Short Communication

Links between brain cortical regions and EEG recording sites derived from forward modelling

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Abstract. Electroencephalography (EEG) provides no direct link between electrode positions and underlying signal generators. Inferences based on spatial proximity between scalp positions and cortical structures are not reliable. More accurate source localization is obtained by solving both the forward and the inverse problem, but is technically challenging. In this paper, we provide a reference table of correspondence between EEG sensors and cortical anatomical regions based on a realistic head model. We also present a universal algorithm to compute the solution by using a forward model to determine the sensitivity for electrodes of any defined electrode positioning system and cortical anatomical parcellation.

Key words: Electroencephalography — Source localization — Electrode positions — Forward model — Brain parcellation

The signal obtained using electroencephalography (EEG) from each electrode provides no direct reference to its sources, yet this insight might considerably enhance the information provided by EEG recordings. Assumptions about the location of EEG sources can be made by establishing the correspondence of individual electrodes to the neuronal activity within the brain based on either spatial *proximity* or *sensitivity* derived from a forward model. Earlier studies report only proximity-based correspondence (Giacometti et al. 2004; Okamoto et al. 2004; Koessler et al. 2009), but it has been argued that validity of such approaches for constructing robust solutions is limited (Cohen 2014). With a high number of electrodes, EEG source localisation based on solving both the forward and the inverse problem may be carried out to reveal the origins of electrical activity measured on the scalp (Michel et al. 2004; Hallez et al. 2007). However, this procedure is computationally demanding and therefore not well suited for fast and efficient initial or exploratory analyses. For such purposes, the process could be simplified and accelerated by computing a general solution for a given electrode positioning system.

In this work, our aim is to provide the user with accurate estimates of loci of the underlying neural generators of EEG without the need to conduct an extensive source reconstruction analysis. Based on an average cortical anatomy (Fonov et al. 2009), we present reference tables of the correspondence between electrode recording sites and brain cortical regions for the International 10-10 positioning system (Chatrian et al. 1985) as well as the equidistant EasyCap M10 montage (EASY-CAP GmbH, Herrsching, Germany). We also present a general algorithm, which is easily adjustable to a particular electrode positioning system, subject anatomy, conductivity model, etc.

The algorithm was implemented in Matlab and is provided in the Supplementary Material. It relies on the Brainstorm toolbox (Tadel et al. 2011) and its selected components and templates. The process begins by importing a boundary element method (BEM) surfaces (scalp, outer

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skull, inner skull, cortical surface) based on the default ICBM (International Consortium for Brain Mapping) 152 anatomy (Fonov et al. 2009), a non-linear average of 152 subjects which includes FreeSurfer (Fischl 2012) surface-based atlases, followed by importing the channel file of co-registered EEG sensor positions directly from Brainstorm (see Fig. 1 for a schematic description). In the next step, we use Brainstorm's internal call to Open-MEEG (Gramfort et al. 2010) to compute the forward model with the cortical surface set as the source space. This process is the only computationally demanding part of the algorithm, taking up minutes to tens of minutes on a modern CPU depending on the complexity of the model. The cortical mesh composed of ~15,000 vertices, the channel file, and the forward model solution are then exported to the workspace as variables. In order to obtain sensitivity values for each electrode and cortical grid vertex combination, we first call a built-in function to convert the unconstrained gain matrix to an orientation-constrained model in which the orientation of each dipole is normal to the cortical surface. We then compute the absolute values of each element in the gain matrix and find the maximum value (amplitude) and its index (electrode) in each column (vertex). The channels with maximum sensitivity for each vertex are subsequently transformed

into Brainstorm-specific structure called *scout*, mainly to utilise its plotting features, e.g. to draw a sensitivity map overlaying the cortex. The scout file is essentially a Matlab *struct* which groups vertices referenced by their indices and maintains their relationship to a set of areas, regions of interest, or in this case electrode names and positions. In the final step, we export two cortical structural parcellations of the default ICBM 152 brain anatomy, namely *Destrieux* (Destrieux et al. 2010; consisting of 148 regions) and *Mindboggle* (Klein and Hirsch 2005; consisting of 62 regions), to the workspace and determine the intersections between the sets of vertices of the highest sensitivity for each electrode (in the following referred to as "vertex sets") and the anatomical regions as defined by the two atlases. The result is a reference table listing the electrodes and the corresponding anatomical regions ordered by the extent of their intersections, or, in other words, the strength of their linkage. We set an arbitrary threshold of intersection at 10% to keep the output reasonably concise and significant.

The algorithm was tested with a variety of positioning systems and found to be universally applicable. The only computationally demanding step is the calculation of the forward model handled by an external toolbox, which can take even hours if one chooses a cortical model with too many vertices. Since the imported BEM surfaces based on the default anatomy include a high-resolution version of the cortex composed of about 23 times the number of vertices as the normal-resolution cortex that we used, we decided to see whether the increase in resolution significantly affects the result. Upon qualitative inspection, we found that this was not the case and this approach therefore did not justify the major time and memory penalty.

For the 10-10 system, we found that each electrode yielded maximum sensitivity for at least 22 (*Cb1, Cb2*) and at most 594 (*AF3*) vertices, 238.1 ± 120.7 vertices on average. For the *Mindboggle* atlas, the minimum intersection between the vertex set and the corresponding cortical region of the strongest linkage was 11.8% (*Cz* with *precuneus R*) and the maximum was 54.5% (*Cb2* with *lateraloccipital R*), 26.0 ± 9.5% on average. We note that for medial electrodes, this number is effectively split between the hemispheres such as in the case of *Fz* which corresponds to *superiorfrontal R* (33.2%) and *superiorfrontal L* (21%), thus 54.2% combined. A union of two regions of the strongest linkage yielded a mean intersection of 43.5 ± 11.9% (min = 22.9%, max = 72.7%) and for a union of three regions this value was 56.0 ± 13.9% (min = 32.7%, max = 90.9%). In other words, the average intersection between location of vertices that maximally contribute to the EEG signal at a given electrode of this montage and the three mostly involved anatomical cortical regions is 56%. With three regions included, more than 80% intersection was found for 5 electrodes: AF10, F9, F10, CP1, and CP2. The reference tables are provided in the Supplementary Material, which also
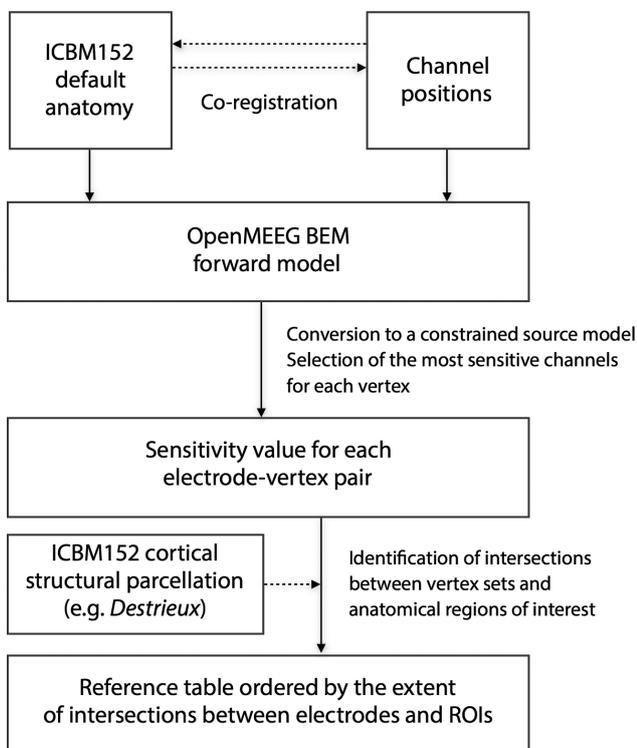

Figure 1. Schematic description of the procedure to obtain the reference tables.

contains the analyses using the *Destrieux* atlas and the results for the M10 montage.

Results for both atlases indicate that some sensors are sensitive to specific cortical areas, for example the signal measured by the electrodes *AF9* (in the 10-10 system) or *61* (in the M10 system) may be considered highly sensitive to the left orbital gyrus. On the other hand, electrodes such as *Fpz* (10-10) or *20* (M10) appear to be sensitive to multiple areas and thus inferences about the sources of the signals from these sensors should be done with more caution. Our results support the findings of Koessler et al. (2009) who reported that the specificity of individual electrodes varies greatly across the cortex. However, even if there is no strong intersection with a given structural region, we found that it is usually sufficient to consider the next one or two regions to achieve a correspondence of more than 40–60%.

To obtain the sensitivity parcellation for the chosen positioning system, we used effectively the same process as Giacometti et al. (2014), but instead of constructing the table of correspondence based on the intersection between regions of structural parcellation and electrode proximity, we used electrode sensitivity, which we believe yields a more accurate solution. Although Giacometti et al. (2014) claim there is little difference between sensitivity- and proximity-based solutions, this only applies to positioning systems with few electrodes such as the International 10-20 system containing 21 electrodes (Jasper 1958). Since we are able to compute a general sensitivity-based solution, we see no reason to resort to proximity-based solutions.

The method presented in our paper may be used to aid experimental planning and preliminary interpretation of EEG data such as the results of topographic mapping. The use of a general sensitivity-based solution may also be advantageous in the process of choosing an electrode layout, especially when the user focuses on a given region of interest, to gather preliminary evidence during early stages of an experiment, or in studies using transcranial magnetic stimulation or near-infrared spectroscopic imaging (Okamoto et al. 2004; Koessler et al. 2009). Future investigations should implement quantitative analyses to express the accuracy of the general solution numerically, for example based on simulated activity and individual subject anatomy.

The algorithm, reference tables, analyses using the *Destrieux* atlas, the results for the M10 montage, and additional relevant information are provided as a supplement to this paper. This information is also available at *http://brain.sav.sk/eegchan2src*.

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1   Additional results

The analysis outlined in the results section of the paper was also performed using the *Destrieux* atlas. The maximum sensitivity figures at each electrode were the same since this measure is independent on the atlas. The minimum intersection between the vertex set and the corresponding region of the greatest linkage was 8.6 % (C1; *left superior parietal lobule*), the maximum was 37.5 % (AF9; *left orbital gyrus*), 17.5 ± 6.3 % on average. When we included two regions of the strongest linkage, the mean intersection was 29.8 ± 9.2 % (min = 15.9 %, max = 59.1 %), for three areas the mean intersection was 39.7 ± 11.6 % (min = 23.2 %, max = 77.3 %). This percentage is lower than for *Mindboggle* likely because the number of anatomical regions (and thus location specificity) is lower for the *Mindboggle* than for the *Destrieux* atlas.

For the *M10* montage, we found that each electrode yielded maximum sensitivity for at least 8 (sensor 56) and at most 528 (sensor 24) vertices, 231.6 ± 114.0 vertices on average. For the *Mindboggle* atlas, the minimum intersection between the vertex set and the corresponding cortical region of the greatest linkage was 9.7 % (sensor 6; *precentral L*) and the maximum was 52.6 % (sensor 55; *lateraloccipital R*), 26.6 ± 10.2 % on average. Including two areas of the strongest linkage yielded a mean of 44.5 ± 14.2 % (min = 17.8 %, max = 89.4 %), and including three regions, this value was 57.4 ± 16.0 % (min = 25.1 %, max = 100 %, more than 80 % for 6 electrodes: 2, 53, 55, 56, 57, and 60).

Finally, we performed the same analysis using the *M10* montage also for the *Destrieux* atlas. The minimum intersection between the vertex set and the corresponding area of the strongest linkage was 13.3 % (sensor 20; *right superior frontal gyrus*), the maximum was 74.4 % (sensor 61; *left orbital gyrus*), 31.6 ± 15.2 % on average. Including two or three areas of the strongest linkage resulted in a mean intersection of 50.3 ± 18.5 % (min = 24.1 %, max = 100 %) or 62.7 ± 17.3 % (min = 33.1%, max = 100 %) respectively.

2   Script *eegchan2src.m* v1.0

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% eegchan2src.m
% version 1.0
% 24 August 2017
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This script for MATLAB relies on Brainstorm and OpenMEEG:
% Tadel F, Baillet S, Mosher JC, Pantazis D, Leahy RM (2011)
% Brainstorm: A User-Friendly Application for MEG/EEG Analysis
% Computational Intelligence and Neuroscience, vol. 2011, ID 879716
% http://neuroimage.usc.edu/brainstorm/
% Gramfort A, Papadopoulo T, Olivi E, Clerc M (2010)
% OpenMEEG: opensource software for quasistatic bioelectromagnetics
% Biomedical engineering online, 9(1), 45
% http://openmeeg.github.io
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 1    EXPORT FROM BRAINSTORM AND INITIAL PREPARATION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
load('cortex.mat') % default anatomy (ICBM152) cortex previously exported
                   % from Brainstorm
load('bem.mat') % OpenMEEG BEM previously exported from BrainStorm

% convert the gain matrix to a constrained source model
% (ref. Brainstorm support thread 918)
gain_constrained = bst_gain_orient(bem.Gain, bem.GridOrient);
clear bem

% remove non-EEG channels (if present)
```