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Effects of electrode drift in transcranial direct current stimulation

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Abstract

Background—Conventional transcranial direct current stimulation (tDCS) methods involve application of weak electrical current through electrodes encased in saline soaked sponges affixed to the head using elastic straps. In the absence of careful preparation, electrodes can drift from their original location over the course of a tDCS session.

Objective—The current paper investigates the influence of electrode drift on distribution of electric fields generated by conventional tDCS.

Methods—MRI-derived finite element models of electric fields produced by tDCS were used to investigate the influence of incremental drift in electrodes for two of the most common electrode montages used in the literature: M1/SO (motor to contralateral supraorbital) and F3/F4 (bilateral frontal). Based on these models, we extracted predicted current intensity from 20 representative structures in the brain.

Results—Results from separate RM-ANOVAs for M1/SO and F3/F4 montages demonstrated that 5% incremental drift in electrode position significantly changed the distribution of current delivered by tDCS to the human brain ($F's > 8.6$, $p's < .001$). Pairwise comparisons demonstrated that as little as 5% drift was able to produce significant differences in current intensity in structures distributed across the brain ($p's < .03$).

Conclusions—Drift in electrode position during a session of tDCS produces significant alteration in the intensity of stimulation delivered to the brain. Elimination of this source of variability will facilitate replication and interpretation of tDCS findings. Furthermore,

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measurement and statistically accounting for drift may prove important for better characterizing the effects of tDCS on the human brain and behavior.

Keywords

transcranial direct current stimulation; electrode drift; MRI-derived finite element models; tDCS reproducibility; electrode placement

Introduction

The number of applications for transcranial direct current stimulation (tDCS) is growing exponentially.^{1–21} However, this nascent method of non-invasive brain stimulation is faced with issues regarding the reproducibility of published findings, an issue commonly faced by new areas of study. As tDCS has shown great promise in the treatment of depression and pain, provides a strong scientific tool for probing structure-function relationships in the brain, and allows non-invasive modulation of neuroplastic response,^{1,6–8,10,21–27} improving the reproducibility of tDCS effects is a foremost concern for advancing this area of non-invasive brain stimulation. In the current paper, we will address a key methodological factor potentially contributing to reproducibility of tDCS findings: electrode drift. We will use MRI-derived finite element models of electric fields produced by tDCS to assess the impact of electrode drift on distribution of current flow and current intensity in the human brain.

Conventional methods of tDCS involve the application of a weak electrical current to the scalp through biocarbon electrodes encased in saline-soaked sponges.^{14,28} The relative location of these electrodes alters where in the brain electrical stimulation is delivered.^{21,29,30} The location of electrodes is typically determined using the International 10–20 EEG measurement system, a method that provides reproducible and consistent placement of electrodes for different head sizes.^{14,31} Electrodes are commonly affixed to the head using a combination of elastic straps and fixtures. This combination allows for placement of the electrode at the site of 10–20 target locations. However, unless care is taken, these commonly used elastic straps can drift from the initial site of preparation during the course of an experiment. For example, we have observed that electrodes can drift several centimeters from the initial site of preparation over the course of a twenty-minute stimulation session unless carefully prepared and monitored. This drift has many potential sources (over or under tightened of straps, oily/thin hair, etc.), but can typically be avoided using careful preparation techniques. However, this issue has received little to no attention in the tDCS literature and has yet to be addressed empirically. While prior research has investigated static effects of electrode shape, size, and location,^{30,32–35} the current work is the first to evaluate dynamic effects of change in electrode position over time on tDCS generated electric fields.

In the current paper, we posit that electrode drift can significantly alter the pattern of brain stimulation delivered during a tDCS session. If true, this would undermine reproducibility of study effects and brain structure-function interpretations from tDCS results. Furthermore, to the extent that tDCS effects are linked to the specific anatomy stimulated by a montage, variability in current flow based on drift potentially decreases the ‘signal-to-noise’ of tDCS

by adding heterogeneity to the neural structures being stimulated. This heterogeneity may erode the effect sizes of otherwise well designed tDCS studies, increasing the number of subjects necessary to demonstrate a tDCS-induced behavioral change. The current paper tests whether 5% vertical drift of electrodes from their original location results in a significant change in the predicted DC electrical field stimulating the brain, as computed by MRI-derived finite element models. We test this hypothesis for two montages commonly found in the clinical and research literature: M1/SO and F3/F4. As 5% drift can equal approximately 1 to 1.5 cm on average-sized human heads, this work will provide insight into the importance of consistent and stable electrode preparation in tDCS.

Materials and Methods

MRI-derived finite element modeling

MRI-derived finite element models used to map electrical fields produced by tDCS were calculated using Soterix HD-Explore software. Model solutions in HD Explore were calculated in a single individual using methods described previously.^{29,30,34} Briefly, model solutions in HD Explore were based on a 36-year-old male brain scanned on a 3T Siemens Trio scanner (Erlangen, Germany). The T1-weighted images were collected using gradient echo (GRE) sequence with TE= 2.3 ms, TR= 1900 ms, 280 × 320 matrix scan with 208 sagittal slices and had a isotropic resolution of 1 mm³. Scans were segmented into seven masks (1. soft tissue; 2. bone; 3. air; 4. eyes; 5. cerebrospinal fluid; 6. cortical gray matter; 7. white matter) using a combination of automated methods (FSL, FMRIB Analysis Group, Oxford, UK) and manual segmentation tools (Simpleware Ltd, Exeter, UK). The soft tissue mask comprised skin, fat, and muscle; while the cerebrospinal fluid mask included macroscopic brain blood vessels, in addition to CSF. Electrodes and gel were rendered as CAD files and imported into ScanCAD (Simpleware Ltd, Exeter, UK) for manual positioning over the scalp of the 3D model. The finite element adaptive meshes generated from the segmentation and CAD masks, consisting of >5,000,000 tetrahedral elements (>9,000,000 degrees of freedom) were imported into COMSOL Multiphysics 3.5 (Comsol Inc, MA).

Models in HD Explore were solved using a linear system solver of conjugate gradients with a relative tolerance of 1×10⁻⁶. The electrical properties of tissues were defined by the average isotropic conductivity (S/m): cortical and deep gray matter 0.276 S/m; white matter: 0.126 S/m; CSF 1.65 S/m; bone 0.01 S/m, eyes 0.4 S/m, scalp with fat and muscle tissue 0.465 S/m). We simulated conventional 25 cm² sponge-based anode and cathode electrodes using an array of high-definition disk electrodes of 4 mm radius. 4mm HD electrodes were configured to cover the 25 cm² surface area of the conventional sponge covered biocarbon electrodes. This method has previously been shown to produce finite element models that deviate by only 5% from models specifically modeling conventional electrode comprised of biocarbon electrodes covered in a rectangular sponge soaked in saline for application of tDCS.³⁶

The Laplace equation $\nabla(\sigma \nabla V) = 0$ (V: potential; σ : conductivity) was solved and the boundary conditions used were (1) inward current flow = J_n (normal current density) applied to the exposed surface of the anode electrode (2), ground applied to the exposed surface of

the cathode electrode(s) and (3) all other external surfaces treated as insulated. Current density corresponding to 2 mA was applied. Plots of electrical field magnitude were plotted on the brain. In addition, directionality of current flow was investigated, depicted with directional arrows in model plots.

Montage/Model Selection—M1 referenced to SO (supraorbital) and F3 referenced to F4 montages were chosen as test cases for the current study due to their common use in the literature. 25cm² electrodes were modeled. Using the 10-5 International measurement system, 5% incremental shifts in the positions of the electrodes from the original placement at M1/SO or F3/F4 were subsequently calculated. The M1/SO (C3/Fp2) montage was compared to C3h/AFp6, C1/AF6h, and C1h/AFF6h montages, each representing an incremental vertical drift of 5% at each electrode site. The F3/F4 montage was compared to FFC3/FFC4, FC3/FC4, and FCC3/FCC4, each representing an incremental vertical drift of 5% at each electrode site (total drift across electrode sites = 10%). All models were set with the anode electrode on the left and cathode on the right.

Analyses of finite element models—For each model, we acquired whole brain maps of the predicted distribution of the electrical field, predicted peak electrical current intensity in the brain, and current intensity at twenty representative structural locations distributed across the brain (see Table 1 for locations and intensity data). The field intensity at each selected location was entered as the dependent variable in separate repeated measures analyses of variance (RM-ANOVA) with Montage Location (e.g., F3/F4, FFC3/FFC4, FC3/FC4, FCC3/FCC4) as the independent variable. Pairwise comparisons of field intensities at each location using least significant differences (LSD) assessed for differences between individual pairs of montages.

Results

M1/SO

RM-ANOVA of current intensity in the twenty selected brain regions demonstrated that 5% shifts in each electrodes position significantly altered the distribution of predicted current intensity across sites ($F_{(3, 57)} = 40.4$, $p < .001$, Partial Eta Squared = .68). Pairwise comparisons demonstrated that change in current intensity was significantly different between each model and its nearest vertical neighbor (p 's $< .001$, see Table 2). Thus, a 5% vertical shift in electrode position significantly altered the intensity of stimulation across the brain. These effects can be seen in the whole brain maps of the predicted distribution of the electrical field in Figure 1. These effects are also reflected by change in the estimated peak electric field intensity across models (Table 1).

F3/F4

RM-ANOVA of current intensity demonstrated that 5% shifts in electrode position significantly altered the distribution of current intensity across sites ($F_{(3, 57)} = 8.6$, $p < .001$, Partial Eta Squared = .31). Change in current intensity was significantly different between all four of the compared models (p 's $< .05$, see Table 2). As with M1/SO models, a 5% shift in electrode positions significantly altered the intensity of stimulation across the brain in

F3/F4 models. This effect is reflected in the whole brain maps of the predicted distribution of the electrical field (Figure 2) and change in the estimated peak electric field intensity across models (Table 1).

Discussion

Results from finite element models demonstrate that 5% drift in electrode positions significantly alters the predicted distribution of the electrical field generated by tDCS in the human brain. A 5% shift in electrode position is typically equal to a 1 to 1.5 cm shift in electrode location on an average sized human head. These findings highlight the critical attention necessary to how and where we place electrodes when using conventional tDCS.

We have observed that electrode drift is most common under several circumstances. If straps are over tightened, the pressure created can cause the strap to move upward. This is especially the case for thin and/or oily hair. Even in the absence of over tightened straps, oily and thin hair presents an issue for electrode drift. Furthermore, when large quantities of hair are present, it can be difficult to keep the electrodes in one location for more than a few seconds. These issues can be mitigated to some degree by utilizing specific elements of the head's physical anatomy. For example, the curvature at the base of the skull when used in combination with the flat portion of the forehead can improve stability of strap placement. Furthermore, placing the portion of the strap at the back of the head underneath long hair, rather than on top of the hair, creates a more stable preparation for the strap and the electrodes. In the M1/SO montage, when the strap proceeding across the top of the head is too tight, this can lead to increased vertical movement of the horizontal strap. However, if either strap is too loose, electrodes can drift downward. This represents a difficult factor for readily replicable and stable electrode placement, as over or under-tightened straps are both detrimental to stable placement. Some researchers attach an elastic strap under the chin to prevent upward drift. Another approach involves use of a strap that proceeds across the lower curvature at the back/base of the skull. Both are effective methods for preventing upward drift.

As elastic straps are pliable and thus difficult to standardize, their use in tDCS may represent a critical hurdle for readily replicable montage preparation not only across laboratories, but also between experimenters in a given laboratory. Head-size specific straps preconfigured for popular montages are now commercially available (e.g., Easy Strap, Soterix Medical). These straps use a flexible but non-pliable plastic that contours to the head and utilizes strap configurations aimed at preventing electrode drift. As these straps are configured for different head sizes, they avoid the pitfalls of over or under-tightening straps and provide a more easily standardized method for electrode placement. Whether using elastic straps or preconfigured head-size specific straps, attention to electrode drift is an important factor that requires attention to improve reproducibility and interpretability of tDCS findings.

These issues raise the question of whether the amount of drift within a stimulation session should be measured and accounted for in tDCS studies. These measures may hold promise as a covariate accounting for drift related variability in tDCS studies. Furthermore, the process of measuring drift may also assist in focusing the attention of researchers on careful

electrode placement preparation procedures. These measures can be performed with little extra time or effort on the part of the experimenter. For example, after placing the electrodes via the International 10–20 method for a given montage, a horizontal and vertical mark, made using either a sharpie or wax pencil, can be placed at the bottom two corners of each electrode. Use of separate marker colors for drift markers versus electrode placement marks from 10–20 methods can be helpful for keeping track of marker types. At the end of the tDCS session, the vertical, horizontal and straight-line displacement of the two corners from the original marks are then measured. These three measures per electrode corner allow reconstruction of not only drift distance, but also rotation of the electrodes. This simple method affords a calculation of average drift distance from before and after stimulation or a full recreation of electrode position. We have noted in over 40 recent observations of tDCS sessions (n observations = 42) in our laboratories that the average electrode drift distance was consistently 2mm or less over 20 minutes sessions of tDCS in the presence of this procedure and careful preparation (average electrode drift = 1.21 mm, SD = 1.0).

While the current investigation focused on modeling the effects of electrode drift on the electric fields generated by tDCS, these data also provide insight into the importance of careful and consistent placement of electrodes at a targeted location on the head. While drift considers spatial change in the position of electrodes over time, electrode placement/positioning considers the effects of electrodes at different spatial locations on the head. This issue may arise from subtle differences in experimenters' approaches to electrode placement. Lack of consistent placement of electrodes at a targeted location between experimenters or laboratories could produce the same effects modeled in this paper. Variability in the pattern of stimulation delivered to the brain from a 5% shift in electrode position suggests that tDCS may be highly sensitive to differences in electrode placement, potentially arising from different experimenters using slightly different approaches to electrode placement. While the 10–20 International Measurement System is reported for selection of electrode location in many papers, the application of this system is not universal. Our results suggest that even relatively small differences in electrode placement between individuals can add heterogeneity to the brain areas stimulated, potentially diminishing the putative effects of tDCS. Like electrode drift, this represents another source of variability undermining replicability and effectiveness of tDCS.

Conclusions

In summary, finite element models demonstrate that as little as 5% drift (~1 to 1.5cm on the average size head) in electrode locations significantly alters the predicted electric field. These results suggest that subtle differences in the location of electrodes, whether from electrode drift during a stimulation session or from different approaches to electrode placement, significantly alters the distribution and flow of current delivered to the human brain. Our data suggest that careful consideration should be given to electrode placement methods. Furthermore, measuring and reporting the amount of electrode drift in experiments will improve the ability of tDCS researchers to produce reproducible effects and interpret results. Further still, statistically accounting for electrode drift may prove useful in better controlling statistical models of tDCS effects on behavior. Most importantly, careful

preparation of electrodes to eliminate drift and insure consistent placement will help improve consistency of tDCS application across the field as a whole.

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Highlights

Electrode drift alters distribution of current in tDCS over time

Electrode drift alters peak current intensity delivered to brain regions

Drift may contribute to heterogeneity of tDCS findings

Measurement and control of drift may reduce variability in tDCS effects

Figure 1.

Finite element models for M1/SO models at 5% increments of drift. Representative and evenly distributed slices of the brain for each modeled montage configuration are displayed with the right most column displaying the MRI slice depicted in the adjacent models. Each column of models represents a 5% shift in electrode position. The field intensity legend and position of electrodes (red = anode, blue = cathode electrode) can be found at the bottom of the figure. Black arrows depicted within models depict predicted direction of current flow. Slice positions are listed in MNI coordinate on the right with unlisted values set at zero (e.g., $x = 0$, $y = 43$, $z = 0$). White circles in each image represent the center point of the coordinate position within the slice. All models are plotted with the same range of field intensity: 0–0.45 V/m. L = left, R = right, F = front.

Figure 2.

Finite element models for F3/F4 models at 5% increments of drift. Representative and evenly distributed slices of the brain for each modeled montage configuration are displayed with the right most column displaying the MRI slice depicted in the adjacent models. Each column of models represents a 5% shift in electrode position. The field intensity legend and position of electrodes (red = anode, blue = cathode electrode) can be found at the bottom of the figure. Black arrows depicted within models depict predicted direction of current flow. Slice positions are listed in MNI coordinate on the right with unlisted values set at zero (e.g., $x = 0$, $y = 43$, $z = 0$). White circles in each image represent the center point of the coordinate position within the slice. All models are plotted with the same range of field intensity: 0–0.51 V/m. L = left, R = right, F = front.

Table 1

Field Intensity Change Across Brain Locations

Location	MNI			Field Intensity (V/m)									
	X	Y	Z	M1/SO	C3h/AFp6	Cl/AF6h	Clh/AF6h	F3/F4	FFC3/FFC4	FC3/FC4	FCC3/FCC4		
R Sup Orb frontal	25	56	0	0.26	0.24	0.19	0.14	0.21	0.16	0.14	0.11		
L Ant Cingulate	-5	47	2	0.14	0.12	0.1	0.07	0.16	0.12	0.11	0.1		
L Mid Temporal	-54	3	-26	0.13	0.1	0.08	0.06	0.08	0.07	0.08	0.09		
R insula	41	13	-8	0.15	0.13	0.11	0.09	0.14	0.12	0.13	0.12		
L Mid Frontal (DLPFC)	-48	21	38	0.26	0.22	0.17	0.13	0.14	0.12	0.16	0.19		
R Mid Frontal (DLPFC)	43	21	38	0.19	0.19	0.18	0.16	0.21	0.18	0.22	0.22		
L Putamen	-28	0	0	0.18	0.15	0.12	0.09	0.14	0.12	0.14	0.15		
R Hippocampus	31	-25	-8	0.14	0.12	0.11	0.08	0.1	0.09	0.11	0.12		
M1 L Motor Cortex	-37	-21	58	0.17	0.15	0.08	0.08	0.13	0.14	0.18	0.21		
M1 R Motor Cortex	37	-21	58	0.17	0.17	0.17	0.16	0.14	0.15	0.2	0.23		
R Posterior Cingulate	6	-40	26	0.16	0.15	0.14	0.11	0.08	0.08	0.1	0.12		
R Cerebellum	41	-65	-33	0.05	0.04	0.04	0.03	0.04	0.04	0.05	0.06		
L Inferior Parietal	-40	-50	50	0.15	0.12	0.07	0.07	0.08	0.08	0.11	0.14		
L Precuneus	-5	-62	43	0.11	0.1	0.09	0.07	0.05	0.05	0.07	0.1		
R Superior Parietal	30	-60	55	0.13	0.13	0.12	0.1	0.09	0.1	0.14	0.18		
L Lingual Gyrus	-23	-90	-15	0.06	0.05	0.04	0.03	0.04	0.04	0.05	0.06		
R Superior Temporal	61	-25	9	0.11	0.1	0.09	0.08	0.09	0.09	0.11	0.13		
L Inferior Frontal	-45	32	14	0.22	0.19	0.16	0.12	0.19	0.15	0.16	0.15		
R SMA	9	7	60	0.16	0.17	0.17	0.17	0.13	0.14	0.17	0.17		
L Mid Cingulate	-7	-17	46	0.14	0.14	0.12	0.1	0.09	0.1	0.12	0.14		
Peak Field Intensity (V/m):				0.69	0.65	0.56	0.45	0.51	0.56	0.64	0.62		

R = Right, L = Left, Ant = Anterior, Mid = Middle, DLPFC = dorsolateral prefrontal cortex, SMA = supplementary motor association cortex, M1/SO = C3/Fp2, Peak Field Intensity = Peak intensity in the brain

Table 2

Pairwise Comparisons

Montage Compared	Mean Difference	SE	p
M1/SO vs. C3h/AFp6	0.015	0.003	<.001*
C3h/AFp6 vs. C1/AF6h	0.021	0.004	<.001*
C1/AF6h vs. C1h/AFF6h	0.021	0.003	<.001*
F3/F4 vs. FFC3/FFC4	0.009	0.004	0.036*
FFC3/FFC4 vs. FC3/FC4	-0.02	0.004	<.001*
FC3/FC4 vs. FCC3/FCC4	-0.012	0.004	0.008*

*
p<.05, SE = standard error