Published in final edited form as:

Brain Stimul. 2016 ; 9(6): 952–954. doi:10.1016/j.brs.2016.08.009.

Response to the Response to “Does tDCS Actually Deliver DC Stimulation? ”

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Dear Editor

We appreciate the response [1] from Salimpour et al. clarifying some of the concerns that we raised earlier [2]. This new response raises further methodological and conceptual concerns related to the original article [3].

First, DC-DC converter technology merely converts one voltage to another. This technology is used where the circuitry in question requires a specific *voltage*, but available voltage sources are only capable of providing voltage that is different from the specific voltage needed by the circuitry in question. A common example is cellular phones where batteries have output of 3.8 V (or less as it discharges) but cellular phone circuits require constant supply of 5 V. A DC-DC converter *converts* the available battery voltage (3.8 VDC) to the required 5 V. For tDCS use, a constant *current (not voltage)* is required. Batteries are used as voltage sources in commercial tDCS treatment devices (typically 9 V or 18 V if two batteries are needed).

One may question whether or not thinking in terms of voltage or current makes any difference. The required argument is based on Ohm's law ($V = IR$). The premise of converting a given voltage into a given current holds only in cases where resistance (R) remains constant. This gives rise to an important, subtle distinction. When current passes *in vivo*, the body offers changing resistance as a function of time [4,5]. This phenomenon has been demonstrated many times and reported in tDCS-related patents [6]. We have also observed this effect in our clinical research setting (Fig. 1). For this reason, constant current

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circuits are used in tDCS devices to maintain constant delivered current across time-varying human tissue resistance. DC-DC converters can only deliver constant voltage – *not constant current*. For tDCS usage, a constant voltage device as proposed by Salimpour et al. cannot deliver constant current because of resistance variations over time. Their reported constant 1 mA current (with some flickers which we believe is the result of poor recording setup or electrode poor contacts) is an indirect evidence that current clamp circuitry was used and not a DC-DC converter.

Second, ramping functionality is designed to minimize negative subject experiences normally associated with tDCS. Examples include feeling of skin sensations such as tingling, burning, itching, electric shock, etc., while simultaneously reducing applied voltage requirements. The authors should be careful in suggesting that ramping periods are not experimentally relevant. Human tissue resistance is highest at the beginning of stimulation [4], e.g., see Fig. 1.

Third, our methodology concerns remain as the authors fail to mention the details of their optically isolated, current-detection system. Similarly, they fail to mention the manufacturer and model of the commercial tDCS system used. Based on our own experience, we do not believe that the presence of a stereotactic system and recording equipment would lead to large current surges as the authors claim. If the authors indeed tested their setup as reported, they could have easily excluded such possibilities. Pinpointing the noise source and eliminating electrical noise are the first steps toward quality electrophysiological experimentation. The tDCS findings as presented need to receive the same rigorous scrutiny prior to publication. The authors appear misinformed when mentioning the impedance of tDCS electrodes as being about 10 k Ω . Human body itself typically offers resistance of 10 k Ω at the beginning of stimulation. This resistance typically declines to less than 5 k Ω within a minute or two (Fig. 1). Electrodes themselves have negligible resistance (a few Ohms at most) because of their large surface area and the normal saline solution used in sponges to enhance conduction. Measuring electrode resistance during test setup should have made this low resistance values obvious.

We now consider the definitions of resistance and impedance. Resistance is a circuit's tendency to inhibit Direct Current (DC). Impedance, on the other hand, is a circuit's tendency to inhibit Alternating Current (AC). In inductive or capacitive circuits subjected to AC currents, the actual currents are not in phase with applied voltages. For example, in capacitive circuits currents lead applied voltages while in inductive circuits currents lag applied voltages. Additionally, impedance varies with the frequency of the applied electric potential. In such circuits, impedance at 100 Hz is different from that at 10 kHz. Consequently, reporting impedance requires that the measurement frequency be specified. This reporting practice has become standard in neurophysiological experiments where impedance of the microelectrode tip is reported in k Ω or M Ω at 1 kHz. However, "resistance" is the required usage when reporting on tDCS experiments since the very definition of tDCS includes the words "Direct Current" (DC), which is a null frequency (0 Hz).

Fourth, in the original letter, the authors themselves report the non-tDCS related signal strength in the range of -50 dB to -80 dB [3]. As we explained in our initial response, a signal of -45 dB literally means a signal strength of only $1/32,768$ of reference signal strength ($1/32,768 = (1/2)^{15} \cong -3 \text{ dB} \times 15 = -45 \text{ dB}$) [2]. We wish to re-emphasize that non-tDCS waveform signal strength during tDCS application at -50 dB or less is truly negligible. Before exploring the implications of such negligible signal artifacts on cortical activity, we recommend the authors to prioritize on examining experimental configurations and verifying correspondence of test values to experimental values.

Finally, we would mention that the $\pm 5 \mu\text{A}$ peak-to-peak (p-p) noise current is the norm for commercial tDCS devices. We used $10 \mu\text{A}$ p-p noise on a 1 mA delivered current to make the case that 1% variability is comparable to -45 dB signal strength ratio – a quite acceptable number indeed.

In conclusion, commercial tDCS devices deliver reasonably stable DC currents. Here we demonstrate the performance of a typical commercial device during a brief tDCS session (Fig. 1). As mentioned above, it would have been helpful had the authors actually specified the manufacturer and model of the tDCS device used as well describing in detail their experimental configuration including the manufacturer and model of the recording system employed. This way, both the scientific community and the manufacturers will have the ability to replicate the publishing authors' published experimental results and support/refute the claims made by them.

Acknowledgments

PYC acknowledges fellowship grant support from SC-CoAST/NIH StrokeNet (U10NS086490) and American Heart Association (15SFDRN24480016); WF acknowledges grant support from American Heart Association (14SDG1829003 and 15SFDRN24480016) and National Institutes of Health (P20GM109040); PYC and WF acknowledge grant support from South Carolina Translational Research Discovery Grant (UL1 TR001450) and pilot grant from National Center of Neuromodulation for Rehabilitation (P2CHD086844).

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Figure 1.

Real-time monitoring of applied voltage, injected current, and body resistance during a two-minute tDCS application showing ramp-up and ramp-down. A commercial tDCS device was used to demonstrate stable delivery of current without flickers or jumps. Iontophoresis device (Chattanooga Ionto, Chattanooga Group, Hixson, TN) was used for tDCS application in combination with a DAQ device for voltage (blue) and current (green) measurements (DI-245, DATAQ Instruments, Akron, OH). Body resistance (red) was derived using Ohm's law ($V = IR$). Actual injected current was 2 mA, but the current was scaled by 10× to ease visual comparison. This plotting technique allows time-based comparison between applied voltage and applied current at 2 mA. Note: the high body resistance initially declines rapidly to <10 kΩ during the initial ramp-up period and starts increasing during ramp down (see inset) consistent with the literature. The peak-to-peak fluctuations/noise floor in injected current using this commercial device was less than 0.5%, or less than 10 μA. We found comparable results with other commercial tDCS devices as well. (For interpretation of the

references to color in this figure legend, the reader is referred to the web version of this article.)

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