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Deep brain stimulation device-specific artefacts in MEG recordings

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Deep brain stimulation (DBS) is a highly effective treatment in therapy refractory movement disorders [1]. However, its mechanisms of action are still elusive, and the proposed concepts are under debate. Using magnetoencephalography (MEG), noninvasive recordings of cortical neural activity can be performed during active DBS [2]. However, MEG is prone to artefacts induced by electrical stimulation and movement of ferromagnetic DBS hardware components [3–6]. The movement of these components results from arterial pulsation and minor head movements [4,6]. To reduce DBS artefacts in MEG recordings several methods have been proposed [4]. Although hardware and software characteristics may differ between DBS devices from different manufacturers, no systematic comparison between devices exists. The aim of the present study was thus to characterize DBS artefacts based on phantom recordings with three different DBS devices in two MEG systems and to test whether established artefact reduction methods can sufficiently reduce artefacts.

Phantom recordings were performed in Berlin (125-channel-MEG system, Yokogawa ET 160, Tokyo, Japan – abbreviated YGK) and Düsseldorf (306 channel-MEG system, Neuromag, Elekta Oy, Helsinki, Finland – abbreviated NMG). A gelatine phantom was used and DBS impulse generators (IPG), extension cables, and electrodes from three different manufacturers were attached (Abbott (ABT), Boston Scientific (BSC) and Medtronic (MDT)). To simulate brain signal we used a 13 Hz sinusoid dipole (Fig. 1B). The phantom was placed on top of an inflatable box, that was filled with air every 2 s to simulate the movements due to arterial pulsation and minor head movements (Fig. 1C) [4]. We recorded 60 s with the dipole and the movement mechanism turned on, the stimulation turned off (Off + mov) and on (On + mov) as well as a reference recording with the dipole activated and without DBS hardware or movement (Ref). The raw MEG data from phantom recordings is available under the following doi: https://doi.org/10.18112/openneuro.ds004738.v1.0.0.

To analyze the MEG data, we used Brainstorm [7]. As an artefact reduction approach, we first applied temporal signal space suppression (tSSS) [8]. Second, we used the independent component analysis-mutual information (ICA-MI) algorithm [9]. Finally, we applied the Hampel filter to the data cleaned with ICA-MI and tSSS [10]. To assess how effective the cleaning approaches are, we calculated the root mean squared error (RMSE) of the logarithmic power between the cleaned recordings (On + mov) and a reference recording (Ref) [4].

Electrical stimulation induced artefacts at the stimulation frequency (130 Hz, ABT: 127 Hz) and contaminated the spectrum with additional frequency peaks (Supplementary Fig. 3). The movement of hardware components resulted in low-frequency activity, least prominent in BSC recordings (Supplementary Figs. 3B and E). Even when switched Off, the IPGs emitted signals that led to relevant artefacts: For the BSC device, this artefact consisted of peaks with a distance of 2 Hz (Fig. 1FK) both in the stimulation on and off conditions; the ABT device had artefacts with low-frequency peaks across the spectrum and an elevated low-frequency noise; the MDT device artefacts occurred every 10 Hz while the stimulator was turned off (Fig. 1DH).

Applying tSSS shifted the baseline downwards, especially in the NMG recordings (Supplementary Fig. 5) and did not reduce the electrical or movement-related artefacts. The ICA-MI approach reduced the movement-related artefact as well as the electrical stimulation artefact in some of the recordings (Fig. 1J and K). When combining the Hampel filter and ICA-MI, both the movement and electrical stimulation artefact were reduced. Furthermore, ICA-MI alone reduced the IPG-related artefacts, especially in the case of BSC recordings. However, after both, tSSS and ICA-MI, there are residuals of the movement-related artefacts that resemble a physiological alpha peak (Fig. 1KL).

In this study, we identified IPG-related artefacts, contaminating the power spectrum across various physiologically relevant frequencies. Overall, movement-related artefacts were weaker for NMG recordings with BSC devices. The reduction of stimulation, movement, and IPG-related artefacts was most successful when combining ICA-MI and Hampel filter. However, the cleaning of movement-related artefacts can result in artefactual spectral peaks.

Movement artefacts are caused by the arterial pulsation and the resulting slight movement of ferromagnetic DBS hardware components [3–6]. In comparison to ABT and MDT devices, the BSC hardware induced the weakest movement-related artefacts. In the meantime MDT developed new extension cables with less ferromagnetic components, that were not tested in our study.

The reduction of movement-related artefacts was most successful with ICA-MI. Unlike previous studies, instead of using a reference EMG

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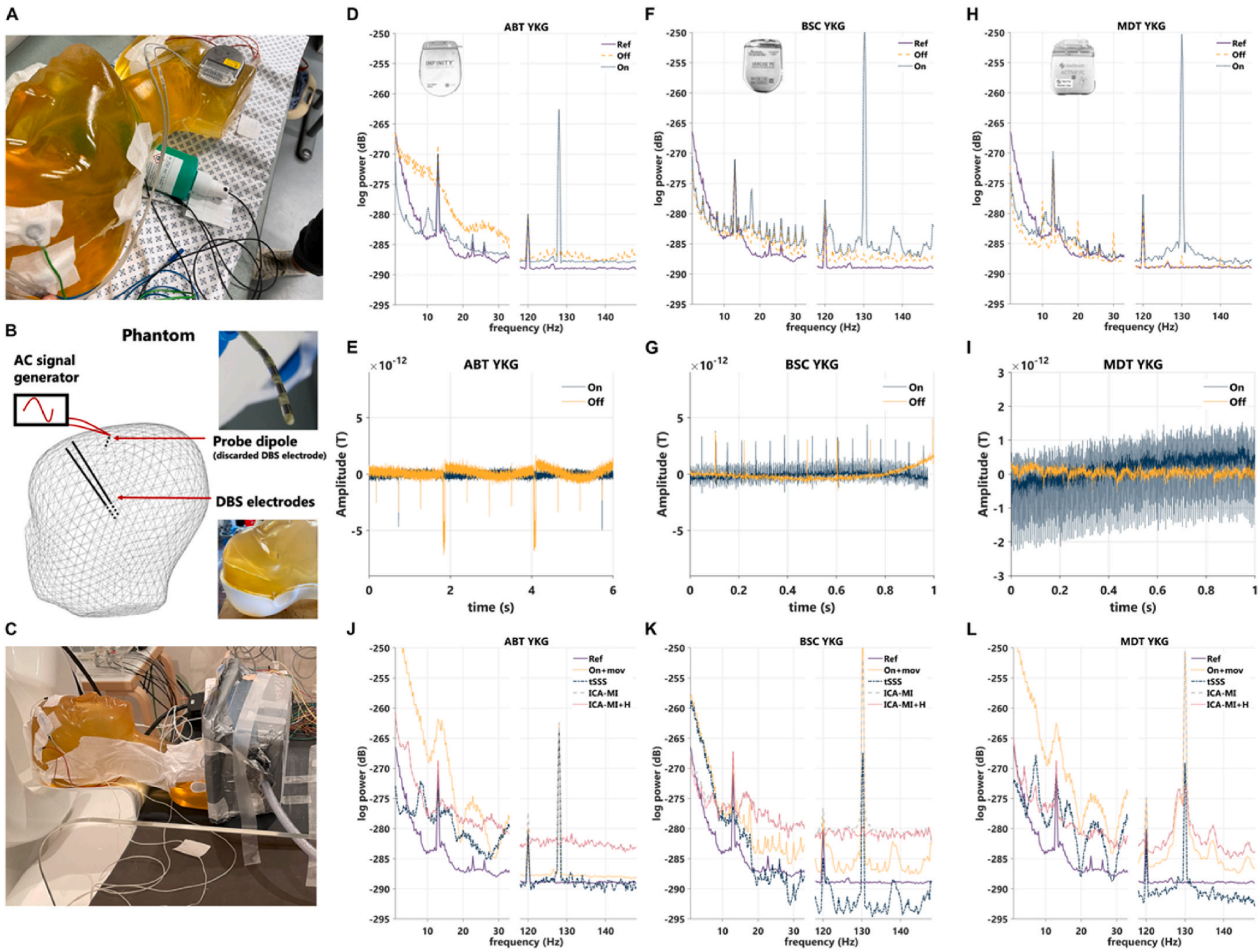

Fig. 1. Phantom setup, IPG-related artefacts in frequency and time domain, and reduction of movement-related and stimulation-induced artefacts. A. The IPG was placed on the right chest region of the phantom and the cables were led along the neck and to the right side of the head. **B.** The AC signal generator produced a dipole signal and was attached to a discarded DBS electrode. The phantom head contained two DBS electrodes that were changed between the recordings. To this end the phantom was pulled out of the MEG helmet with the MEG bed, but was not moved in relation to the inflatable box (see **C**). **D, F, H.** Average power spectrum density (PSD) plots across channels for Yokogawa (YKG) recordings with DBS devices from Abbott (ABT), Boston Scientific (BSC) and Medtronic (MDT). Reference recording (Ref) was performed without an implantable pulse generator (IPG) and only the dipole turned on. The Off condition was recorded with the IPG inside the magnetic-shielded room and the IPG turned Off, while only dipole activity was turned on as in the reference file. The On condition was recorded with the IPG turned On and only the dipole activity turned on without movement. **E, G, I.** Exemplary time series signal showing the IPG-related artefacts in the stimulation Off (yellow) and On (blue) conditions. **J, K, L.** Average power spectrum density (PSD) plots across channels for YKG recordings for the three DBS devices from Abbott (ABT), Boston Scientific (BSC) and Medtronic (MDT) showing the difference between artefact reduction approaches. On + mov = dipole, movement and IPG turned on. ICA-MI + H= ICA and mutual information + Hampel filter. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

recording above the IPG, we used the channel with the largest movement-related artefact as reference for the ICA-MI algorithm, because the movement of the DBS system is not directly reflected in the EMG signal [9]. Yet, the use of a MEG channel as reference for ICA-MI might result in a rejection of physiological activity. In a supplementary patient analysis we observed no reduction in alpha power using a MEG sensor as reference signal (Supplementary Fig. 8A). Furthermore, the IPG-related artefact appears to be larger than the electrical stimulation artefact in the time series in this patient example and was reduced using ICA-MI (Supplementary Fig. 8A).

Surprisingly, tSSS neither reduced the movement-related nor the stimulation-induced artefacts. Unlike in Kandemir et al. the movement-related artefact was weaker and the phantom head was slightly smaller (i.e. slimmer) in our study, while the cables were attached on top of the head and were in similar proximity to the MEG sensors. Thus, it could be that tSSS might not have been able to differentiate the artefact from inner sphere activity [4].

One important limitation of our work is the focus on the sensor space. Source reconstruction with a linearly constrained minimum variance (LCMV) beamformer can reduce DBS-related artefacts. An LCMV beamformer is a spatial filter and suppresses external noise sources [6]. In some studies recruiting patients in the perioperative stage the application of LCMV beamforming was sufficient to reduce the movement-related artefacts [5], which, however, was not always the case for patients with implanted DBS systems [3]. Finally, the preprocessing pipeline used for patient data analysis has to be tailored based on the respective recordings and the amount of artefact contamination.

In conclusion, device-specific IPG-related artefacts have to be considered for MEG-DBS studies. Movement-related artefacts were weakest for NMG recordings with BSC devices. Although the IPG-related artefacts were strongest for this condition, they were well mitigated with ICA-MI. Another relevant aspect are the remnants of movement-related artefacts after cleaning, which resemble physiological activity and thus need to be carefully considered.

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CRediT authorship contribution statement

Bahne H. Bahners: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Roxanne Lofredi:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Tilmann Sander:** Methodology, Resources, Writing – review & editing. **Alfons Schnitzler:** Funding acquisition, Resources, Supervision, Writing – review & editing, Project administration. **Andrea A. Kühn:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Esther Florin:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

AS received consultant and speaker fees from Medtronic Inc., Boston Scientific and Abbott. RL received speaker fees from Medtronic Inc. AAK received consultant and speaker fees from Medtronic Inc., Boston Scientific and Stada Pharm. BHB, TS and EF declare that they have no known competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brs.2024.01.005.

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