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Topic of concern in TMS research: Cases of mismatch between indicated and actual current direction of TMS coils and proposal of preventive measures

It is well-known that administering transcranial magnetic stimulation (TMS) stimuli with different current directions can yield different neurophysiological outcomes, such as a higher motor threshold and a longer latency after inducing anterior–posterior (AP)- as compared to PA-directed currents in the primary motor cortex (M1), probably due to distinct neuronal pathways being involved [1,2]. As a result, being correctly informed about the current direction of a TMS coil is crucial in TMS research, amongst others to ensure a correct choice, interpretation, and reporting of the experimental parameters [3]. Usually, the current direction of a TMS coil is clearly indicated by arrows, allowing to draw conclusions about the induced current direction in the cortex. For instance, arrows that point posteriorly on the middle part of a figure-of-eight coil indicate an initial AP-directed current between the two windings and therefore induce an initial PA-directed current (referring to the first phase of the induced current) in the underlying brain tissue. However, this current direction can potentially be indicated incorrectly on the TMS coil, without the user being aware. Alarmingly, we recently discovered that this was the case in three of our TMS coils (out of a total of 18). More specifically, in two MC-B65-HO-2 coils from MagVenture (P/N: 9016E0462, SN: 1029 and 1030, manufactured in 2019; MagVenture, Farum, Denmark) the current direction indicated on the coil was opposite of the actual current direction, and in one D110 cone coil from Magstim (P/N: 9902–00, SN: 661, manufactured in 2009; Magstim Co. Ltd., Whitland, Dyfed, UK), the current direction was indicated in opposing directions on the two sides. Fortunately, we were able to anticipate these issues due to measurements with a magnetic field probe before starting data acquisition. Both manufacturers were informed and required us to send the respective coils in for oscilloscope measurements. In case of the MagVenture coils, this has been done and the manufacturer adjusted the current direction labels to fit the actual current direction. For the Magstim coil, this was not an option due to the start of a data acquisition and we reversed the labels ourselves according to the results obtained with the magnetic field probe. Nevertheless, this is not the first report of mismatch between the current directions reported by the manufacturers and the actual current direction, and in that case errata were published to correct all earlier publications using this setup [4].

Based on our experience and the likeliness that more coils display erroneous current directions, we would like to call the TMS community to action. Unfortunately, researchers cannot blindly assume that information provided by the manufacturers will always be correct, but should take responsibility based on the principle “to measure is to know”. Therefore, to rule out inconsistencies between the indicated and the true current direction, we propose an efficient and low-cost solution for exploring a TMS coil’s current direction using a magnetic field probe.

Here, we explain two methods to measure the direction of magnetic field changes with time (dB/dt) produced by a TMS coil. We exemplarily present measurements on the commonly used figure-of-eight coil (see Fig. 1), but a comparable procedure can be applied for other coil shapes. Firstly, we introduce a simple and quick way to determine the initial current direction of a TMS coil by making use of a custom-made, easy-to-build single-loop magnetic field probe, consisting of a paper clip and a BNC cable (see Ref. [5], see own creation in Fig. 1A using a 32 mm long, 0.79 mm thick nickel plated iron paper clip). To do so, a paper clip is bent into a loop shape with two straight ends, which are respectively connected to the signal (middle pin) and ground (outer case) of a female BNC connector and cable (see Fig. 1A). If necessary, tape can help to keep the loop in place. Since the deflections produced by the paper clip probe will depend on the connection of the loop to the BNC connector’s signal and ground, and on the direction in which the loop is held relative to the magnetic field change, this must be carefully checked and indicated at the paper clip probe (see Fig. 1A and B, with “S” indicating the side of the loop that is connected to the signal). The other side of the BNC cable is linked to an analogue-to-digital-converter for digitization of the signal, and the locally measured dB/dt is visualized in a voltage-by-time plot. Besides a sufficiently high sampling rate (here: 50,000 Hz), one should also ensure that the oscilloscope channel connected to the probe is not set to “invert” and that the stimulator is not set to “reversed” current direction (if this setting is available) as each would result in a flipped signal polarity. Furthermore, as opposed to commercially available calibrated three-dimensional (3D) magnetic field probes, this loop probe should only be used for qualitative (i.e., positive vs. negative initial signal deflections, see Fig. 1B and C) but not for quantitative judgements about a TMS coil’s magnetic field. Lastly, the paper clip is a one-dimensional probe, and therefore, if desired, magnetic field changes for different planes would need to be measured consecutively (see Fig. 1C, right side). To measure the direction of the magnetic field induced by a TMS coil, this paper clip loop probe will be held to the most focal site of the stimulation surface of a figure-of-eight coil, parallel to its AP-line and with the signal part pointing away from the coil handle (as shown in Fig. 1B). The resulting waveform will then be compared to the examples in Fig. 1B. Monophasic and biphasic pulses with a positive or negative initial deflection will respectively indicate an initial induced magnetic field that is PA-directed (depicted in red) or AP-directed (depicted in blue) (with the first and second phase being physiologically more relevant for mono- and biphasic pulses, respectively [6,7]).

Secondly, additional and more detailed measurements can be conducted to verify the results, although not required for determining a coil’s initial current direction. In Fig. 1C, a schematic overview is presented on how to position the paper clip loop and which results to expect in a figure-of-eight coil for different locations and planes. However, if a calibrated 3D magnetic field probe is available, measurements for all

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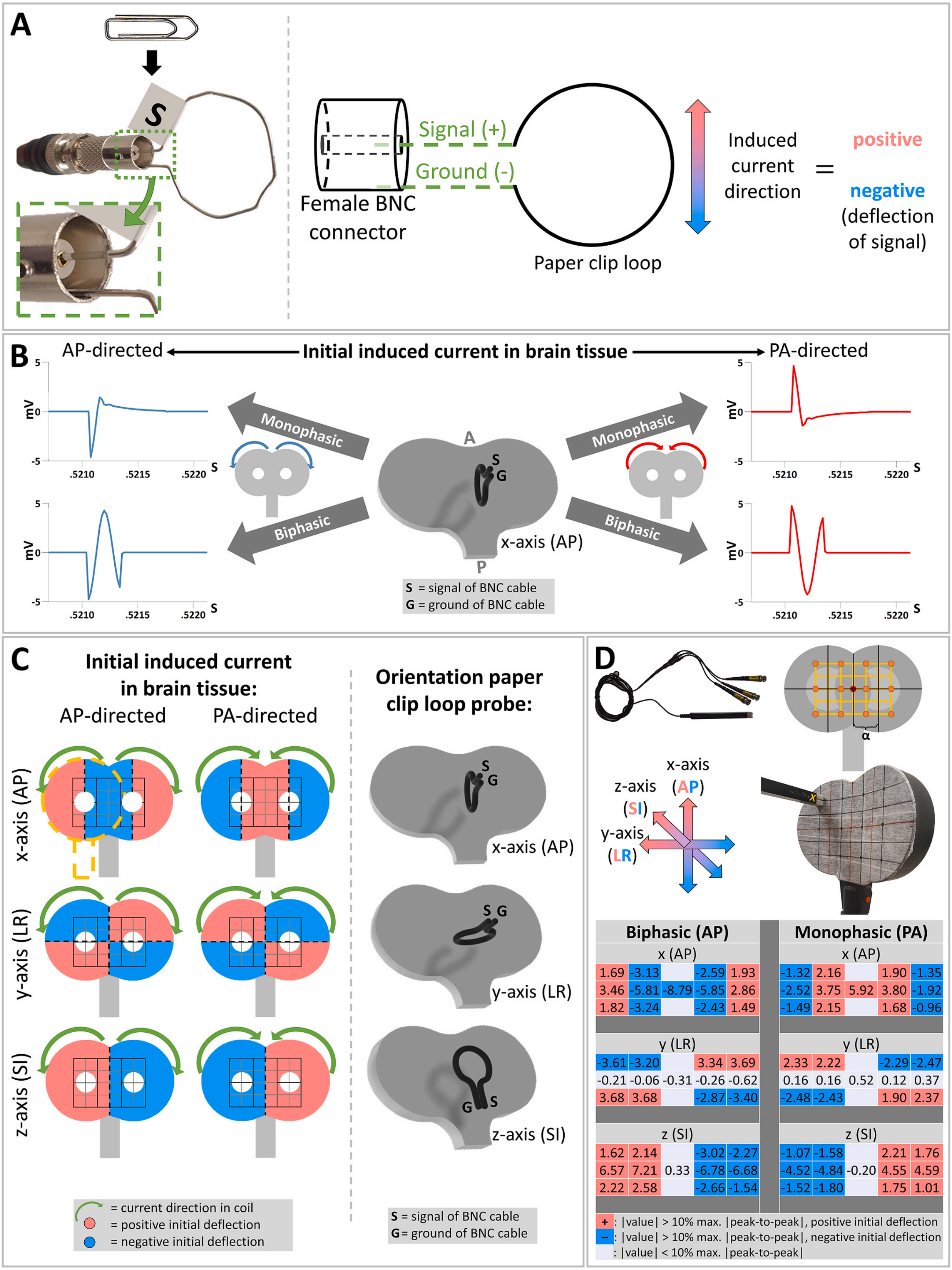

Biphasic (AP)					Monophasic (PA)				
x (AP)					x (AP)				
1.69	-3.13		-2.59	1.93	-1.32	2.16		1.90	-1.35
3.46	-5.81	-8.79	-5.85	2.86	-2.52	3.75	5.92	3.80	-1.92
1.82	-3.24		-2.43	1.49	-1.49	2.15		1.68	-0.96
y (LR)					y (LR)				
-3.61	-3.20		3.34	3.69	2.33	2.22		-2.29	-2.47
-0.21	-0.06	-0.31	-0.26	-0.62	0.16	0.16	0.52	0.12	0.37
3.68	3.68		-2.87	-3.40	-2.48	-2.43		1.90	2.37
z (SI)					z (SI)				
1.62	2.14		-3.02	-2.27	-1.07	-1.58		2.21	1.76
6.57	7.21	0.33	-6.78	-6.68	-4.52	-4.84	-0.20	4.55	4.59
2.22	2.58		-2.66	-1.54	-1.52	-1.80		1.75	1.01

+ : |value| > 10% max. |peak-to-peak|, positive initial deflection
− : |value| > 10% max. |peak-to-peak|, negative initial deflection
: |value| < 10% max. |peak-to-peak|

(caption on next page)

Fig. 1. Overview of the measurement procedure and results obtained with a paper clip magnetic field probe and a 3D magnetic field probe. All measurements were performed at the bottom side of the coil. Directions are abbreviated as anterior–posterior (AP), left–right (LR), and superior–inferior (SI). **[A]** Constructing a magnetic field probe out of a paper clip and a female BNC connector. Magnetic field changes in the direction of the signal part of the BNC cable ("S" mark) will lead to positive deflections. **[B]** Determining a TMS coil's initial current direction with a paper clip magnetic field probe. Typical signals for monophasic and biphasic pulse forms (sampling frequency: 50,000 Hz) are shown. Signals with a positive or negative initial deflection are shown in red and blue, respectively. **[C]** Overview of the initial current directions that should be measured in a figure-of-eight TMS coil when aiming to induce AP- or PA-directed initial currents in the underlying brain tissue in all three planes, and how to position the paper clip loop probe for each plane to obtain these results. The orange dashed shape exemplarily indicates a round TMS coil. **[D]** More detailed measurement procedure with 3D magnetic field probe. The 13 measurement points were marked on a 5 × 7 grid, spaced α/2 with α being the distance between the coil center and the winding center. The tip of the 3D magnetic field probe was placed flat on the coil, with the "x" mark (see yellow x) pointing to the right. The table shows the peak-to-peak amplitudes for measurements at the 13 points for biphasic pulses set to induce an initial AP-directed current, and monophasic pulses set to elicit an initial PA-directed current in the hypothetically underlying brain tissue. Red and blue shading indicate positive and negative initial deflections of the signal, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

three planes can even be conducted simultaneously and the relative field strength at each point can be compared. We performed and present these measurements in Fig. 1D as a confirmation of the paper clip method, using the MagVenture MagProbe 3D (MagVenture, Farum, Denmark; P/N: 9016E0351; output voltage: 1 V per 1.4 kT/s ±5%; three orthogonally arranged copper wire loops of 10 windings each). This probe was linked to an analogue-to-digital-converter via three BNC connectors for digitization and visualization of signals in the x-, y-, and z-direction, respectively. We prepared the bottom side of the coil (i.e., the surface that would be pointed to the scalp) with tape (3M™ Micropore™ surgical tape 1530–1, 2.5 cm broad, ±0.02 mm thick) and used a marker to indicate a 5 × 7 grid, centered around the midpoint of the coil, and spaced by half of the distance between the midpoint of the coil and the center point of one coil winding (see Fig. 1D, distance "coil center–winding center" indicated as α). On this grid, the center of the coil and twelve other, equally distributed points have been indicated, to cover areas that are indicative of magnetic field changes in all three directions (see orange dots in Fig. 1D) and the magnetic field probe was placed orthogonally directly to the coil surface. The stimulator intensity was set to elicit signals with a maximal deflection of ±4.5 mV at the coil center in the AP-direction (here equal to 30/28 A/μs for monophasic/biphasic stimulation) in order to avoid ceiling effects above/below ± 5 mV. For monophasic and biphasic TMS pulses separately, per point five stimuli were administered, averaged, and summarized (Fig. 1D). Please note that the focus here was on the directionality of the magnetic field and that for the purpose of evaluating the coil winding shape, a finer grid would be necessary to map the complete magnetic field distribution.

Both procedures described above for a figure-of-eight coil can similarly be applied to other coil shapes. For example, for a double cone coil we would expect similar results as in a figure-of-eight coil. In a round or oval coil however, the paper clip loop probe would yield results comparable to a single loop of the figure-of-eight coil (see exemplary circular coil indicated by orange dashed shape in Fig. 1C).

In conclusion, to be able to make proper inferences and avoid unwanted variability of the induced current directions, we highly recommend to measure the current direction of TMS coils before performing any TMS measurements. Researchers should take responsibility and test the current directions of their TMS coils.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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