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REVIEW ARTICLE

Effects of transcranial direct current stimulation on surgical skills acquisition: a systematic review

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Abstract

Background: Surgical training is opportunity based, and multiple factors including exposure time, case volume and simulation training contribute to achieving competencies. We aimed to evaluate the effects of transcranial direct current stimulation (TDCS) as an adjunct to attain surgical skills faster. **Methods:** A registered systematic review (PROSPERO number CRD42020211985) of randomized trials (RCTs) on Biosis, Cochrane Central, EMBASE, MEDLINE, PsycINFO databases was carried out. Studies included compared active TDCS to sham stimulation in a surgical task involving trainees. Outcomes were grouped into four domains to overcome the heterogeneity of study outcomes: speed of skills acquisition; proficiency, i.e. ability to achieve a pre-determined score/level of proficiency; accuracy and error reduction; and composite outcomes involving more than one domain. **Results:** Four RCTs were identified involving 143 participants in total (61 sham, 82 TDCS). All studies utilized simulation training: three in laparoscopic training (peg transfer and pattern cutting), and one in neurosurgery training (tumour resection exercise). The mean age of the participants was 24.5±1.5 years, 58% (n=83) were female and 92% (n=131) were right hand dominant. Use of TDCS was associated with improved speed of skills acquisition, proficiency, accuracy and a less steep learning curve. This performance advantage was sustained for at least 6 weeks. **Conclusions:** TDCS may be a useful, safe adjunct for surgical simulation training. It is associated with improved skills acquisition in both laparoscopic and neurosurgical training tasks. Further research is needed to evaluate its use in other surgical specialties.

Keywords: *transcranial direct current stimulation; surgical education; simulation training; motor skill learning*

Introduction

Mechanism of TDCS

Transcranial direct current stimulation (TDCS) is a form of non-invasive brain stimulation whereby low amplitude electrical current is applied to the scalp through a pair of positively (anode) and negatively charged (cathode) sponge electrodes to modulate neuronal excitability, primarily of the sensorimotor cortex.[1] At a cellular level, TDCS shifts the neuronal resting membrane potential by either depolarization or hyperpolarization.[2,3] This shift facilitates or inhibits the generation of action potentials, thus modulating the excitability of cortical neurons[4] and possibly altering the function of non-neuronal glia cells.[5,6] These modulations, applied to a specific cortical region could improve certain targeted brain functions such as gross and fine motor skills with after effects beyond the stimulation period.[3,7]

Use in the medical field

The use of TDCS has been studied in various fields of medicine. A recent International Federation of Clinical Neurophysiology consensus guideline suggested potential therapeutic use in neuropathic pain modulation, fibromyalgia, depressive disorders and addiction disorders.[8] Its effect has been controversial in post-stroke rehabilitation of patients with motor dysfunction.[8–11] As a result of its effect on primary motor cortex (M1) excitability, TDCS has been evaluated as a method to enhance motor skill learning, fine motor task performance and coordination.[12–14]

Use in surgical education

Surgical residency training is challenging because it involves acquiring both theoretical knowledge and fine motor skills to perform surgeries safely. Since its inception, it has been structured as opportunity-based training where trainees' exposure might not be standardized and subsequently their ability to attain expected competencies may vary.[15,16] To help trainees achieve these abilities, simulation training has now been integrated into most training programmes.[17] Moreover, recently imposed duty hour restrictions (DHR) potentially reduce that exposure and have unclear effects on the ability to attain milestones and competencies.[18–22] It is also difficult to assess the impact of the current COVID-19 pandemic on attaining skills.[23] In addition to simulation, TDCS has been hypothesized to help trainees attain skills faster.[24] In this systematic review, we aim to explore the available literature on the use of TDCS to facilitate motor skill learning in the context of surgical education.

Methods

Data sources

We performed a systematic review by searching Biosis (via ClarivateAnalytics); the Cochrane Central Register of Controlled Trials and Cochrane Database of Systematic Reviews; Embase Classic and Embase; MEDLINE; and PsycINFO. The search strategies designed by a librarian (IM) used text words and relevant indexing to identify clinical trials on the effects of TDCS on the acquisition of surgical skills in trainees. The MEDLINE strategy was applied to all databases, with modifications to the search terms as necessary. No language limits were applied. The search strategies were peer reviewed by two librarians. In addition, clinical trials registries (clinicaltrials.gov) and the US Food and Drug Administration were searched. This review is registered in the International Prospective Register of Systematic Reviews (PROSPERO number CRD42020211985).

Only randomized trials comparing TDCS with shams or controls, i.e. no TDCS, were included. These had to have an objective outcome measured in a surgical simulation training exercise. Studies evaluating outcomes such as force, speed or accuracy but not in a surgical simulation training exercise were excluded. Non-randomized trials were also excluded. Nineteen studies were identified in Web of Science and Scopus (20 October 2020) by carrying out citation searches for the reference lists of included studies. The MEDLINE strategy was re-run before submission (via Ovid 2020 August to 27 October 2020). Ten records were found.

Study selection and data extraction

We included all randomized trials comparing TDCS with sham in the setting of surgical simulation training. Sham utilized the same setup as TDCS but did not have current actively delivered on the participants' scalp. The outcomes of interest were grouped in four domains to overcome the heterogeneity between the results of the studies: domain 1 for speed of skills acquisition; domain 2 for proficiency, i.e. ability to achieve a pre-determined score/level of proficiency; domain 3 for accuracy and error reduction; and domain 4 for composite outcomes involving more than one domain. Abstract and full text review was performed by two authors independently (AN and EG) for study selection. Disagreement was reconciled by a third author (FRS). The same two authors extracted the data, including study design, method of TDCS, participants' demographics, detailed outcomes reported. Risk of bias was assessed using the Cochrane revised risk of bias tool for randomized trials (RoB 2)[25] by two authors (AN and FRS).

Results

Results of the systematic search are presented in Fig. 1. Four randomized controlled trials (RCTs) involving 143 participants (61 sham, 82 TDCS) were included.[26–29] These studies compared TDCS with sham and reported outcomes within our four pre-defined domains. Three additional studies were considered initially, and their authors were contacted. These were not available in full text for data extraction (two were in the process of peer review, the third was not accessible despite contacting the authors) and were not included in the analysis.

Study design

The study protocols are summarized in Appendix 1, including the different modalities of stimulation. Three studies applied a single 20-min TDCS session during laparoscopic simulation training[27,28] and neurosurgical simulation training.[26] The fourth study had six 20-min TDCS sessions during laparoscopic training spread over three visits.[29] Most studies used anodal stimulation over the primary motor cortex (M1) of the dominant hemisphere.[26–28] The most recent study by Cox et al.[29] had three arms: sham, anodal TDCS over bilateral M1 (BM1), and anodal TDCS over the supplementary motor area (SMA).

Risk of bias assessment

The results of the RoB 2 are presented in Table 1. Three of the four studies recruited only medical or veterinary students; the risk of bias in random sequence generation was judged as unclear in these. Moreover, all studies did not have a true control arm with no TDCS device and therefore no stimulation as opposed to sham. In addition, three of the four studies are published from the same institution by the same first author.[26–28]

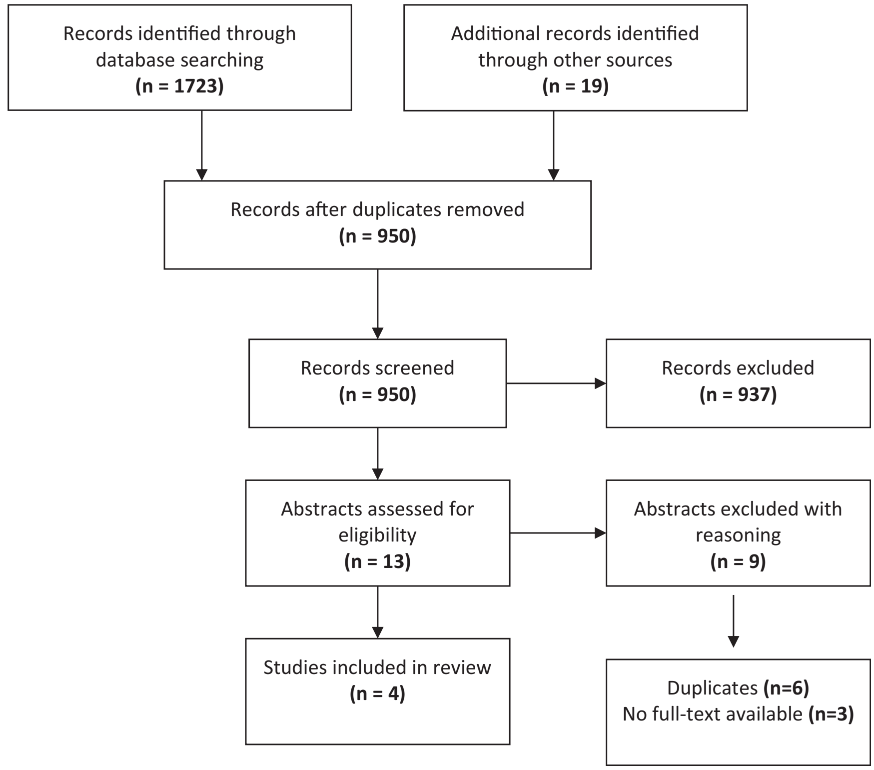

Figure 1. PRISMA flow diagram showing the search algorithm.

Table 1. Risk of bias assessment (RoB 2) in the included studies

	Ciechanski et al., 2017[26]	Ciechanski et al., 2018[27]	Ciechanski et al., 2019[28]	Cox et al., 2020[29]
Random sequence generation	Unclear risk. Comment: minimization versus clinician judgement	Unclear risk. Comment: minimization versus clinician judgement	Unclear risk. Comment: minimization versus clinician judgement	Low risk
Allocation concealment	Low risk; sealed envelope	Low risk; sealed envelope	Low risk; sealed envelope	Low risk
Blinding of participants and personnel	Low risk	Low risk	Low risk	Low risk
Blinding of outcome assessment	Low risk	Low risk	Low risk	Low risk
Incomplete outcome data	Low risk	Low risk	Low risk	Low risk
Selective reporting	Low risk	Low risk	Unclear risk. Comment: coherence and event-related potentials outcomes recorded but not reported	Low risk
Other bias	Placebo effect	Placebo effect	Placebo effect	Placebo effect; attrition bias because 84.5% completed the protocol

Demographics

The mean age of the participants was 24.5±1.5 years; 58% (n=83) were female and 92% (n=131) were right hand dominant. One study reported previous surgical experience,[29] video gaming, self-identification as athletes and/or musicians (detailed baseline characteristics of the participants are shown in Table 2.)

Outcomes

Effects of TDCS on speed of skills acquisition (domain 1)

The most recent randomized trial by Cox et al.[29] measured the effect of TDCS versus sham on speed by recording the time needed to complete a peg transfer laparoscopic task, in addition to the number of times the task was completed in a

Table 2. Baseline characteristics of participants in individual studies

	Ciechanski et al., 2017[26]		Ciechanski et al., 2018[27]		Ciechanski et al., 2019[28]		Cox et al., 2020[29]		
	Sham (n=11)	TDCS (n=11)	Sham (n=19)	TDCS (n=20)	Sham (n=11)	TDCS (n=11)	Sham (n=20)	TDCS BM1 (n=20)	TDCS SMA (n=20)
Age (years), mean (SD)	24.6 (2.1)	25.8 (3.0)	24.7 (3.3)	26.3 (4.1)	25.5 (4.7)	25.9 (3.6)	22.7 (3.7)	21.9 (5.2)	23.5 (5.4)
Female sex, %	73	73	53	45	27	27	70	60	80
Non-Hispanic ethnicity, %							90	90	85
Right handedness, %	100%	100%	89%	90%	100%	91%	90	85	90
Prior open experience, %							15	5	10
Prior laparoscopic experience, %							5	5	10
Musician, %							40	25	45
Gamer, %							5	35	5
Athlete, %							55	55	60

BM1, bilateral primary motor cortex; SD, standard deviation; SMA, supplementary motor area; TDCS, transcranial direct current stimulation.

given time frame. The findings were improvement in speed of completion that did not reach statistical significance (pre-test: 135.7±31.3 s, 166.8±59.5 s, and 159.2±93.0 s for sham, BM1, and SMA respectively; post-test: 59.5±18.3 s, 55.3±15.4 s, and 54.5±13.1 s for sham, BM1, and SMA respectively; P=0.6).

Effects of TDCS on proficiency (domain 2)

Proficiency was reported in two studies.[26,27] The first study[26] reported the results of a simulated neurosurgery task involving resecting a brain tumour. It reported an improved percentage of tumour resected with TDCS (P=0.029) compared with sham (P=0.354). The second study[27] evaluated two simulated laparoscopic tasks: peg transfer and pattern cutting. It was found that TDCS increased the number of participants who achieved 90% proficiency compared with sham for peg transfer (35% versus 5%; P=0.039 and for pattern cutting (85% versus 58%; P=0.083).

Effects of TDCS on accuracy and error reduction (domain 3)

In their neurosurgery simulation task, Ciechanski et al.[26] considered excessive forces applied on the tumour and healthy brain as an error. These were both reduced in participants receiving TDCS (P<0.001 for tumour tissue, P=0.003 for healthy brain tissue). Cox et al.[29] described a trend towards a reduction in error for improper peg transfer but no clear difference in pegs transferred outside the field of view.

Effects of TDCS on composite outcomes (domain 4)

All four studies reported composite outcomes evaluating more than one domain.[26–29] Ciechanski et al. reported scores for both peg transfer and pattern cutting laparoscopic tasks in their 2018[27] and 2019[28] studies. These were calculated using previously published scoring systems[30] and accounted for time to completion of task and errors made. Mean scores for pattern cutting improved in participants receiving TDCS versus sham (208 versus 186, P=0.022)[27] in both studies but not for peg transfer. The third study in laparoscopy[29] used another scoring system and established that participants in the BM1 TDCS arm had a less steep learning curve and improved scores compared with sham.

Moreover, Ciechanski et al.[26] reported on the effectiveness and efficiency of brain tumour resection. Effectiveness was described as the ratio of healthy brain tissue resected (an error) to tumour resected. There was no statistically significant difference (t=0.600; P=0.552). Resection efficiency entailed the ratio of excessive forces on the tumour to tumour resected and described a statistically significant improvement with TDCS (t=2.897; P=0.006).

Skills retention

At 6 weeks, skills retention was present in laparoscopic peg transfer and neurosurgical tumour resection but not in laparoscopic pattern cutting.[26,27] The remaining two studies did not report the outcome.[28,29]

TDCS safety and ethical considerations

Itching (18%–75%),[27,28] tingling (21%–64%)[27,28] and burning (11%–45%)[27] were the most commonly reported side effects. Three participants had symptoms that precluded completion of the study protocol.[29] No major adverse events were reported in all four studies.[26–29] This mirrors the established safety of TDCS in trials.[31]

The ethical aspect of performance enhancement by means of TDCS has yet to be explored in the surgical education literature. Proving its utility in skills acquisition will give rise to issues with equity in distribution, availability and access to TDCS.

Discussion

This is a systematic review and commentary on the use of TDCS to facilitate motor skill acquisition in surgical training. A rigorous search of the literature yielded a handful of studies discussing the use of this novel technology.[26–29] Attaining new skills within surgical residency training is usually a product of cumulative exposure to procedures and opportunities to practice under supervision. Simulation training has expanded the opportunities to practice skills beyond the operating room and gain competence in a safe environment with no fear of morbid complications.[32,33] It is especially crucial now to maximize opportunities to learn with the shift towards controlled duty hours for trainees.[18,20–22] The rationale for the use of TDCS is to exploit its modulatory effect on the motor or supplementary motor cortex to facilitate the processing of neuronal activity in sensory motor networks and thus accelerate motor skill learning and fostering skill retention by inducing synaptic plasticity.[1–3] In doing so, the ability to learn or improve upon the skill may be achieved in less time. This is extrapolated from the existing literature, albeit with mixed results that suggest that TDCS improves fine motor skills learning, which, similar to surgical skills, require coordination and dexterity.[34,35]

The overall results suggested a positive effect of TDCS on both neurosurgical[26] and laparoscopic[27–29] simulation training. Evidently, outcomes were heterogeneous which prevented a robust meta-analysis. We attempted to combine the various outcomes reported into four distinct domains that we believe are important when assessing attaining surgical skills: learning speed; achieving pre-specified target performance; and task accuracy. The fourth domain is any combination of these domains.

Multiple inferences can be made on the effects of TDCS on surgical training. First, speed of laparoscopic task completion measured directly[29] (domain 1) and indirectly as part of composite scores[27,28] (domain 4) increased with TDCS. Anodal TDCS in which the dominant side motor area is stimulated improved speed in unimanual but not bimanual tasks.[27,28] In a bilateral TDCS montage whereby the dominant and non-dominant motor cortices received anodal and cathodal stimulation, respectively, bimanual tasks were studied and improvement was observed.[29] Bilateral motor cortical stimulation has been shown to improve learning of complex fine motor tasks by inducing cortical excitability.[35,36] Second, it appears that TDCS helps participants achieve pre-determined levels of proficiency faster[27] with an increased number of participants achieving 80% proficiency in both pattern cutting and peg transfer laparoscopic tasks with TDCS versus sham. This is an important consideration in modern competency-based surgical training; achieving pre-determined milestones influences progress in training and board certification.[37] Third, for a meticulous task such as brain tumour resection, TDCS improved both proficiency and accuracy of task completion. Highly complex surgeries such as neurosurgical oncology procedures are associated with significant comorbidities, and these have increased after implementation of DHR for trainees in large-scale studies.[38,39] Simulation training with TDCS would help trainees to be efficient in achieving desired milestones in high-stake procedures despite DHR. In addition, the improved skills appeared to be retained up to 6 weeks beyond the training exercise. The authors postulate that if TDCS can be delivered via commercially available equipment, it could be used as an adjunct in surgical simulation training.

Some limitations must be noted. All but one of the RCTs did not have a control group. The study by Ciechanski et al.[26] included a group of residents that served as reference. The addition of real controls would enhance outcome comparison and allow better measurements of the effect of TDCS on skills acquisition. In addition, only four studies were identified despite a rigorous search of databases and that was confounded by the heterogeneity of reported outcomes.

Future directions

This review reveals encouraging results on the use of TDCS in surgical training that need further investigation. Changes such as modifications in the stimulation protocol to include cerebellar or pre-motor cortex stimulation, a comparison of stimulation during the task (online) versus stimulation before the task (offline) and skill transfer to other than the trained tasks would enhance our understanding of this adjunct. This could be the topic of further research.

Conclusion

TDCS seems to be a useful, safe and promising adjunct to surgical simulation training. It is associated with improved skills acquisition in both laparoscopic and neurosurgical training tasks. Further research is needed to evaluate its use in other surgical specialties.

Conflict of interests

None declared.

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Appendix 1: Detailed methodology of the included studies

	Ciechanski et al., 2017[26]	Ciechanski et al., 2018[27]	Ciechanski et al., 2019[28]	Cox et al., 2020[29]	
Trial design	Double-blinded, randomized and sham-controlled	Double-blinded, randomized and sham-controlled	Parallel design, double-blinded, randomized and sham-controlled	Double-blinded, randomized, and sham-controlled	
Field	Neurosurgery	FLS	FLS	FLS	
Stimulation details					
Type	Anodal (1 anode + 1 cathode)	Anodal (1 anode + 1 cathode)	Anodal (1 anode + 4 cathodes)	Anodal (1 anode + 1 cathode)	
Electrode holder	Head strap	Head strap	Electrode cap	Head strap	
Anode location	Dominant M1 C3 and C4	Dominant M1 C3 and C4	Dominant M1 C3 and C4	Bilateral M1: 20% to the left of vertex over C3	SMA: 15% anterior to vertex over Cz
Cathode location	Contralateral supraorbital area	Contralateral supraorbital area	On the contralateral hemisphere, surrounding F3 or F4	Bilateral M1: 20% to the right of vertex over C4	SMA: 10% posterior from the nasion over Fpz
Conductive solution	Normal saline	Normal saline	High-viscosity electrolyte gel	Normal saline	
Duration	20 min × 1 session	20 min × 1 session	20 min × 1 session	20 min × 6 sessions	
Voltage	1 mA	1 mA	1 mA	2 mA	
Sham details	1 mA, 45 s ramp-up, hold for 60 s, 45 s ramp-down	1mA, 45 s ramp-up, hold current for 60 s, 45 s ramp-down	1 mA, 30 s ramp-up, 30 s ramp-down	30 s ramp-up, 30 s ramp-down	
Training details					
TDCS during training (online)	Yes	Yes	Yes	Yes	
Account for hand dominance	Yes	Yes	Yes	No	
Retention test	6 weeks after	6 weeks after	6 weeks after	None	
Device used	DC Stimulator (neuroConn; Ilmenau, Germany)	DC Stimulator (neuroConn; Ilmenau, Germany)	Soterix 1 × 1 tDCS with 4 × 1 adaptor (Soterix Medical, New York)	Soterix 1 × 1 tDCS (Soterix Medical, New York)	

FLS, Fundamentals of Laparoscopic Surgery; M1, primary motor cortex; SMA, supplementary motor area; TDCS, transcranial direct current stimulation.