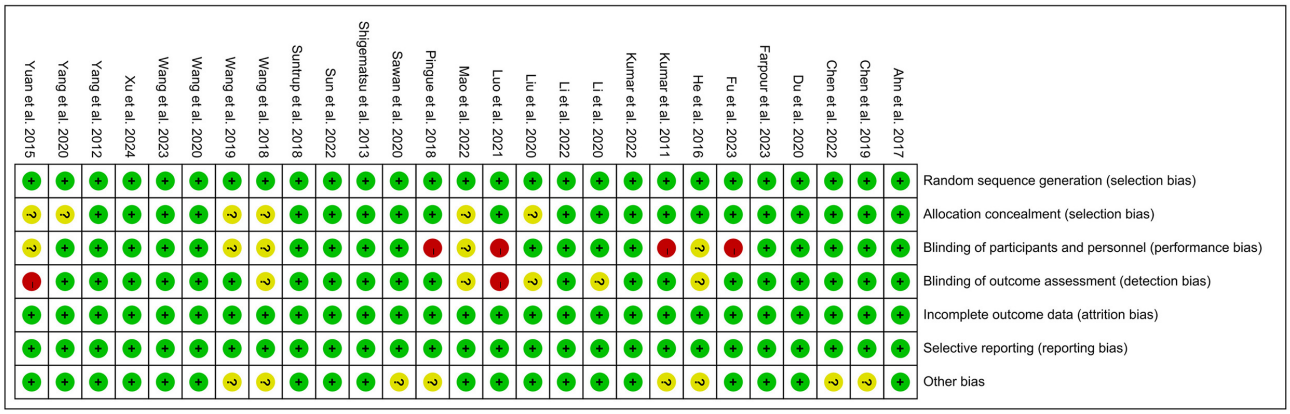


Fig. 3. Risk of bias summary: review authors' judgements for each risk of bias domain in each included study. References for the included studies [12,13,14,16,17,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44].

SMD = –0.84, 95% CI [–1.05, –0.62], $p < 0.001$, Fig. 6B; SMD = 1.09, 95% CI [0.61, 1.57], $p < 0.001$, Fig. 7A, Ref. [13,16,17,23,24,25,26,28,30,31,32,33,34,35,36,37,38,40, 41,43]; SMD = 1.19, 95% CI [0.88, 1.51], $p < 0.001$, Fig. 7B).

3.4.1 Efficacy of tDCS Applied to Different Brain Regions in Patients With Post-Stroke Dysphagia

Meta-analysis based on negative outcome scales showed that, compared with control conditions, anodal tDCS delivered to the lesional hemisphere, the contralesional hemisphere, or bilaterally all significantly improved swallowing function in patients with post-stroke dysphagia (Unaffected: SMD = –0.74, 95% CI [–1.08, –0.40], $p < 0.001$; Affected: SMD = –0.74, 95% CI [–1.05, –0.43], $p < 0.001$; Bilateral: SMD = –1.18, 95% CI [–2.32, –0.05], $p = 0.04$, Fig. 8, Ref. [12,14,28,29,30,31,32,33,36,40,41,42,44]). The corresponding analysis of positive indicators yielded the same pattern: anodal tDCS to either hemisphere alone or to both hemispheres together was superior to sham (Unaffected: SMD = 1.47, 95% CI [0.52, 2.42], $p = 0.002$; Affected: SMD = 1.64, 95% CI [0.92, 2.37], $p < 0.001$; Bilateral: SMD = 1.49, 95% CI [0.44, 2.53], $p = 0.005$, Fig. 9, Ref. [16,17,23,25,26,28,30,31,32,33,34,36,38,40,41]). However, subgroup analyses of both positive and negative outcome indicators demonstrated no differences in efficacy for improving swallowing function in patients with PSD among the three stimulation site protocols (subgroup difference: $p = 0.75$, Fig. 8; subgroup difference: $p = 0.95$, Fig. 9).

3.4.2 Efficacy of Different tDCS Current Intensities in Patients With Post-Stroke Dysphagia

Pooled analysis of favorable outcome measures indicated that tDCS intensities from 1.0 mA to 2.0 mA all produced significant improvements over control (SMD = 1.38, 95% CI [0.97, 1.78], $p < 0.001$, Fig. 10, Ref. [13,16,23,25,26,28,30,31,33,34,35,36,37,40,41,43]), with subgroup analyses suggesting that 1.4 mA might be the most effective intensity (1.0 mA: SMD = 1.07, 95% CI [0.66, 1.47], $p < 0.001$; 1.2 mA: SMD = 3.58, 95% CI [–1.41, 8.57], $p = 0.16$; 1.4 mA: SMD = 1.91, 95% CI [0.10, 3.71], $p = 0.04$; 1.5 mA: SMD = 0.83, 95% CI [0.57, 1.09], $p < 0.001$; 2.0 mA: SMD = 1.50, 95% CI [0.44, 2.55], $p = 0.005$, Fig. 10). Analysis of negative indicators likewise showed significant benefits for intensities between 1.0 mA and 2.0 mA (SMD = –0.66, 95% CI [–0.87, –0.44], $p < 0.001$, Fig. 11A, Ref. [12,14,17,25,27,28,29,32,36,39,40,41,42,43,44]), whereas 2.0 mA failed to differ statistically from sham (SMD = –0.47, 95% CI [–0.97, 0.04], $p = 0.07$). Subgroup analyses suggest that tDCS at 1.8 mA may yield more favorable therapeutic effects for patients with PSD. (1.0 mA: SMD = –0.73, 95% CI [–1.07, –0.39], $p < 0.001$; 1.4 mA: SMD = –0.64, 95% CI [–1.27, –0.02], $p = 0.04$; 1.5 mA: SMD = –0.78, 95% CI [–1.31, –0.24], $p = 0.004$; 1.6 mA: SMD = –0.70, 95% CI [–1.34, –0.06], $p = 0.03$; 1.8 mA: SMD = –0.82, 95% CI [–1.61, –0.03], $p = 0.04$, Fig. 11A). In the subgroup analysis according to stimulation intensity, 1.4 mA yielded the largest point estimate among outcome measures in which higher scores indicate better swallowing function (SMD = 1.91, 95% CI [0.10, 3.71], $p = 0.04$). No corresponding data for 1.8 mA were available for these outcomes, precluding a direct comparison between 1.4 mA and 1.8 mA. Among outcome measures in which lower scores indicate better swallowing function, 1.8 mA yielded the largest effect estimate (SMD = –0.82, 95% CI [–1.61, –0.03], $p = 0.04$). Furthermore, we calculated the Surface Under the Cumulative Ranking Curve (SUCRA) values for each tested tDCS current intensity to quantify the probability of each intensity being the optimal stimulation parameter for patients with post-stroke dysphagia. The cumulative ranking probability plot revealed the following efficacy hierarchy for improving swallowing function: 1.8 mA, 1.6 mA, 1.5 mA, 1.4 mA, 1.0 mA, and 2.0 mA (Fig. 11B,C).

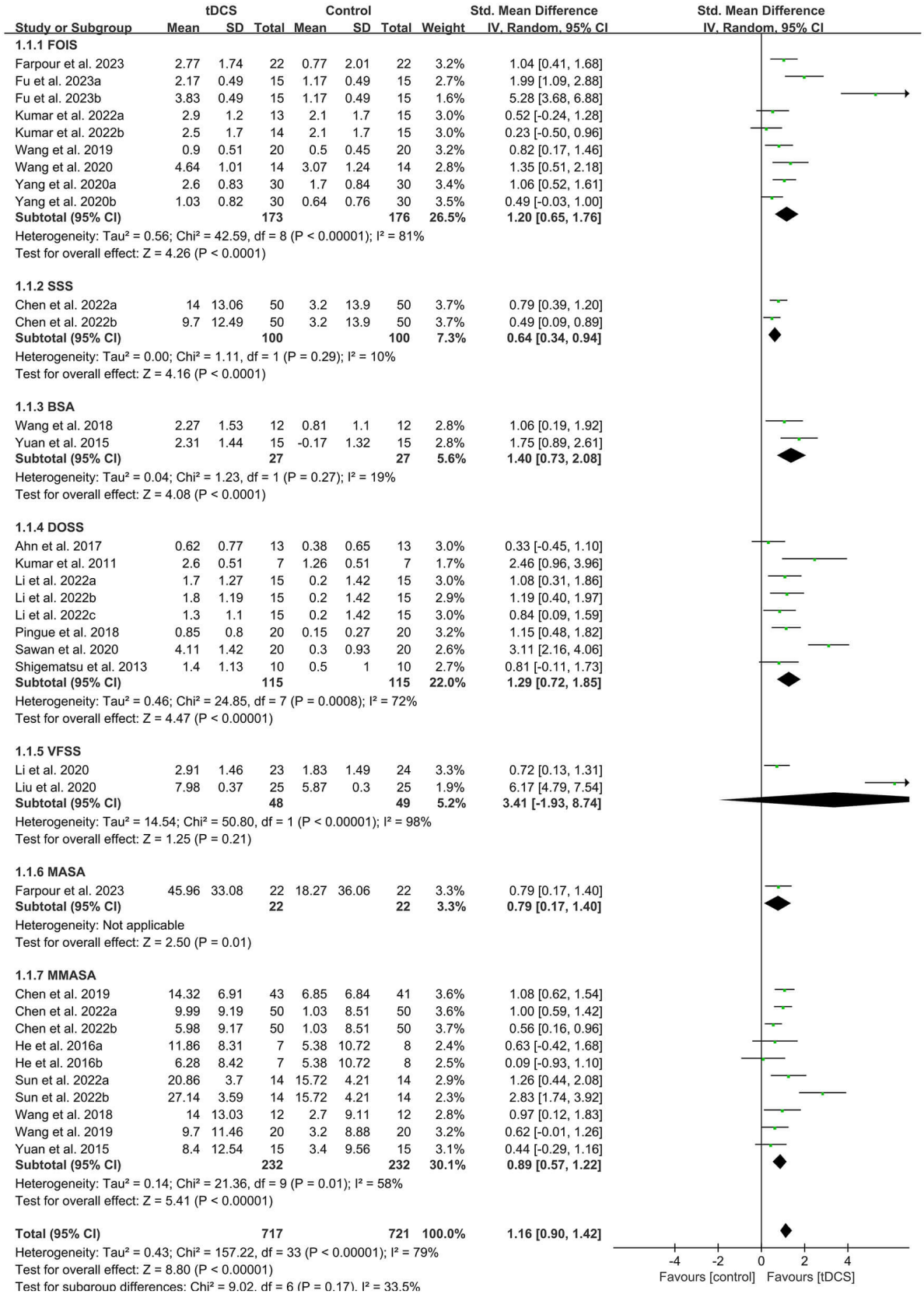


Fig. 4. Efficacy of tDCS for Post-stroke Dysphagia (positive outcome indicators). References for the included studies, categorized by subgroup, are as follows: FOIS: [13,25,28,35,36,40]; SSS: [38]; BSA: [34,37]; DOSS: [16,17,23,24,26,41]; VFSS: [32,33]; MASA: [13]; MMASA: [30,31,34,35,37,38,43].

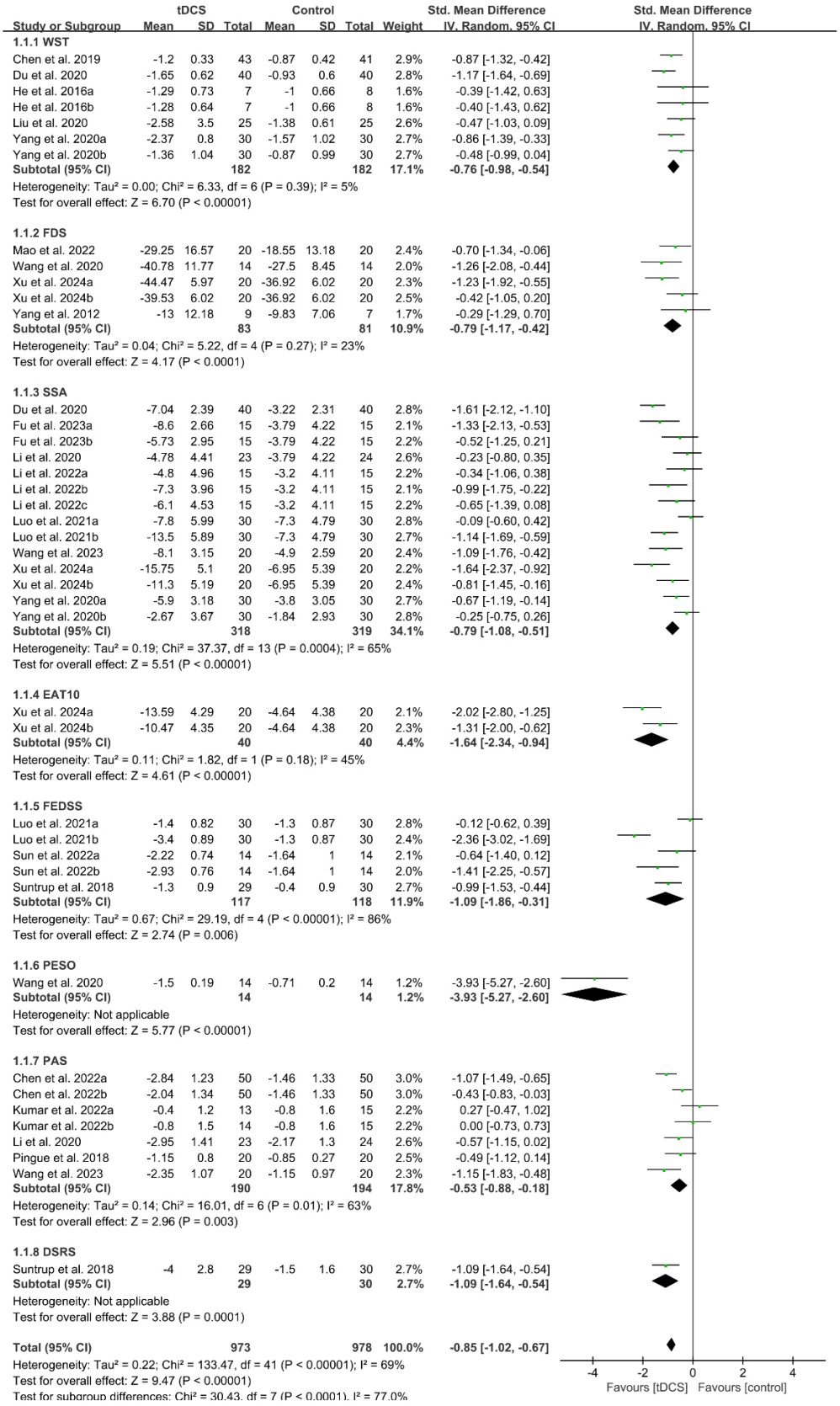


Fig. 5. Efficacy of tDCS for Post-stroke Dysphagia (negative outcome indicators). References for the included studies, categorized by subgroup, are as follows: WST: [30,31,33,36,39]; FDS: [12,28,29,44]; SSA: [14,32,36,39,40,41,42,44]; EAT10: [44]; FEDSS: [27,42,43]; PESO: [28]; PAS: [14,17,25,32,38]; DSRS: [27].

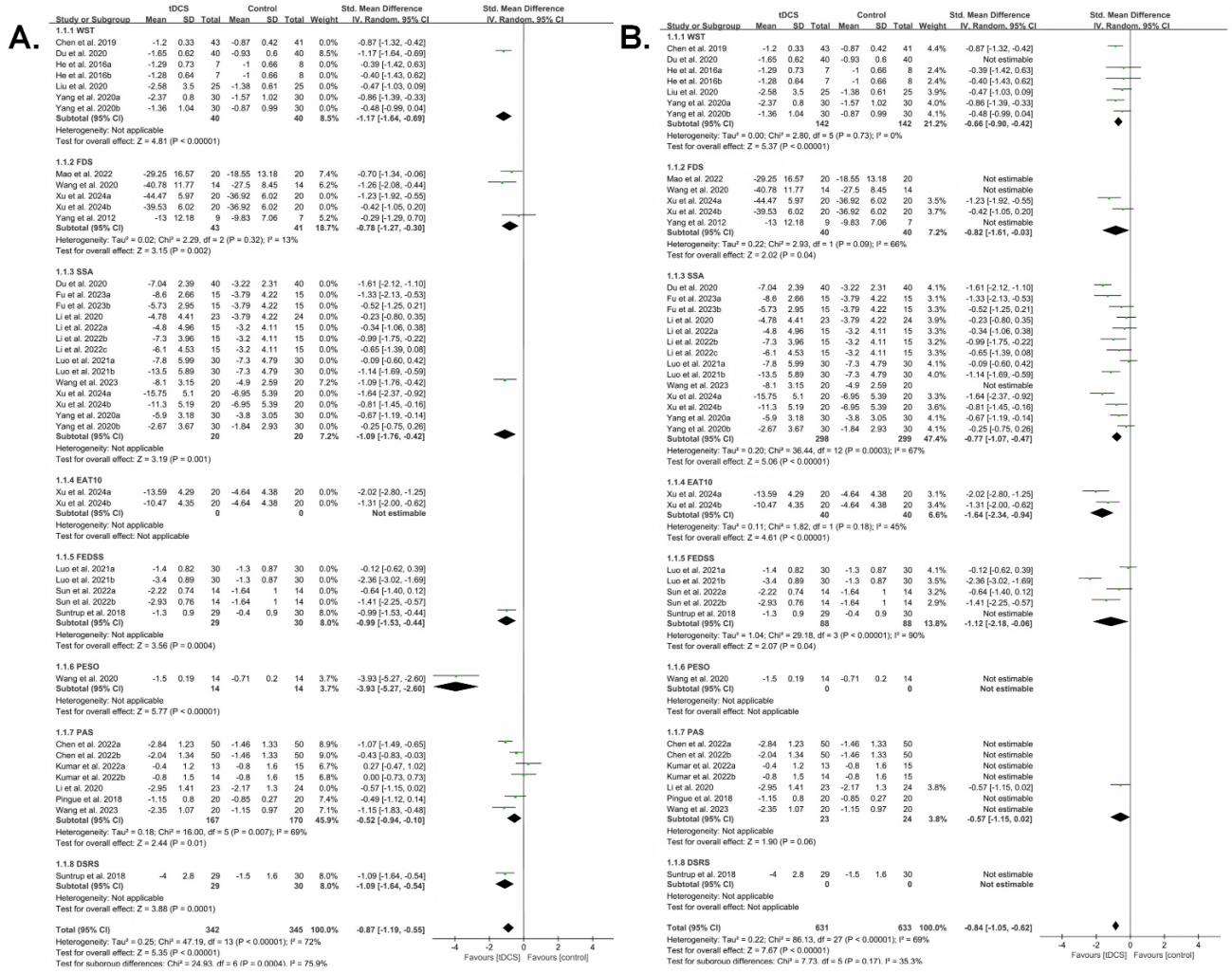


Fig. 6. Forest plot of all negative outcome indicators ((A) Analysis restricted to included English-language studies; (B) Analysis restricted to included Chinese-language studies). References for the included studies, categorized by subgroup, are as follows: WST: [30,31,33,36,39]; FDS: [12,28,29,44]; SSA: [14,32,36,39,40,41,42,44]; EAT10: [44]; FEDSS: [27,42,43]; PESO: [28]; PAS: [14,17,25,32,38]; DSRS: [27].

3.4.3 Efficacy of Different tDCS Session Durations in Patients With Post-Stroke Dysphagia

Meta-analysis of positive outcomes revealed that single sessions lasting either 20 min or 30 min were both significantly better than control (SMD = 1.17, 95% CI [0.84, 1.50], $p < 0.001$, Fig. 12, Ref. [16,17,23,24,25,26,30,31,33,34,35,36,37,38,39,40,41,43]). Nevertheless, prolonging stimulation duration to 30 minutes failed to generate a substantially larger therapeutic benefit relative to the conventional 20 minutes regimen (20 min: SMD = 1.15, 95% CI [0.80, 1.49], $p < 0.001$; 30 min: SMD = 1.28, 95% CI [0.18, 2.38], $p = 0.02$, subgroup difference: $p = 0.82$, Fig. 12). Analysis of negative indicators drew consistent conclusions: both the 20-minute and 30-minute single-session interventions were more effective than sham stimulation (20 min: SMD = –0.69, 95% CI [–0.94, –0.45], $p < 0.001$; 30 min, SMD = –0.70, 95% CI [–1.20, –0.21], $p = 0.005$, Fig. 13, Ref. [12,14,17,25,27,28,29,32,36,38,39,40,41,42,44]). However, the 25-minute intervention showed no significant difference in efficacy compared with sham stimulation (SMD = –1.22, 95% CI [–3.42, 0.97], $p = 0.27$). Additionally, the 30-minute protocol did not yield significantly better outcomes than the 20-minute protocol (subgroup difference, $p = 0.89$, Fig. 13). However, only five RCTs in this subgroup analysis adopted a 30-minute stimulation duration. The statistical comparison between the 20-minute and 30-minute protocols was underpowered; hence, the findings of this subgroup should be interpreted with caution.

3.4.4 Efficacy of tDCS in PSD Patients With Different Lesion Locations

Meta-analysis of the positive outcome scales showed that, compared with the control group, tDCS significantly improved swallowing function regardless of whether the

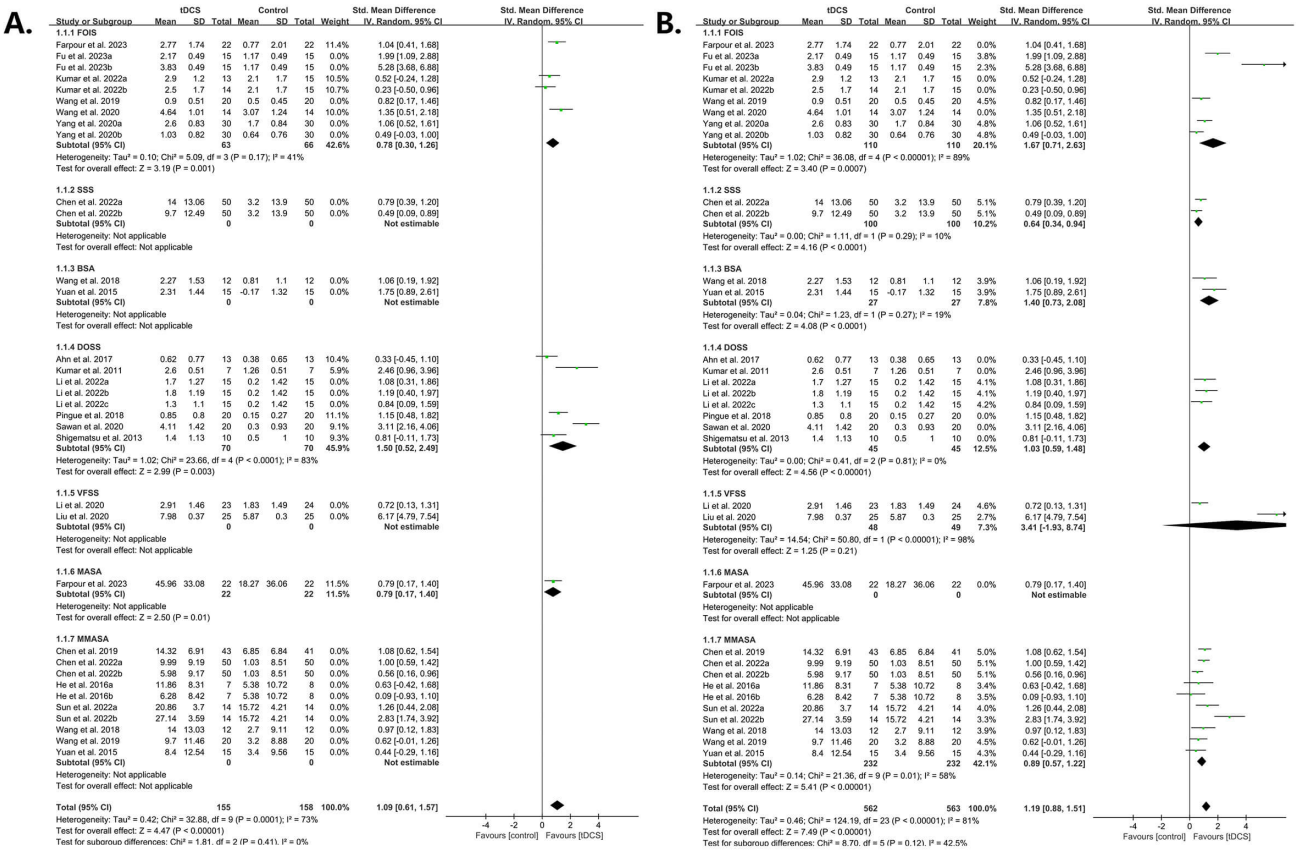


Fig. 7. Forest plot of all positive outcome measures (A) Analysis restricted to included English-language studies; (B) analysis restricted to included Chinese-language studies. References for the included studies, categorized by subgroup, are as follows: FOIS: [13,25,28,35,36,40]; SSS: [38]; BSA: [34,37]; DOSS: [16,17,23,24,26,41]; VFSS: [32,33]; MASA: [13]; MMASA: [30,31,34,35,37,38,43].

stroke lesion was supratentorial or infratentorial (SMD = 1.57, 95% CI [0.94, 2.21], $p < 0.001$, Fig. 14, Ref. [17,28,32,35,37,40,43]). The benefit appeared somewhat larger in patients with supratentorial lesions than in those with infratentorial lesions (Supratentorial: SMD = 2.11, 95% CI [0.81, 3.41], $p = 0.002$; Infratentorial: SMD = 1.23, 95% CI [0.55, 1.92], $p = 0.0004$, Fig. 14). The corresponding analysis of negative indicators likewise demonstrated a significant advantage of tDCS over control in both anatomic subgroups (SMD = –0.73, 95% CI [–0.97, –0.48], $p < 0.001$, Fig. 15, Ref. [12,17,28,32,40,43]), with virtually identical effect sizes for supratentorial and infratentorial lesions (Supratentorial: SMD = –0.72, 95% CI [–1.13, –0.31], $p = 0.0006$; Infratentorial: SMD = –0.73, 95% CI [–1.04, –0.41], $p < 0.001$, Fig. 15).

3.4.5 Efficacy of tDCS in PSD Patients at Different Stroke Phases

Pooled analysis of positive outcomes indicators revealed that tDCS was clearly superior to control in the acute and sub-acute phases, with the gain being most pronounced in the Sub-acute group (Fig. 16, Ref. [16,23,24,28,30,31,32,33,35,36,37,38,39,40,41,43]), while a statistically significant benefit was also detected in the chronic phase (Acute: SMD = 1.17, 95% CI [0.69, 1.64], $p < 0.0001$; Subacute: SMD = 1.72, 95% CI [1.05, 2.39], $p < 0.0001$; Chronic: SMD = 0.59, 95% CI [0.26, 0.91], $p = 0.0004$, Fig. 16). Analysis of negative indicators, however, showed significant improvement with tDCS in all three phases (Acute: SMD = –0.78, 95% CI [–1.11, –0.44], $p < 0.0001$; Subacute: SMD = –0.91, 95% CI [–1.38, –0.45], $p = 0.0001$; Chronic: SMD = –0.77, 95% CI [–1.23, –0.31], $p = 0.001$, Fig. 17, Ref. [12,14,27,28,29,32,40,41,42,43,44]).

3.4.6 Comparison of tDCS Efficacy Between PSD Patients With Pseudobulbar and Bulbar Palsy

Relative to control interventions, tDCS significantly improved swallowing function in patients with pseudobulbar palsy (SMD = –0.86, 95% CI [–1.39, –0.33], $p = 0.001$) but failed to do so in those with bulbar palsy (SMD = –0.48, 95% CI [–0.99, 0.04], $p = 0.07$, Fig. 18, Ref. [36]). However, there was no significant difference in the improvement of swallowing function following tDCS intervention between the two types of patients (subgroup difference: $p = 0.31$, Fig. 18).

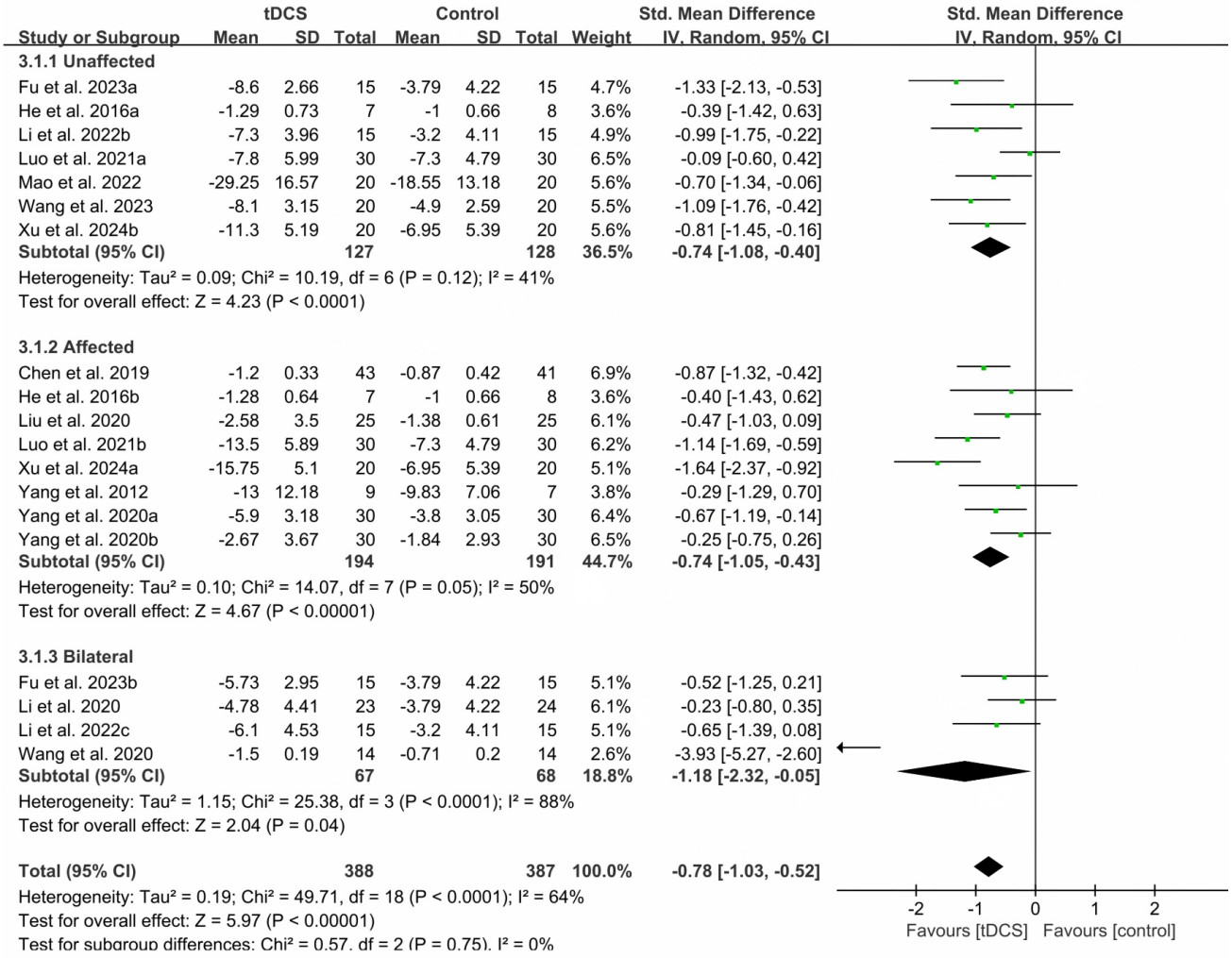


Fig. 8. Efficacy of tDCS applied to different brain regions in patients with post-stroke dysphagia (negative outcome indicators). References for the included studies, categorized by subgroup, are as follows: Unaffected: [12,14,31,40,41,42,44]; Affected: [29,30,31,33,36,42,44]; Bilateral: [28,32,40,41].

3.5 Adverse Events

A total of 19 RCTs reported adverse events (Table 2), but adverse events occurred in only two studies. A total of 12 patients experienced adverse reactions, and the types of adverse reactions included local itching, transient burning sensation beneath the electrodes, short-lived headache, and rash. All adverse reactions were mild in severity, spontaneously resolved without additional treatment, and were well tolerated by participants. No subject discontinued trial participation due to adverse effects.

4. Discussion

The present meta-analysis demonstrates that tDCS yields consistent improvements in swallowing function among patients with post-stroke dysphagia relative to control groups receiving conventional swallowing therapy alone. Subgroup synthesis further indicates that intensities between 1.0 mA and 1.8 mA are all effective, that 20 min and 30 min session durations are equally efficacious, that lesions located either supratentorially or infratentorially respond equally well, and that acute, sub-acute and chronic patients all gain measurable benefit—most pronounced in the sub-acute phase. Furthermore, the intervention tends to exert a more prominent therapeutic benefit in patients with pseudobulbar palsy relative to those with true bulbar palsy. Based on these findings, we discuss the clinical implications for individualized parameter selection and propose a network-level mechanistic model to account for the heterogeneous efficacy patterns identified across different stimulation regimens.

4.1 Selection of Cortical Target

Teismann et al. [45] examined 37 PSD patients and found that dysphagia was associated with a bilateral reduction of cortical excitability; they argued that disruption of the bilateral swallowing network, rather than unilateral damage, underlies the deficit. Ahn et al. [23] subsequently showed that concurrent anodal tDCS over both

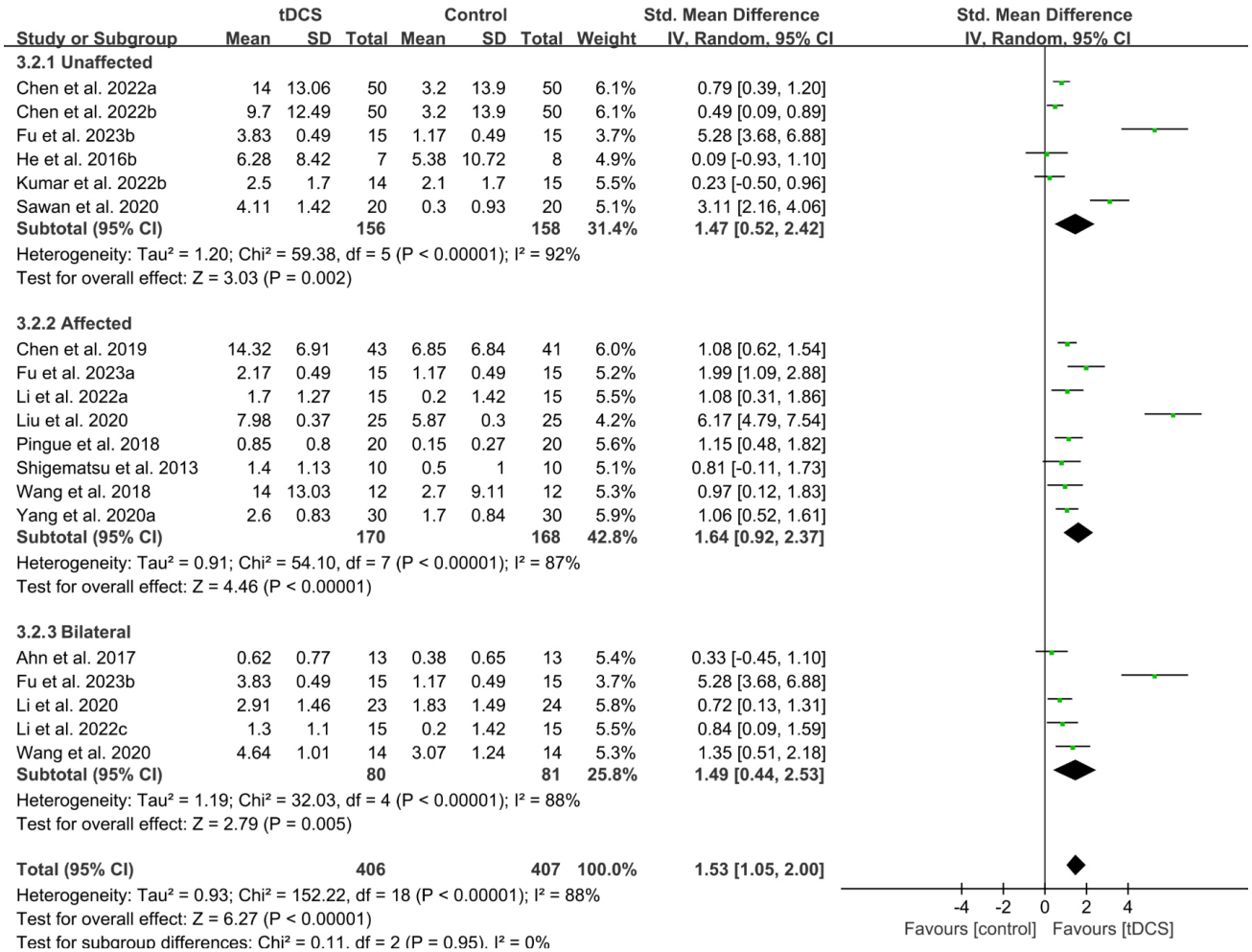


Fig. 9. Efficacy of tDCS applied to different brain regions in patients with post-stroke dysphagia (positive outcome indicators). References for the included studies, categorized by subgroup, are as follows: Unaffected: [25,26,31,38,40]; Affected: [16,17,30,33,34,36,40,41]; Bilateral: [23,28,32,40,41].

hemispheres, combined with conventional therapy, produced additive benefit. Neurophysiological studies indicate that the brain-stem central pattern generator for swallowing receives bilateral corticobulbar drive [46,47], and—unlike limb muscles—pharyngeal and laryngeal muscles are innervated by corticobulbar projections from both hemispheres. As early as 2006, Daniels et al. [48] observed that healthy volunteers exhibit hemispheric dominance that varies across swallowing phases: the left hemisphere is dominant during the oral phase, whereas the right hemisphere is more influential during the pharyngeal phase. Accordingly, post-stroke swallowing recovery differs substantially from upper/lower extremity motor rehabilitation; swallowing recovery is inherently a bilateral physiological process, even when one hemisphere becomes functionally dominant over time. Collectively, the above mechanistic evidence provides theoretical support for the findings of our subgroup analyses, indicating that tDCS can effectively improve swallowing function in patients with PSD regardless of whether stimulation is applied to the lesional hemisphere, the contralesional hemisphere, or both hemispheres simultaneously.

4.2 Stimulus Intensity of tDCS

Our subgroup analyses demonstrate that therapeutic efficacy for swallowing improvement varies markedly across different tDCS current intensities in patients with PSD. In the meta-analysis based on positive-outcome, 1.4 mA appeared to be the most potent intensity, whereas for negative outcome metrics, 1.4 mA ranked second only to 1.8 mA. Notably, higher current intensity does not always correspond to superior therapeutic effects: although raising intensity to 2.0 mA still yielded larger benefits relative to 1.0 mA, its efficacy was inferior to that observed at 1.8 mA. This inverted-U dose–response relationship is consistent with previous published evidence. Du et al. [39] applied electroencephalography (EEG) to detect tDCS-mediated neurophysiological alterations among PSD pa-

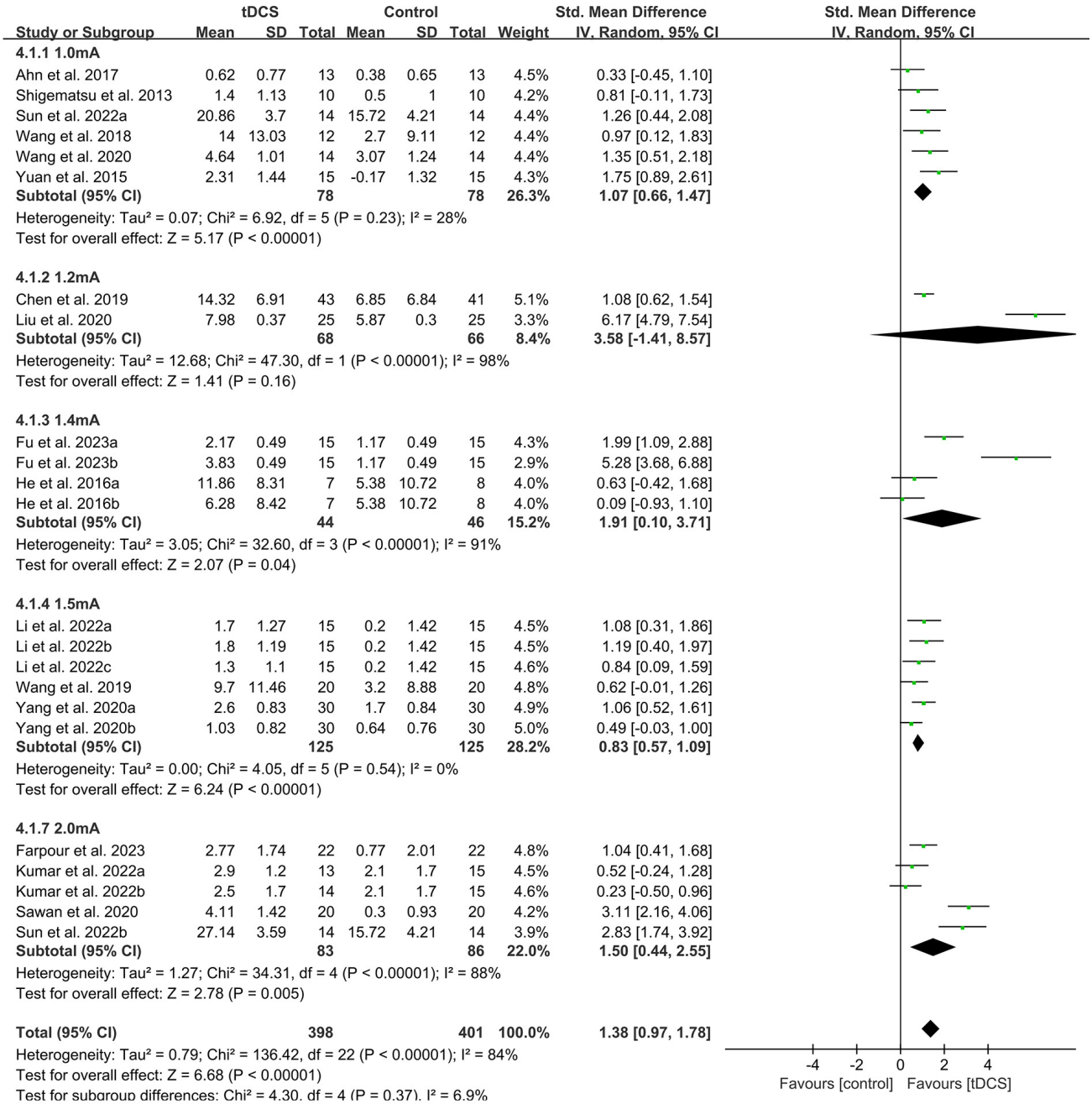
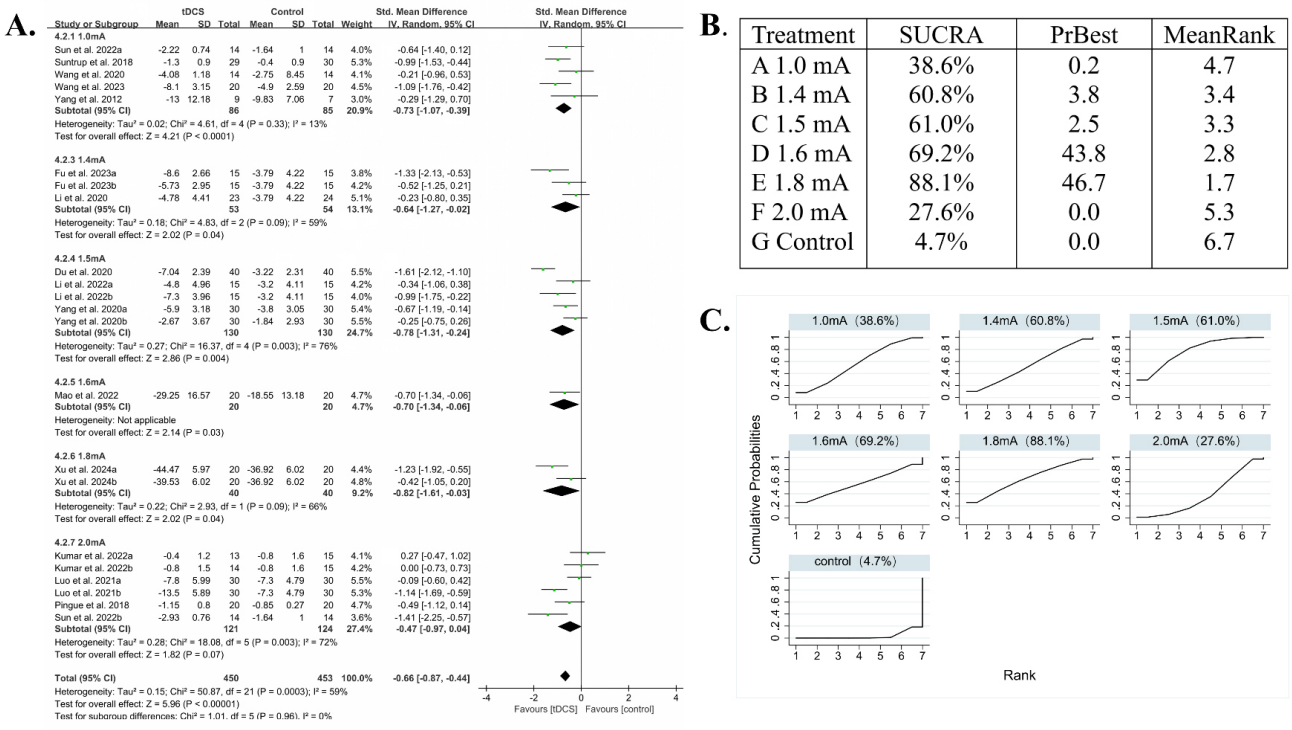


Fig. 10. Efficacy of different tDCS current intensities in patients with post-stroke dysphagia (positive outcome indicators). References for the included studies, categorized by subgroup, are as follows: 1.0 mA: [16,23,28,34,37,43]; 1.2 mA: [30,33]; 1.4 mA: [31,40]; 1.5 mA: [35,36,41]; 2.0 mA: [13,25,26,43].

tients and reported that stimulation at 2.0 mA induced a larger elevation in α-peak frequency compared with 1.0 mA, which the authors interpreted as an optimal excitation–inhibition balance correlating with better swallowing performance. Given high skull impedance diverting a substantial proportion of applied current, higher intensities within the therapeutic window are more capable of modulating target cortical excitability as intended. Nevertheless, our pooled results indicate that further increasing intensity beyond 1.8 mA (exemplified by 2.0 mA tDCS) fails to generate additional swallowing improvements; instead, therapeutic efficacy exhibits a mild decline. The fundamental mechanism underlying tDCS consists of modulating neuronal excitability via shifting resting membrane potentials [39]. When the current intensity reaches 1.8 mA, tDCS may exert greater therapeutic effects on swallowing function in patients with post-stroke dysphagia. This plateau phenomenon is presumably attributable to the induction of activity-dependent synaptic fatigue—characterized by neurotransmitter depletion and/or receptor inactivation—



Treatment	SUCRA	PrBest	MeanRank
A 1.0 mA	38.6%	0.2	4.7
B 1.4 mA	60.8%	3.8	3.4
C 1.5 mA	61.0%	2.5	3.3
D 1.6 mA	69.2%	43.8	2.8
E 1.8 mA	88.1%	46.7	1.7
F 2.0 mA	27.6%	0.0	5.3
G Control	4.7%	0.0	6.7

Fig. 11. Comparison of different tDCS current intensities for post-stroke dysphagia. (A) Efficacy of different tDCS current intensities in patients with post-stroke dysphagia (negative outcome indicators). References for the included studies, categorized by subgroup, are as follows: 1.0 mA: [14,27,28,29,43]; 1.4 mA: [32,40]; 1.5 mA: [36,39,41]; 1.6 mA: [12]; 1.8 mA: [44]; 2.0 mA: [17,25,42,43]. (B) SUCRA values, PrBest, and MeanRank for each tDCS current intensity and the control group. (C) Cumulative ranking probability curves for each tDCS current intensity and the control group.

within discrete cortical regions under supra-optimal direct-current intensities [49], consequently attenuating treatment efficacy. In other words, tDCS excites the cortical swallowing motor areas, opens voltage-gated Ca^{2+} channels, raises intracellular Ca^{2+} and increases the release of excitatory neurotransmitters such as glutamate [50,51]. However, the amounts of Ca^{2+}, other transmitters and their receptors are finite, so the excitatory effect of tDCS cannot increase indefinitely with current intensity. On the other hand, the human cerebral cortex possesses homeostatic plasticity: synapses can persistently scale their efficacy up or down (long-term potentiation [LTP] or long-term depression [LTD]) in response to changes in presynaptic activity [52], and the induction thresholds for LTP/LTD are dynamically reset to match postsynaptic activity levels [53]. These adjustments prevent excessive LTP or LTD and keep neural activity within a useful dynamic range [54,55]. Accordingly, excessively high tDCS intensities lead to diminished swallowing-related therapeutic responses in PSD patients. Collectively, our data reveal differential therapeutic magnitudes across tested intensities following a clear inverted-U (parabolic) trend. Within the current intensity range of 1.0–2.0 mA investigated in this study, tDCS at 1.8 mA may achieve greater improvements in swallowing function among patients with post-stroke dysphagia.

4.3 Duration of tDCS Sessions

Pooled analyses of both favorable and unfavorable swallowing outcome scales indicate that prolonging single-session tDCS duration from 20 minutes to 30 minutes fails to produce additional swallowing-related therapeutic gains among patients with PSD. Neurophysiologically, tDCS-induced modulation of cortical excitability may involve calcium-dependent signalling and activity-dependent plasticity [56]. However, the mechanisms underlying the non-linear effects associated with prolonged stimulation durations remain incompletely understood. Taken together, these mechanistic findings suggest that extending single-session stimulation beyond 20 minutes confers no supplementary therapeutic benefit.

4.4 tDCS in PSD Patients With Different Lesion Locations

Regardless of whether stroke lesions (infarction or hemorrhage) are situated in supratentorial or infratentorial territories, tDCS yields significant improvements in swallowing function, with comparable therapeutic magnitudes observed between the two subgroups. Accordingly, lesion anatomical location does not determine clinical responsiveness to tDCS intervention. This phenomenon can be explained by the fundamental working principle of tDCS: weak direct current is applied transcranially to

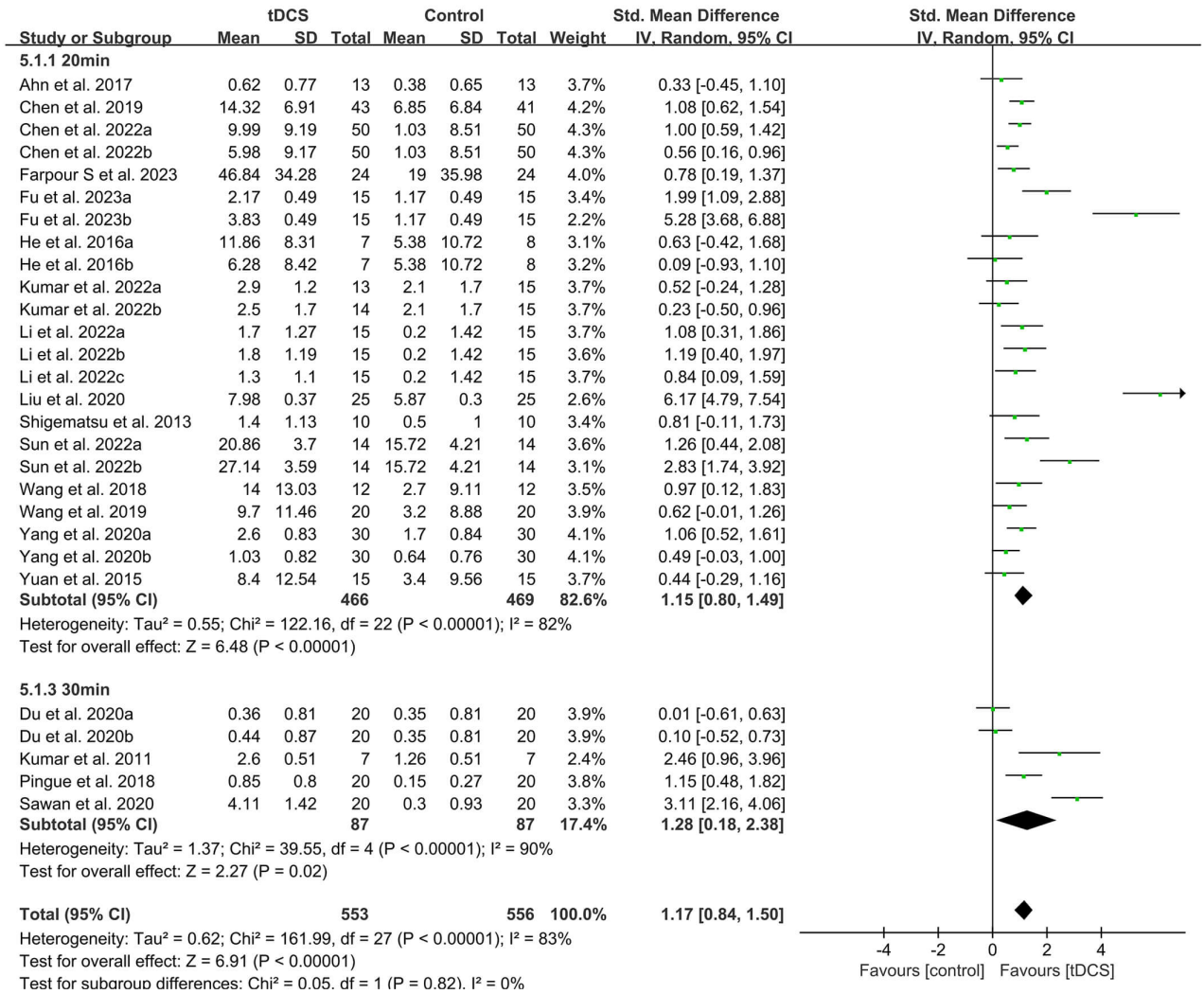


Fig. 12. Efficacy of different tDCS session durations in patients with post-stroke dysphagia (positive outcome indicators). References for the included studies, categorized by subgroup, are as follows: 20 min: [16,23,25,30,31,33,34,35,36,37,38,40,41,43]; 30 min: [17,24,26,39].

modulate transmembrane potentials of cortical neurons, triggering either hyperpolarization or depolarization to remodel local neuronal excitability and synaptic plasticity [57,58]. Furthermore, tDCS induces sustained neurochemical alterations—predominantly via NMDA and GABA-B receptor signaling cascades—that remodel the synaptic microenvironment and stabilize long-term synaptic plasticity [59,60]. Since these modulatory effects take effect at the global cortical level rather than relying on region-specific circuit pathways, lesion localization within supratentorial versus infratentorial compartments exerts no measurable influence on overall treatment efficacy.

4.5 Timing of tDCS Intervention

When comparing treatment outcomes across different stroke stages, significant improvements in swallowing function scores were observed in post-stroke patients receiving tDCS intervention, regardless of whether they were in the acute, sub-acute, or chronic phase. Moreover, patients in the sub-acute stroke phase appeared to achieve greater therapeutic gains from tDCS intervention than those in the acute and chronic phases. Well-documented evidence indicates that spontaneous swallowing recovery commences almost immediately after stroke, driven by endogenous neuroplasticity [61]. Patients who still suffer from dysphagia several months post-stroke may have exhausted these intrinsic compensatory mechanisms. tDCS is thought to amplify functional recovery by modulating cortical excitability, thereby promoting adaptive plasticity [62]; nevertheless, data from animal studies demonstrate that the brain's capacity for such plasticity declines progressively over time following brain injury [63]. Therefore, once contraindications are ruled out, tDCS should be introduced as early as possible during clinical management to capture the window of enhanced neuroplastic responsiveness.

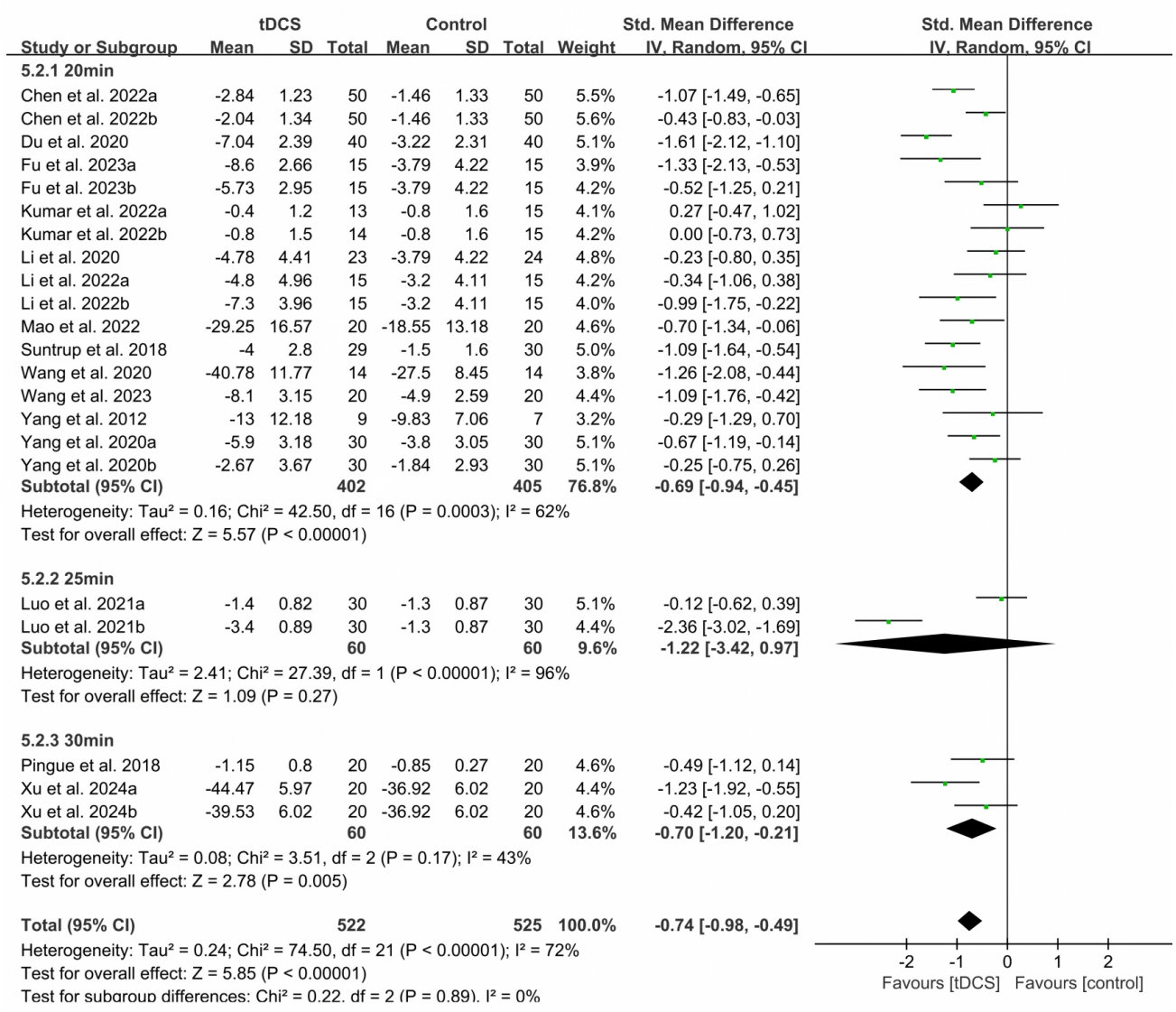


Fig. 13. Efficacy of different tDCS session durations in patients with post-stroke dysphagia (negative outcome indicators). References for the included studies, categorized by subgroup, are as follows: 20 min: [12,14,25,27,28,29,32,36,38,39,40,41]; 25 min: [42]; 30 min: [17,44]. The two entries for Luo et al. (2021) [42] represent two distinct intervention arms (anodal stimulation over the unaffected versus affected hemisphere) compared against a shared sham control group.

4.6 tDCS in PSD Patients With Bulbar or Pseudobulbar Palsy

The comparative analysis across bulbar and pseudobulbar palsy subgroups revealed that tDCS yielded significantly superior therapeutic effects relative to control interventions among patients with pseudobulbar palsy, whereas no statistically significant benefit was detected in those with bulbar palsy. This intergroup discrepancy can be attributed to fundamental differences in the underlying pathophysiology of these two clinical entities. Bulbar palsy arises from lesions involving the medullary swallowing center and presents as lower motor neuron paresis: pharyngeal reflexes are reduced or abolished, laryngeal elevation is weakened, and incomplete relaxation of the cricopharyngeal muscle collectively hinders safe bolus transit through the pharynx [64]. By contrast, pseudobulbar palsy results from bilateral disruption of the corticobulbar pathways, representing an upper motor neuron syndrome predominantly disrupting the oral preparatory and oral swallowing phases, with incoordination or apraxia affecting the soft palate, tongue, and facial musculature [65]. In addition, patients with pseudobulbar palsy demonstrate relatively high rates of spontaneous functional recovery: approximately 50% start to recover swallowing competence within seven days after stroke onset [66]. Collectively, these physiological features render patients with pseudobulbar palsy more susceptible to therapeutic gains from cortical neuromodulation. Nevertheless, only a small number of randomized controlled trials have explicitly recruited participants stratified by bulbar versus pseudobulbar palsy subtypes. Accordingly, these prelimi-

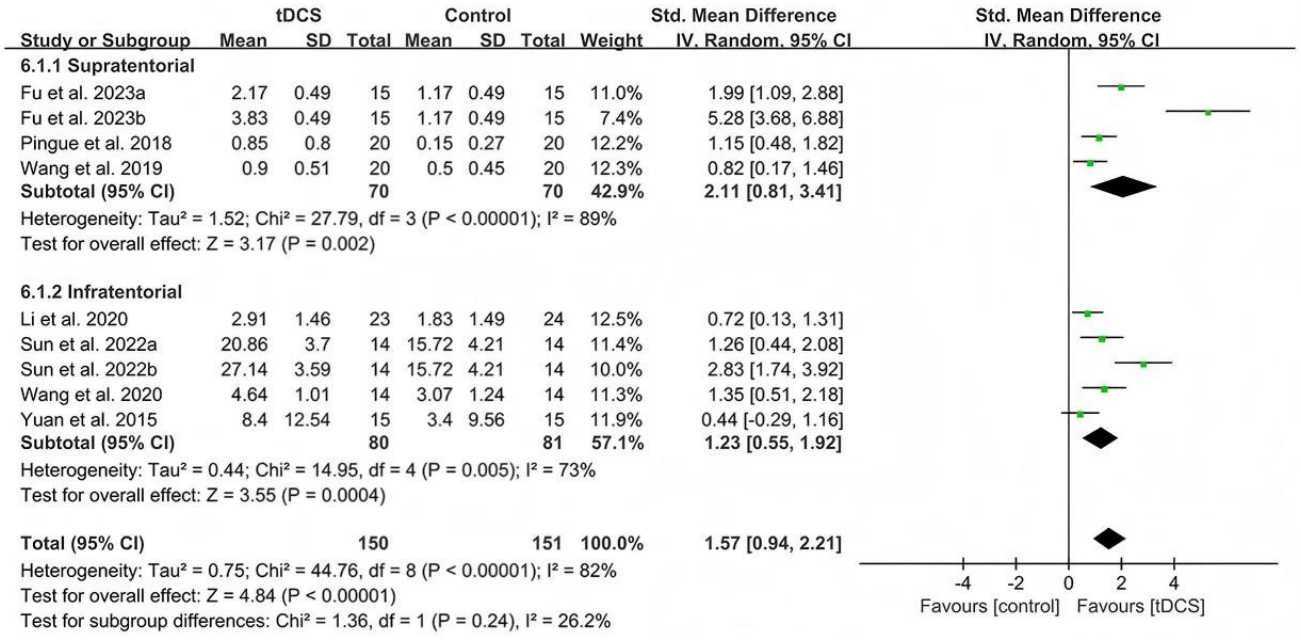


Fig. 14. Efficacy of tDCS in PSD patients with different lesion locations (positive outcome indicators). References for the included studies, categorized by subgroup, are as follows: Supratentorial: [17,35,40]; Infratentorial: [28,32,37,43].

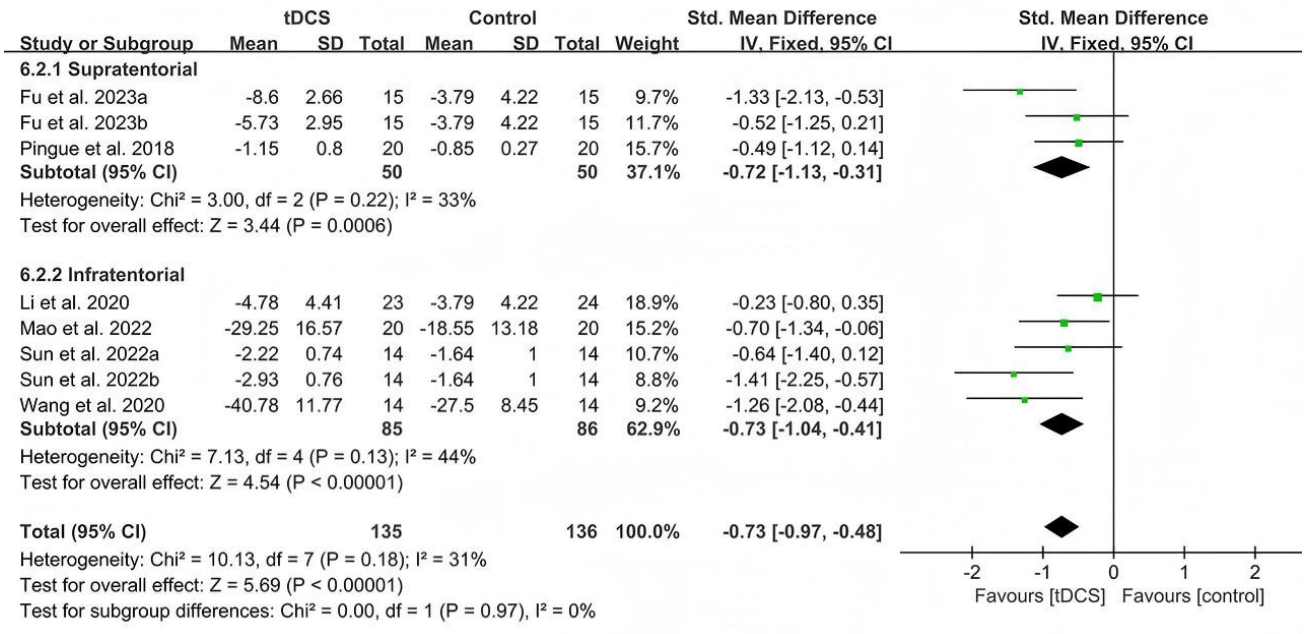


Fig. 15. Efficacy of tDCS in PSD patients with different lesion locations (negative outcome indicators). References for the included studies, categorized by subgroup, are as follows: Supratentorial: [17,40]; Infratentorial: [12,28,32,43].

nary observations warrant further validation in larger, dedicated prospective clinical trials.

4.7 Comparison With Previous Work

Our pooled findings corroborate previous meta-analyses reporting therapeutic benefits of tDCS for swallowing rehabilitation among patients with PSD [15,67]. The present review, however, adopts a more rigorous analytic strategy by separately synthesizing positive and negative outcome scales (earlier reviews merged positive and negative scales, requiring data transformation which complicates interpretation). In addition, we incorporated a greater number of eligible trials and a larger total sample size, enabling exploratory novel subgroup analyses. Beyond this established finding, the present study further confirms that there are no differences in the efficacy of tDCS

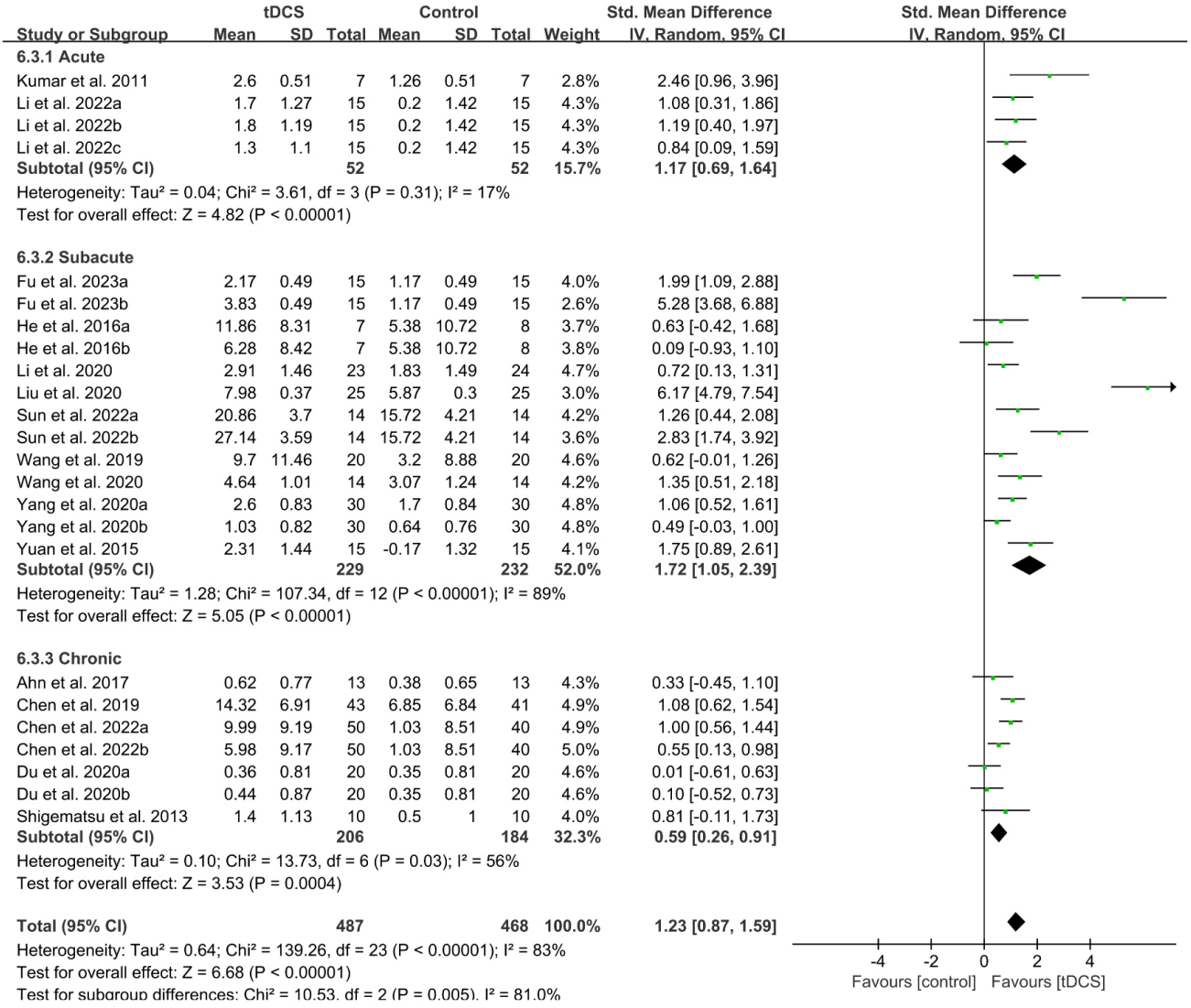


Fig. 16. Efficacy of tDCS in PSD patients at different stroke phases (positive outcome indicators). References for the included studies, categorized by subgroup, are as follows: Acute: [24,41]; Subacute: [28,31,32,33,35,36,37,40,43]; Chronic: [16,23,30,38,39].

for improving swallowing function in patients with PSD among isolated contralesional stimulation, isolated lesional stimulation, and bilateral simultaneous stimulation. Moreover, our analyses suggest 1.8 mA may represent the optimal stimulation intensity, and confirm that prolonging single-session duration beyond 20 minutes produces no additional therapeutic benefit. Meanwhile, it should be noted that the latest stroke rehabilitation guidelines [68] also mention that sufficient evidence regarding the timing of initiating and terminating rehabilitation for stroke patients remains lacking. No unified standard exists to determine when to discontinue rehabilitation interventions, and rehabilitation regimens should be individualized to deliver personalized "rehabilitation prescriptions". Therefore, the optimal tDCS stimulation parameters for patients with PSD should be selected according to individual patient characteristics. Our findings can provide a convenient "reference value" for the choice of individualized stimulation parameters.

4.8 Limitations

Several limitations of this meta-analysis deserve consideration. First, regarding the characteristics of the included literature, many RCTs had small sample sizes, which increases the risk of overestimating the true effect of tDCS. Additionally, substantial heterogeneity detected among some included studies in this meta-analysis is considered to arise mainly from four aspects: discrepancies in tDCS intervention parameters across trials, varied baseline clinical characteristics of participants, inconsistent outcome assessment measures adopted in different studies, and considerable variations in the conventional adjunct swallowing rehabilitation training regimens combined with stimulation. We conducted subgroup analyses stratified by dif-

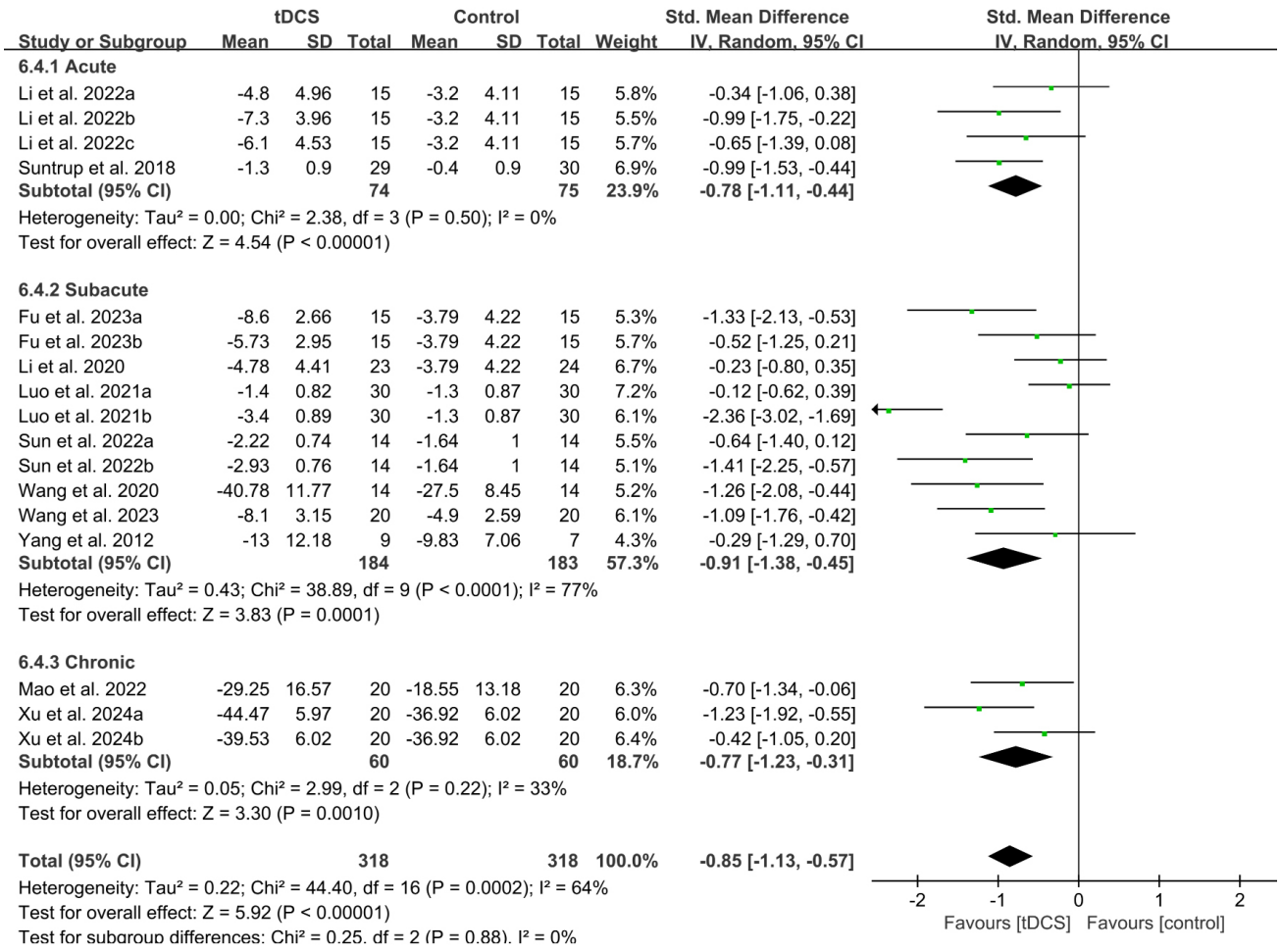


Fig. 17. Efficacy of tDCS in PSD patients at different stroke phases (negative outcome indicators). References for the included studies, categorized by subgroup, are as follows: Acute: [27,41]; Subacute: [14,28,29,32,40,42,43]; Chronic: [12,44].

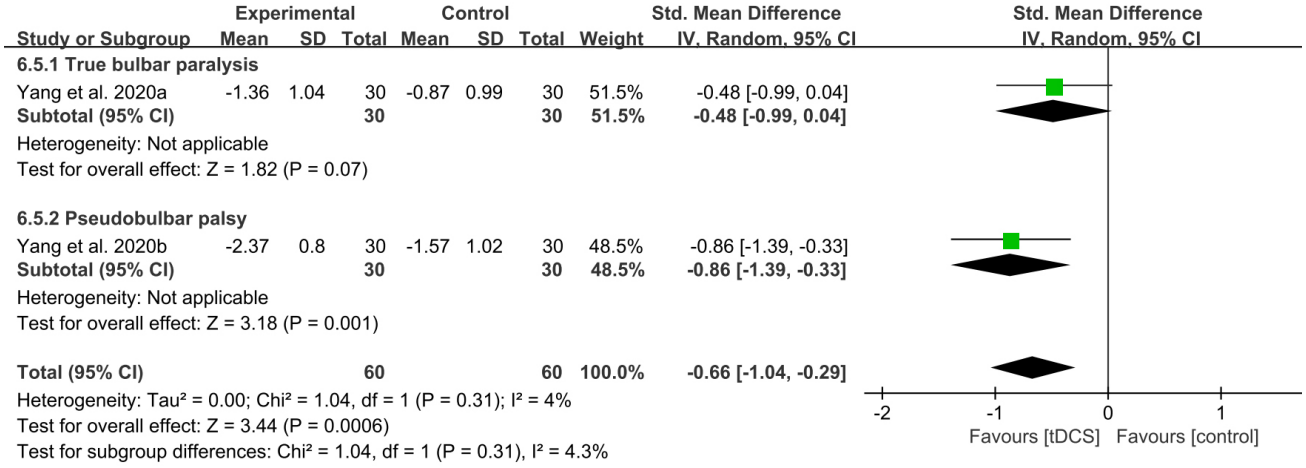


Fig. 18. Comparison of tDCS efficacy between PSD patients with pseudobulbar and bulbar palsy. References for the included studies, categorized by subgroup, are as follows: True bulbar paralysis [36] and Pseudobulbar palsy [36].

ferent intervention parameters (including stimulation intensity, stimulation site, stimulation duration, etc.), performed separate analyses for negative and positive outcome indicators, and carried out comparative analyses between Chinese and English studies. However, interstudy heterogeneity could not be adequately eliminated. Detailed data on stroke severity and baseline severity of dysphagia were not fully available; none of the original trials provided individ-

ual participant data, which precluded adjustments for these baseline confounding factors. In addition, only one study stratified patients by bulbar palsy and pseudobulbar palsy. Owing to the limited number of randomized controlled trials and insufficient overall sample size, the findings of this subgroup analysis have limited reference value. Accordingly, the results with prominent heterogeneity in our study are merely suggestive. A full consideration of various confounding and heterogeneous factors is required when interpreting the study conclusions. We recommend that future large-sample, multicenter clinical trials adopt unified protocols to reduce heterogeneity and validate the findings of the present meta-analysis. Second, critical data limitations restricted our subgroup analyses. Only a small fraction of the included RCTs recruited patients with chronic stroke; consequently, subgroup analyses for this time window were underpowered, yielding discordant patterns with borderline statistical significance. Similarly, as only six of the 27 RCTs adopted bilateral cerebral tDCS, the sample size remains insufficient to definitively conclude whether bilateral stimulation is superior to unilateral stimulation. Third, adverse events were observed in only two studies; therefore, the long-term safety and tolerability of tDCS cannot be fully confirmed. Fourth, concerning methodological constraints, the exploratory parameter network analysis in this study is not a standard NMA. Because the nodes represent different settings of the same intervention rather than distinct independent interventions, this analysis does not conform to the core transitivity assumption of NMA (i.e., connecting multiple distinct interventions via a common comparator). We utilized the network framework solely to visualize evidence connections and explore parameter heterogeneity. Furthermore, the inability to establish strictly unified criteria for pooling certain subgroups may compromise the reproducibility of those specific analyses. Finally, restricting the literature search to English and Chinese publications may have introduced language-related publication bias. Therefore, large-scale, multicenter RCTs with standardized protocols and long-term follow-ups are required to definitively assess the safety, long-term efficacy, and optimal parameter settings of tDCS for post-stroke dysphagia.

5. Conclusion

This meta-analysis demonstrates that tDCS serves as an effective adjuvant intervention for improving swallowing function in patients with PSD, with superior therapeutic effects predominantly observed in the sub-acute recovery phase. Notably, our parameter-specific subgroup analyses refute the conventional "more is better" notion regarding tDCS stimulation parameters. An intensity of 1.8 mA represents a potential optimal "sweet spot", suggesting that higher intensities (2.0 mA) do not necessarily translate to better clinical outcomes. In terms of stimulation site selection, we found that tDCS can effectively improve swallowing function in patients with post-stroke dysphagia when administered to the lesional hemisphere, the contralesional hemisphere, or bilaterally, and there are no statistically significant differences in efficacy among the three stimulation modes. Additionally, prolonging single-session stimulation duration beyond 20 minutes fails to yield incremental clinical benefits. Based on these findings, we recommend a protocol prioritizing at 1.8 mA for 20 minutes to optimize the cost-benefit ratio in clinical practice. Future studies should focus on large-scale RCTs to validate these parameters in stroke populations and further elucidate the neurophysiological mechanisms underlying the non-linear intensity-response relationship.

Key Points

• tDCS is an effective adjuvant intervention for improving swallowing function in patients with PSD.

• For tDCS swallowing interventions in patients with post-stroke dysphagia, 1.8 mA may be the optimal current intensity; when the intensity was raised to 2.0 mA, efficacy plateaued and then declined, manifesting a "ceiling effect".

• Extending a single tDCS session beyond 20 minutes confers no additional clinical benefit for swallowing improvement in PSD patients.

Availability of Data and Materials

The authors confirm that no original data were created in this study, and all data used were extracted from previously published RCTs, which are therefore openly accessible. Furthermore, the data characteristics of these RCTs are available in Tables 2,3 of this manuscript.

Author Contributions

CG: Methodology, Data analysis, Writing – original draft, Writing – review & editing. RQZ: Participated in the conception and design of this study, improved and revised the methodological section, performed the quality assessment, drafted the original manuscript, and critically revised and reviewed the academic content of the discussion section. NZ: Literature search, Literature screening, Data extraction. WS: Literature search, Literature screening, Data extraction. YSD: Writing – review & editing, Methodology, Data verification, Supervision, Funding. YL: Writing – review & editing, Conceptualization, Supervision. All authors have been involved in revising it critically for important intellectual content. All authors gave final approval of the version to be published. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

The authors thank the research teams of all the RCTs included in this study.

Funding

This work is supported by Ganpo Talents Program - Innovation Leading Talent Project (Medical and Health Care Category, grant number gpyc20250228) to YSD.

Conflicts of Interest

The authors declare no conflicts of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.31083/BJHM52794.

References

[1] McCarty EB, Chao TN. Dysphagia and Swallowing Disorders. The Medical Clinics of North America. 2021; 105: 939–954. https://doi.org/10.1016/j.mcna.2021.05.013

[2] Bath PM, Lee HS, Everton LF. Swallowing therapy for dysphagia in acute and subacute stroke. The Cochrane Database of Systematic Reviews. 2018; 10: CD000323. https://doi.org/10.1002/14651858.CD000323.pub3

[3] Gómez-García N, Álvarez-Barrio L, Leirós-Rodríguez R, Soto-Rodríguez A, Andrade-Gómez E, Hernández-Lucas P. Transcranial direct current stimulation for post-stroke dysphagia: a meta-analysis. Journal of Neuroengineering and Rehabilitation. 2023; 20: 165. https://doi.org/10.1186/s12984-023-01290-w

[4] Ramsey DJ, Smithard DG. Assessment and management of dysphagia. Hospital Medicine (London, England: 1998). 2004; 65: 274–279. https://doi.org/10.12968/hosp.2004.65.5.13702

[5] Irwin GM, Leatherman J. Dysphagia. Primary Care. 2025; 52: 171–179. https://doi.org/10.1016/j.pop.2024.09.016

[6] Boaden E, Burnell J, Hives L, Dey P, Clegg A, Lyons MW, et al. Screening for aspiration risk associated with dysphagia in acute stroke. The Cochrane Database of Systematic Reviews. 2021; 10: CD012679. https://doi.org/10.1002/14651858.CD012679.pub2

[7] Reyes-Torres CA, Castillo-Martínez L, Reyes-Guerrero R, Ramos-Vázquez AG, Zavala-Solares M, Cassis-Nosthas L, et al. Design and implementation of modified-texture diet in older adults with oropharyngeal dysphagia: a randomized controlled trial. European Journal of Clinical Nutrition. 2019; 73: 989–996. https://doi.org/10.1038/s41430-019-0389-x

[8] Terré R, Mearin F. Effectiveness of chin-down posture to prevent tracheal aspiration in dysphagia secondary to acquired brain injury. A videofluoroscopy study. Neurogastroenterology and Motility. 2012; 24: 414–419, e206. https://doi.org/10.1111/j.1365-2982.2011.01869.x

[9] Simonelli M, Ruoppolo G, Iosa M, Morone G, Fusco A, Grasso MG, et al. A stimulus for eating. The use of neuromuscular transcutaneous electrical stimulation in patients affected by severe dysphagia after subacute stroke: A pilot randomized controlled trial. NeuroRehabilitation. 2019; 44: 103–110. https://doi.org/10.3233/NRE-182526

[10] Wang Z, Wu L, Fang Q, Shen M, Zhang L, Liu X. Effects of capsaicin on swallowing function in stroke patients with dysphagia: A randomized controlled trial. Journal of Stroke and Cerebrovascular Diseases: the Official Journal of National Stroke Association. 2019; 28: 1744–1751. https://doi.org/10.1016/j.jstrokecerebrovasdis.2019.02.008

[11] Oh DH, Park JS, Kim HJ, Chang MY, Hwang NK. The effect of neuromuscular electrical stimulation with different electrode positions on swallowing in stroke patients with oropharyngeal dysphagia: A randomized trial. Journal of Back and Musculoskeletal Rehabilitation. 2020; 33: 637–644. https://doi.org/10.3233/BMR-181133

[12] Mao H, Lyu Y, Li Y, Gan L, Ni J, Liu L, et al. Clinical study on swallowing function of brainstem stroke by tDCS. Neurological Sciences: Official Journal of the Italian Neurological Society and of the Italian Society of Clinical Neurophysiology. 2022; 43: 477–484. https://doi.org/10.1007/s10072-021-05247-6

[13] Farpour S, Asadi-Shekaari M, Borhani Haghighi A, Farpour HR. Improving Swallowing Function and Ability in Post Stroke Dysphagia: A Randomized Clinical Trial. Dysphagia. 2023; 38: 330–339. https://doi.org/10.1007/s00455-022-10470-0

[14] Wang L, Shi A, Xue H, Li Q, Wang J, Yang H, et al. Efficacy of Transcranial Direct Current Stimulation Combined with Conventional Swallowing Rehabilitation Training on Post-stroke Dysphagia. Dysphagia. 2023; 38: 1537–1545. https://doi.org/10.1007/s00455-023-10581-2

[15] Zhao N, Sun W, Xiao Z, Fan C, Zeng B, Xu K, et al. Effects of Transcranial Direct Current Stimulation on Poststroke Dysphagia: A Systematic Review and Meta-analysis of Randomized Controlled Trials. Archives of Physical Medicine and Rehabilitation. 2022; 103: 1436–1447. https://doi.org/10.1016/j.apmr.2022.03.004

[16] Shigematsu T, Fujishima I, Ohno K. Transcranial direct current stimulation improves swallowing function in stroke patients. Neurorehabilitation and Neural Repair. 2013; 27: 363–369. https://doi.org/10.1177/1545968312474116

[17] Pingue V, Priori A, Malovini A, Pistarini C. Dual Transcranial Direct Current Stimulation for Poststroke Dysphagia: A Randomized Controlled Trial. Neurorehabilitation and Neural Repair. 2018; 32: 635–644. https://doi.org/10.1177/1545968318782743

[18] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. British Medical Journal (Clinical research ed.). 2021; 372: n71. https://doi.org/10.1136/bmj.n71

[19] Bernhardt J, Hayward KS, Kwakkel G, Ward NS, Wolf SL, Borschmann K, et al. Agreed definitions and a shared vision for new standards in stroke recovery research: The Stroke Recovery and Rehabilitation Roundtable taskforce. International Journal of Stroke: Official Journal of the International Stroke Society. 2017; 12: 444–450. https://doi.org/10.1177/1747493017711816

[20] Higgins JPT, Altman DG, Gøtzsche PC, Jüni P, Moher D, Oxman AD, et al. The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. BMJ (Clinical Research Ed.). 2011; 343: d5928. https://doi.org/10.1136/bmj.d5928

[21] Viechtbauer W, Cheung MW. Outlier and influence diagnostics for meta-analysis. Research Synthesis Methods. 2010; 1: 112–125. https://doi.org/10.1002/jrsm.11

[22] Higgins JPT, Thompson SG, Deeks JJ, Altman DG. Measuring inconsistency in meta-analyses. BMJ (Clinical Research Ed.). 2003; 327: 557–560. https://doi.org/10.1136/bmj.327.7414.557

[23] Ahn YH, Sohn HJ, Park JS, Ahn TG, Shin YB, Park M, et al. Effect of bihemispheric anodal transcranial direct current stimulation for dysphagia in chronic stroke patients: A randomized clinical trial. Journal of Rehabilitation Medicine. 2017; 49: 30–35. https://doi.org/10.2340/16501977-2170

[24] Kumar S, Wagner CW, Frayne C, Zhu L, Selim M, Feng W, et al. Noninvasive brain stimulation may improve stroke-related dysphagia: a pilot study. Stroke. 2011; 42: 1035–1040. https://doi.org/10.1161/STROKEAHA.110.602128

[25] Kumar S, Marchina S, Langmore S, Massaro J, Palmisano J, Wang N, et al. Fostering eating after stroke (FEASt) trial for improving post-stroke dysphagia with non-invasive brain stimulation. Scientific Reports. 2022; 12: 9607. https://doi.org/10.1038/s41598-022-14390-9
[26] Sawan SAE, Reda AM, Kamel AH, Ali MAM. Transcranial direct current stimulation (tDCS): its effect on improving dysphagia in stroke patients. The Egyptian Journal of Neurology, Psychiatry and Neurosurgery. 2020; 56: 111. https://doi.org/10.1186/s41983-020-00246-4
[27] Suntrup-Krueger S, Ringmaier C, Muhle P, Wollbrink A, Kemmling A, Hanning U, et al. Randomized trial of transcranial direct current stimulation for poststroke dysphagia. Annals of Neurology. 2018; 83: 328–340. https://doi.org/10.1002/ana.25151
[28] Wang ZY, Chen JM, Lin ZK, Ni GX. Transcranial direct current stimulation improves the swallowing function in patients with cricopharyngeal muscle dysfunction following a brainstem stroke. Neurological Sciences: Official Journal of the Italian Neurological Society and of the Italian Society of Clinical Neurophysiology. 2020; 41: 569–574. https://doi.org/10.1007/s10072-019-04120-x
[29] Yang EJ, Baek SR, Shin J, Lim JY, Jang HJ, Kim YK, et al. Effects of transcranial direct current stimulation (tDCS) on post-stroke dysphagia. Restorative Neurology and Neuroscience. 2012; 30: 303–311. https://doi.org/10.3233/RNN-2012-110213
[30] Chen S, Hu R, Deng X, Yu S. Effectiveness analysis of transcranial direct current stimulation (tDCS) in treating post-stroke dysphagia. Chinese Manipulation and Rehabilitation Medicine. 2019; 10: 13–15. (In Chinese)
[31] He H. Efficacy of transcranial direct current stimulation for post-stroke dysphagia [Master's thesis]. Kunming: Kunming Medical University. 2016. (In Chinese)
[32] Li X, Ouyang Y, Yu T, Huang W, Chen Y, Yang H. Effectiveness of transcranial direct current stimulation for dysphagia after brainstem stroke. Chinese Journal of Rehabilitation. 2020; 35: 625–628. (In Chinese)
[33] Liu J, Wang X, Hua H. Clinical efficacy analysis of post-stroke dysphagia treatment. Chinese Journal of Medical Application. 2020; 11: 49–51. https://doi.org/10.14172/j.issn1671-4008.2020.01.014 (In Chinese)
[34] Wang Z, Bai Y, Zhou J, Gao W, Shen X. Efficacy of transcranial direct current stimulation on post-stroke dysphagia. Family Medicine and Drug Selection. 2018; 9: 379–380. (In Chinese)
[35] Wang S, Shen X, Mo D, Xu J, Tian J, Sun L. Clinical efficacy of transcranial direct current stimulation combined with swallowing training for post-stroke dysphagia. Neural Injury and Functional Reconstruction. 2019; 14: 209–211. (In Chinese)
[36] Yang C, Zhang J, Sun F, Du Q, Tian S. Effects of transcranial direct current stimulation on dysphagia arising from bulbar or pseudobulbar palsy after stroke. Chinese Journal of Physical Medicine and Rehabilitation. 2020; 42: 199–204. https://doi.org/10.3760/cma.j.issn.0254-1424.2020.03.003 (In Chinese)
[37] Yuan Y, Wang J, Wu D. Effects of transcranial direct current stimulation on ataxic dysphagia after stroke. Chinese Journal of Rehabilitation Medicine. 2015; 30: 765–770. (In Chinese)
[38] Chen WY, Wu MY. Observation on the therapeutic effect of transcranial direct current stimulation at different healthy-side cortical areas in stroke patients with dysphagia. Journal of Frontiers of Medicine. 2022; 12: 52–54. (In Chinese)
[39] Du Y, Li X, Liu W, Liu X. Comparison of the efficacy of different intensities of transcranial direct current stimulation in patients with dysphagia after cerebral infarction. Chinese Journal of Rehabilitation Theory and Practice. 2020; 26: 583–587. https://doi.org/10.3969/j.issn.1006-9771.2020.05.018 (In Chinese)
[40] Fu Q. Efficacy observation of bilateral anodal transcranial direct current stimulation for dysphagia after ischemic stroke [Master's thesis]. Yangzhou: Yangzhou University. 2023. (In Chinese)
[41] Li A. Study on the rehabilitative efficacy of transcranial direct current stimulation at different cortical sites in patients with dysphagia following acute ischemic stroke [Master's thesis]. Nanchong: North Sichuan Medical College. 2022. (In Chinese)
[42] Luo J, Bao X, Xie D, Li F, Zhu Y, Wei Z, et al. Efficacy analysis of transcranial direct current stimulation (tDCS) on post-stroke dysphagia rehabilitation. Journal of Gannan Medical University. 2021; 41: 677–680. https://doi.org/10.3969/j.issn.1001-5779.2021.07.009 (In Chinese)
[43] Sun L, Wang S, Shen X. Clinical Effect of Transcranial Direct Current Stimulation with Different Intensities on Dyspha? gia after True Bulbar Paralysis. Neural Injury and Functional Reconstruction. 2022; 17: 587–590. (In Chinese)
[44] Xu T, Gong Z, Yang M, Hu H. Clinical Effect Study of Different Frequency Transcranial Direct Current Stimulation Therapy on Dysphagia after Stroke. Medical Innovation of China. 2024; 21: 5–9. (In Chinese)
[45] Teismann IK, Suntrup S, Warnecke T, Steinsträter O, Fischer M, Flöel A, et al. Cortical swallowing processing in early subacute stroke. BMC Neurology. 2011; 11: 34. https://doi.org/10.1186/1471-2377-11-34
[46] Sasegbon A, Hamdy S. The Role of the Cerebellum in Swallowing. Dysphagia. 2023; 38: 497–509. https://doi.org/10.1007/s00455-021-10271-x
[47] Ertekin C, Aydogdu I. Neurophysiology of swallowing. Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology. 2003; 114: 2226–2244. https://doi.org/10.1016/s1388-2457(03)00237-2
[48] Daniels SK, Corey DM, Fraychinaud A, DePolo A, Foundas AL. Swallowing lateralization: the effects of modified dual-task interference. Dysphagia. 2006; 21: 21–27. https://doi.org/10.1007/s00455-005-9007-2
[49] Qi S, Cao L, Wang Q, Sheng Y, Yu J, Liang Z. The Physiological Mechanisms of Transcranial Direct Current Stimulation to Enhance Motor Performance: A Narrative Review. Biology. 2024; 13: 790. https://doi.org/10.3390/biology13100790
[50] Cheng I, Hamdy S. Metaplasticity in the human swallowing system: clinical implications for dysphagia rehabilitation. Neurological Sciences: Official Journal of the Italian Neurological Society and of the Italian Society of Clinical Neurophysiology. 2022; 43: 199–209. https://doi.org/10.1007/s10072-021-05654-9
[51] Stampanoni Bassi M, Centonze D, Gjikolaj B, Alito A, Tisano A, Marchese-Ragona R, et al. Neurogenic Dysphagia: Peripheral and Central Neuromodulation. Clinics and Practice. 2025; 15: 163. https://doi.org/10.3390/clinpract15090163
[52] Abbott LF, Nelson SB. Synaptic plasticity: taming the beast. Nature Neuroscience. 2000; 3 Suppl: 1178–1183. https://doi.org/10.1038/81453
[53] Turrigiano GG, Nelson SB. Homeostatic plasticity in the developing nervous system. Nature Reviews. Neuroscience. 2004; 5: 97–107. https://doi.org/10.1038/nrn1327
[54] Abraham WC. Metaplasticity: tuning synapses and networks for plasticity. Nature Reviews. Neuroscience. 2008; 9: 387. https://doi.org/10.1038/nrn2356
[55] Hulme SR, Jones OD, Abraham WC. Emerging roles of metaplasticity in behaviour and disease. Trends in Neurosciences. 2013; 36: 353–362. https://doi.org/10.1016/j.tins.2013.03.007
[56] Liu A, Vöröslakos M, Kronberg G, Henin S, Krause MR, Huang Y, et al. Immediate neurophysiological effects of transcranial electrical stimulation. Nature Communications. 2018; 9: 5092. https://doi.org/10.1038/s41467-018-07233-7
[57] Notturno F, Pace M, Zappasodi F, Cam E, Bassetti CL, Uncini A. Neuroprotective effect of cathodal transcranial direct cur-

rent stimulation in a rat stroke model. Journal of the Neurological Sciences. 2014; 342: 146–151. https://doi.org/10.1016/j.jns.2014.05.017

[58] Alonzo A, Brassil J, Taylor JL, Martin D, Loo CK. Daily transcranial direct current stimulation (tDCS) leads to greater increases in cortical excitability than second daily transcranial direct current stimulation. Brain Stimulation. 2012; 5: 208–213. https://doi.org/10.1016/j.brs.2011.04.006

[59] Stagg CJ, Nitsche MA. Physiological basis of transcranial direct current stimulation. The Neuroscientist: a Review Journal Bringing Neurobiology, Neurology and Psychiatry. 2011; 17: 37–53. https://doi.org/10.1177/1073858410386614

[60] Siebner HR, Lang N, Rizzo V, Nitsche MA, Paulus W, Lemon RN, et al. Preconditioning of low-frequency repetitive transcranial magnetic stimulation with transcranial direct current stimulation: evidence for homeostatic plasticity in the human motor cortex. The Journal of Neuroscience: the Official Journal of the Society for Neuroscience. 2004; 24: 3379–3385. https://doi.org/10.1523/JNEUROSCI.5316-03.2004

[61] Mann G, Hankey GJ, Cameron D. Swallowing function after stroke: prognosis and prognostic factors at 6 months. Stroke. 1999; 30: 744–748. https://doi.org/10.1161/01.str.30.4.744

[62] Lefaucheur JP, Antal A, Ayache SS, Benninger DH, Brunelin J, Cogiamanian F, et al. Evidence-based guidelines on the therapeutic use of transcranial direct current stimulation (tDCS). Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology. 2017; 128: 56–92. https://doi.org/10.1016/j.clinph.2016.10.087

[63] Biernaskie J, Chernenko G, Corbett D. Efficacy of rehabilitative experience declines with time after focal ischemic brain injury. The Journal of Neuroscience: the Official Journal of the Society for Neuroscience. 2004; 24: 1245–1254. https://doi.org/10.1523/JNEUROSCI.3834-03.2004

[64] Buchholz DW. Neurogenic dysphagia: what is the cause when the cause is not obvious? Dysphagia. 1994; 9: 245–255. https://doi.org/10.1007/BF00301918

[65] Finegan E, Kleinerova J, Hardiman O, Hutchinson S, Garcia-Gallardo A, Tan EL, et al. Pseudobulbar affect: clinical associations, social impact and quality of life implications - Lessons from PLS. Journal of Neurology. 2025; 272: 266. https://doi.org/10.1007/s00415-025-12971-y

[66] Barer DH. The natural history and functional consequences of dysphagia after hemispheric stroke. Journal of Neurology, Neurosurgery, and Psychiatry. 1989; 52: 236–241. https://doi.org/10.1136/jnnp.52.2.236

[67] Speyer R, Sutt AL, Bergström L, Hamdy S, Pommée T, Balaguer M, et al. Neurostimulation in People with Oropharyngeal Dysphagia: A Systematic Review and Meta-Analysis of Randomised Controlled Trials-Part II: Brain Neurostimulation. Journal of Clinical Medicine. 2022; 11: 993. https://doi.org/10.3390/jcm11040993

[68] Jesuthasan A, Maung M, Ajina S, Warburton E. Rehabilitation Guidelines in Stroke. British Journal of Hospital Medicine (London, England: 2005). 2025; 86: 1–23. https://doi.org/10.12968/hmed.2024.1040