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The effect of dipole housing and feeding wires in physical phantoms for EEG

Abstract: Current dipoles are well established models in the localization of neuronal activity to electroencephalography (EEG) data. In physical phantoms, current dipoles can be used as signal sources. Current dipoles are often powered by constant current sources connected via twisted pair wires mostly consisting of copper. The poles are typically formed by platinum wires. These wires as well as the dipole housing might disturb the electric potential distributions in physical phantom measurements. We aimed to quantify this distortion by comparing simulation setups with and without the wires and the housing. The electric potential distributions were simulated using finite element method (FEM). We chose a homogenous volume conductor surrounding the dipoles, which was 100 times larger than the size of the dipoles. We calculated the difference of the electric potential at the surface of the volume conductor between the simulations with and without the connecting wires and the housing. Comparing simulations neglecting all connecting wires and the housing rod to simulations considering them, the electric potential at the surface of the volume conductor differed on average by 2.85 %. Both platinum and twisted pair copper wires had a smaller effect on the electric potentials with a maximum average change of 6.38 ppm. Consequently, source localization of measurements in physical head phantoms should consider these rods in the forward model.

Keywords: Electroencephalography, Magnetoencephalography, Forward modelling, Source localization

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1 Introduction

Electroencephalography (EEG) is a method to record electric potentials at the scalp and is often used for source reconstruction. Physical phantoms are models with predefined properties and were used to evaluate EEG setups [1], [2]. The source signals can be emitted by dipoles in physical phantoms [1]–[3]. For example, the dipole is driven with an impressed sinusoidal constant current of 500 µA [3]. The connecting wires of the constant current source to the current dipole poles are typically twisted pair wires. The setup of the dipoles including the housing and the feeding wires might cause distortions to the electric potential distribution. In this study, we aimed to quantify these distortions caused by the connecting wires. To achieve this aim, we used an equivalent computer aided design model of one of our physical current dipoles including the dipole housing and connecting wires. We simulated the electric potential distribution (originating from the current dipole) in a homogenous volume conductor and compared the setups with and without the connecting wires.

2 Materials and Methods

The computer aided design model corresponds to the original geometry of the current dipole including a dipole housing and the volume conductor. We constructed a dipole housing consisting of a nonconductive polymer with a rounded shape (thickness 3 mm, length 10 mm). The upper part (dipole housing) included two platinum wires, where each wire had a diameter of 0.5 mm and a length of 3.4 mm. The platinum wires were placed vertically mirrored and along the x-axis, see Figure 1. Twisted pair copper wires were added, each with a diameter of 0.21 mm and a length of 334 mm, at the inner ends of the platinum wires. We modelled the twisted copper wires with 0.6 turns per millimetre along the z-axis. The copper wires were housed along the z-axis in a polymer rod (housing rod) with a diameter of 3 mm and a length of 338 mm. Figure 1 depicts the constructed current dipole and the dipole housing.

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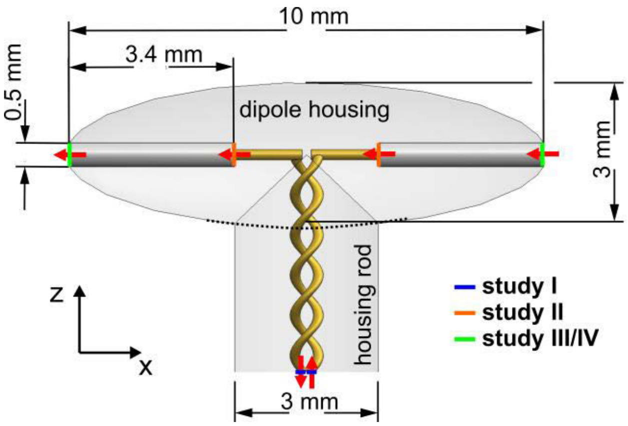

Figure 1: The platinum wires (silver) of the dipole are connected with twisted pair copper wires (yellow), each with a diameter of 0.21 mm. The dipole housing (grey) consists of a nonconductive polymer. The schematic shows only the upper region of the current dipole model and dipole housing. The total length of the cooper wires (including the feeding area of current) in z-direction is 334 mm. The blue, orange and green lines indicate the active feeding areas for impressed currents (red arrows show directions) per simulation study. The dotted line marks a speration domain.

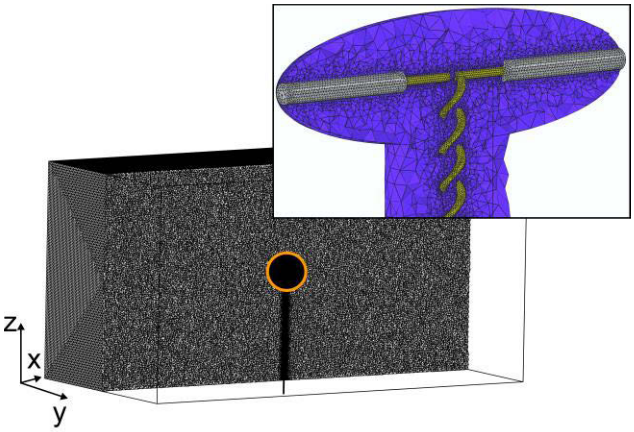

Figure 2: A coronal cut through the volume mesh. The inset depicts a cut through the mesh of the dipole housing in the central xy-plane; the wires were not sliced. The copper wires are depicted in yellow, the platinum wires in grey, the dipole housing in blue and the volume conductor in white. The black area surrounded by the orange circle depicts the testing sphere.

The volume conductor around the current dipole had the dimensions of 1177 mm in x-, 590 mm in y- and 600 mm in z-direction. This volume represented a homogenous conductor, with an electrical conductivity of 0.33 S/m defined by 0.17 % sodium chloride in deionized water. These dimensions (factor 100 in x-direction between dipole and volume conductor) enabled a relatively undisturbed field propagation to easily consider the distortions caused by the connecting wires. The current dipole was placed in the centre of the homogenous volume conductor. In addition, a testing sphere (diameter of 100 mm) was modelled around the current dipole. This sphere (factor 10 in x-direction larger than dipole) was only used to analyse the distortions of current dipole.

The built volume conductor including the current dipole model were loaded in Comsol Multiphysics® (COMSOL AB, Stockholm, Sweden) for meshing and solving the electric forward problem. We created a tetrahedral mesh using the Delauny triangulation as implemented in Comsol®. An element size of 0.005–0.1 mm was used for the copper and platinum wires, 0.2–8 mm for the dipole housing as well as the sphere and the volume conductor. This resulted in total number of approximately 24.5 million elements and an average element quality of 0.69 (quality index: skewness). Figure 2 depicts the meshed model in a coronal cut with an enlarged view of the dipole.

We performed four simulation studies. In each study, we applied an impressed current of 25 µA in total to the electrical circuit network. This resulted in a dipole strength of 250 nAm (total current multiplied with distance between poles). The dipole strength corresponded to values reported in clinical studies [4]. Simulation study I: We integrated the copper and platinum wires in the dipole model, this model corresponds to the real current dipole model. Simulation study II: We neglected the copper wires but integrated the platinum wires in the dipole model. Simulation study III: We neglected both the copper and platinum wires in the dipole model. Depending on the simulation study, we adapted the electric conductivity of the neglected domain to $1 \cdot 10^{-13}$ S/m. Thus, the neglected domains had an electric conductivity equivalent to the dipole housing. Further, we changed the terminal of the applied current to the most distant boundary of the used metal domain. Simulation study IV: We neglected the lower section (separated by the dotted line in Figure 1) of the housing rod by setting this domain to 0.33 S/m. Otherwise study IV is identical to study III. Study IV allows to determine the distortions caused by the housing rod. The equivalent circuit diagram shows this methodology for studies I to IV (Figure 3). The active feeding areas for the impressed current per study are shown in Figure 1.

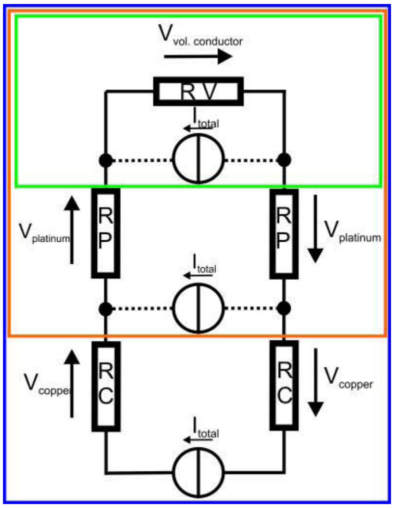

Figure 3: Equivalent circuit diagram of the dipole simulation studies. The rectangles represent the networks considered in study I (blue), study II (orange) and study III/IV (green). The resistors represent the contribution of copper wire (RC), platinum wire (RP) and volume conductor (RV).

In Comsol®, we used the physics of electric currents and each study was solved by the generalize minimal residual method in a stationary approach. Table 1 depicts the used electrical conductivities for all domains in the model.

We determined the electric potential distribution on the surface of the homogenous volume conductor and on the surface of the testing sphere with 100 mm diameter similar to EEG measurements. We calculated the difference of the electric potential on the surface in each simulated node (256755 nodes for the homogenous volume conductor and 7762 nodes for the testing sphere) between the four simulation studies. This allowed to quantify the distortions caused by the platinum and copper wires and the housing rod.

Table 1: Electrical conductivity of domains

Domain	Electrical conductivity in S/m
Volume conductor	0.33
Platinum wire	$10.4\cdot10^{6}$
Copper wire	$59.9\cdot10^{6}$
Dipole housing	$1\cdot10^{-13}$

3 Results

All four FEM simulations showed the expected dipolar distribution of the electric potential in the volume conductor. Figure 4 a depicts the calculated potential distribution (limited scale range between -10 µV and 10 µV) of the simulation study I in the volume conductor. Compared to the case of an ideal dipole in a homogeneous volume conductor, the equipotential lines of the electric potential inside the dipole housing were distorted around the copper and platinum wires as well as along the z-axis in the dipole housing rod, shown in Figure 4 b (full scale range). The electric potential was similarly distorted inside the dipole housing also in simulation study II and III as shown in the inset of Figure 4 b. The distortion around the copper wires was not present in study II and III. The electric potential was not distorted by the dipole housing rod in study IV (Figure 4 b).

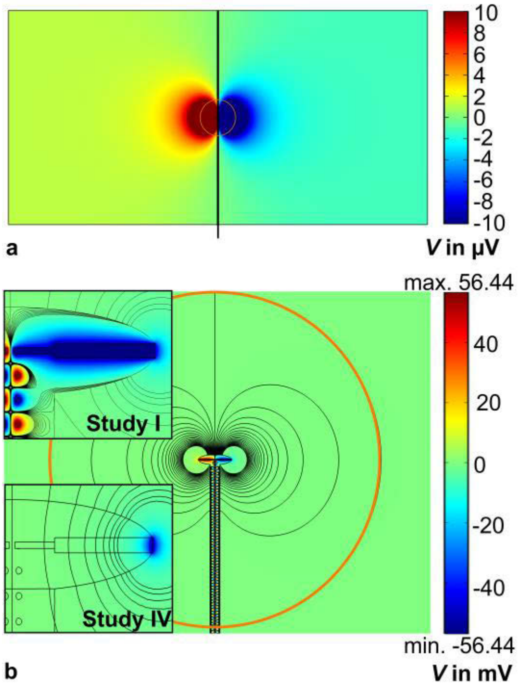

Figure 4: Electric potential distribution of simulation study I in the central xy-plane (equal to Figure 2). a) calculated electric potential (limited scale range -10 to 10 µV) in the volume conductor and the zero potential line marked in black. b) magnification of the current dipole with added equipotential lines (black lines) in a limited range of -1 mV to 1 mV (step width 0.05 mV). The testing sphere is indicated in orange. The insets show the magnification of the negative pole with added equipotential lines in a limited range of -4 mV to 4 mV (step width 0.5 mV) for study I and study IV. The dipole housing domain is shown in both insets.

The difference between study I (reference values) and study II was 5.80 ppm on average for the surface of the homogenous volume conductor. The difference between study I and study III was 6.38 ppm on average. Study I compared with study IV resulted in a difference of 2.85 %. The difference at the surface of the testing sphere was 5.80 ppm comparing studies I and II and 6.36 ppm comparing studies I and III. Comparison of studies I and IV resulted in 7.30 % average difference.

Figure 5 depicts the absolute difference plot of simulation study I and III as an example. The highest difference was found inside the dipole housing (up to 30 mV) as well as inside the copper and platinum wires (up to 57 mV) as expected. The absolute difference was in the range of nanovolt near the testing sphere and below to the outside of volume conductor.

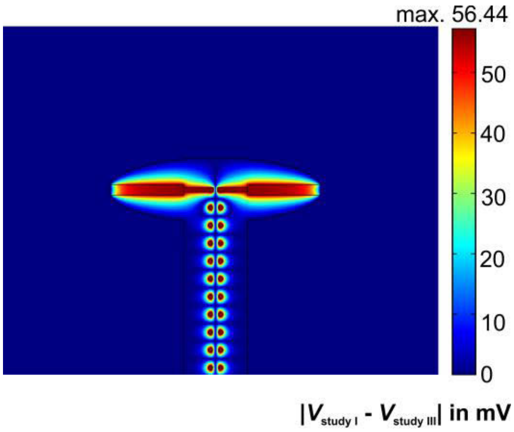

Figure 5: Difference plot of simulation |study I - study III| in the central xy-plane (equal to Figure 2).

The voltage across the resistors RC, RP and RV (Figure 3) was calculated to be 7.36 μV (V_{copper}) across RC, 42.08 nV (V_{platin}) across RP and 112.87 mV ($V_{vol. conductor}$) across RV.

4 Discussion

We performed FEM simulation studies to analyse the distortion of the electric potential originating from connecting wires and the housing rod for a current dipole setup used in physical phantoms. All simulation studies showed a typical dipolar distribution of the electric potential as also observed in previous phantom studies [1]–[3], [5].

Most significantly, the electric potential distribution was distorted by the housing rod, where we found an average change of 7.3 % on a spherical surface surrounding the dipole with a diameter of 100 mm. Consequently, modelling of physical phantoms for EEG measurements using the newly established dipole setup should consider the housing rod of the dipole. We expect a similar influence for the top part of the dipole housing. The distortions might be reduced when using smaller dipole housing rods.

We quantified the distortion of the electric potential caused by the connecting wires of current dipole. These distortions are in general small both at 100 mm and at 1000 mm distance from the dipole. Consequently, modelling related to physical phantom studies using the newly established dipoles will be influenced only slightly. The averaged values at the two different evaluation surfaces differed slightly, which could be caused by the different number of nodes considered for averaging and possible inaccuracies of the mesh.

For EEG phantom studies, we suggest to neglect the influence of the wires in modelling if the required accuracy is less than the effects reported here. Otherwise, modelling the platinum wires and neglecting the copper wires might be sufficient, which has the advantage of a faster modelling and solution time (in comparison to the model also incorporating the copper wires) and allows to consider the major part of the distortion of the connecting wires.

We established a comparative modelling methodology, which can be used for other current dipoles types and in various physical phantom models. Future work will include further simulations and measurements in physical phantoms.

Author Statement

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