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Surface Laplacians (SL) and phase properties of EEG rhythms: Simulated generators in a volume-conduction model

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ABSTRACT

Surface Laplacian (SL) methods offer advantages in spectral analysis owing to the well-known implications of volume conduction. Although recognition of the superiority of SL over reference-dependent measures is widespread, well-reasoned cautions have precluded their universal adoption. Notably, the expected selectivity of SL for superficial rather than deep generators has relegated SL to the role of an add-on to conventional analyses, rather than as an independent area of inquiry, despite empirical findings supporting the consistency and replicability of physiological effects of interest. It has also been reasoned that the contrast-enhancing effects of SL necessarily make it insensitive to broadly distributed generators, including those suspected for oscillatory rhythms such as EEG alpha. These concerns are further exacerbated for phase-sensitive measures (e.g., phase-locking, coherence), where key features of physiological generators have yet to be evaluated. While the neuronal generators of empirically-derived EEG measures cannot be precisely known due to the inverse problem, simple dipole generator configurations can be simulated using a 4-sphere head model and linearly combined. We simulated subdural and deep generators and distributed dipole layers using sine and cosine waveforms, quantified at 67-scalp sites corresponding to those used in previous research. Reference-dependent (nose, average, mastoids reference) EEG and corresponding SL topographies were used to probe signal fidelity in the topography of the measured amplitude spectra, phase and coherence of sinusoidal stimuli at and between "active" recording sites. SL consistently outperformed the conventional EEG measures, indicating that continued reluctance by the research community is unfounded.

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1. Introduction

Concerns have frequently been expressed about the fidelity of EEG measures for representing phase-relationships between electrodes recorded in a scalp montage (Biggins et al., 1991, 1992; Pascual-Marqui, 1993; Nunez et al., 1997; Qin et al., 2010). This concern is relevant for oscillatory activity, because volume conduction combines nearby rhythms that share a common frequency. The resulting composite waveforms at nearby sites may become indistinguishable, being reduced to spectral components by Fourier's theorem, their phases being the weighted sums of equivalent sine and cosine waves. Although these properties apply to all EEG activity, the persistence of oscillatory activity exacerbates the problem of attributing activity to underlying neuronal generators. In contrast to time-locked, event-related paradigms, oscillatory activity at different recording sites cannot be disentangled strictly on the basis of the observed timing (phase) of the signal. Moreover, the likelihood that oscillatory activity may be picked up by the recording reference itself, even for a common recording reference (Fein et al., 1988), emphasizes the deleterious effects of volume conduction on any reference-dependent recording strategy. Guevara et al. (2005) have also indicated that the amplitude of a signal can affect synchrony measures when a common average reference is used. In this regard, a surface Laplacian offers a clear advantage for both of these shortcomings: it is a reference-independent method that eliminates or substantially reduces volume conduction.

Nunez et al. (1997, 1999, 2001, 2015) have consistently supported the value of the surface Laplacian for EEG investigations, including for oscillatory activity. With equal consistency, they have urged caution based on concerns over the loss of information corresponding to the spatial high-pass properties of the Laplacian (i.e., the two integration constants removed by the Laplacian operator from the volume conduction equation; but cf. Nicholson, 1973, for field potential as a weighted integral of volume source current density). The recommendation is therefore to rely on a multi-resolutional approach whereby reference-dependent potential difference topographies (e.g., average reference) are used to measure activity having a broad spatial scale (i.e., distributed activity of low spatial frequency), while the corresponding "high-resolution EEG" topographies are identified and localized by the Laplacian (Nunez and Srinivasan, 2006).

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Unfortunately, these conservative cautions may have led to an unintended consequence in the field: investigators who are not motivated to multiply their analyses and appropriately interpret any differences between methods have been deterred from further pursuing the use of a surface Laplacian as an analysis strategy, particularly at a time when the computational methods were uncommon (Nunez et al., 1999).

We likewise admit that despite our own enthusiasm for the Laplacian (Kayser and Tenke, 2009), we have also routinely repeated the concern about the possible implications of the depth of the empirical generators responsible for our findings, despite our observations that different phenomena had been sufficiently and reliably represented using our methods and parameters (Kayser and Tenke, 2006a; Tenke and Kayser, 2012). Likewise, in recognition of the high-pass properties of the Laplacian, we have also expressed concern about the implications of spatial scale when applied to broadly-distributed generators in surface cortex, particularly in relation to ongoing oscillatory activity. Not surprisingly, reluctance continues to be expressed about the appropriateness of a surface Laplacian for the study oscillatory activity (e.g., Thatcher, 2012).

This study sought to address the question of whether a surface Laplacian can effectively represent broadly distributed oscillatory activity. Oscillatory data were simulated at the scalp in the expanded 10–20 recording system (Pivik et al., 1993) using a forward solution from fixed intracranial dipole generators positioned at locations within a four-shell spherical head (Berg, 2006). Three models were successively constructed to identify and describe the impact of volume conduction, spatial scale, and Laplacian spline flexibility (Perrin et al., 1989) on the capacity of CSD to represent oscillatory activity, particularly in comparison to reference-dependent field potential measures. Model 1 consisted of a pair of isolated dipoles positioned at deep or superficial brain locations directly below one central and one parietal location. The purpose of this simulation was introductory and heuristic, and intended to illustrate the well-known impact of volume conduction and the localizing capacity of CSD. Model 1 also provided a well understood starting point for introducing the impact of these transformations on the measured phase of an oscillatory generator, since they parallel properties of amplitude. Model 2 was an extension of Model 1 in which shallow dipoles were distributed below eight adjacent parietal and occipitoparietal sites to emulate the minimal spatial characteristics of posterior condition-dependent alpha (Tenke and Kayser, 2005; Tenke et al., 2011). Model 3 further expanded on this regional simulation to include all posterior (30/67) scalp locations, with superficial noise added to allow the consideration of standard coherence (i.e., phase stability) measures. The validity of field potential and surface Laplacian topographies resulting from these modeled sources was determined by visually comparing amplitude and phase maps as well as by computing amplitude accuracy estimates for each site in relation to model expectations.

2. Methods

2.1. Simulations

While an intracranial volume-conductor model must reflect the laminar structure of the tissue in the distribution of sources and sinks (Tenke et al., 1993), these micro-scale generators are resolved as dipoles at the coarser scale of the scalp recorded EEG, and correspond well with the surface-to-depth polarity inversion characteristic of active cortical tissue (e.g. Lorente de No, 1947). The resolution of these radial currents completely identifies the minimal properties required of any generator inferred from the scalp topography (Tenke and Kayser, 2012). In the following simulations, generators were assumed to be quasistatic (Freeman and Nicholson, 1975; Nunez and Srinivasan, 2006; Tenke et al., 1993; Tenke and Kayser, 2012).

A spherical four-shell head forward volume-conduction model was used to simulate the scalp topographies corresponding to the locations of isolated dipole generators (Berg, 2006). The outer shell had an 85 mm radius (scalp = 6 mm, conductivity = 0.33 mho/m; bone = 7 mm, 0.0042 mho/m; CSF = 1 mm, 1 mho/m). The brain surface in this model was therefore at a 71 mm radius (brain conductivity = 0.33 mho/m). Electrode placements were defined for a 67-channel scalp montage (cf. Tenke et al., 2010, 2011) using the extended 10–20 system (Jurcak et al., 2007; cf. CSD toolbox tutorial, Kayser, 2009). Radial dipole generators were created for a series of Dipole Simulator models (Berg, 2006) at superficial (2 mm subdural) or deep (15 mm subdural) placements. As an example, Fig. 1 illustrates the placement for dipoles located below electrode C4.

For each dipole, a forward solution was computed for a unit amplitude generator at a single time point (10 nAm source waveform; 3-point triangle waveform). The resulting field potential topographies were then saved as a topography vector using a fixed reference scheme (nose reference). These vectors were applied to sinusoidal source waveforms (2 s × 256 samples/s; 10 Hz sine or cosine, as required) in Matlab for each of the dipoles required in a specific generator model (as detailed below). Because volume conduction is itself linear, the final scalp potential topographies for multiple generators were constructed as the sum of the individual dipole topographies, resulting in a single simulated EEG scalp record (67 channels × 512 points; nose reference [NR]).

By virtue of these methods, all of the imposed and measured signals are sinusoidal waveforms, each with a characteristic amplitude and phase that may be directly measured from the timecourse of the signal. These temporal signals may then be linearly transformed to observe the impact of rereferencing and SL transformations, which also yield sinusoidal waveforms with identifiable amplitudes and phases. However, equivalent measures of amplitude and phase may be quantified directly from their complex Fourier transform pairs (e.g., Smith, 1997). Likewise, rereferencing and SL transformations may be performed following, rather than preceding, the FFT owing to the fact that the complex FFT is a reversible linear transformation.[1]

2.2. Generator models

2.2.1. Model 1

The first model was intended to establish the properties of individual dipolar oscillatory generators with sufficient separation to allow their unambiguous separation by different field potential and surface Laplacian transformations. It consisted of superficial cortical dipoles at depths corresponding to mid-to-deep laminae of superficial cortex (i.e., 2 mm below surface of dura). Two standard 10–20 sites were selected corresponding to focal generators at right central (cosine at site C4) and right parietal (sine at site P4) scalp locations, providing a comparison of the amplitude and phase at ‘active’ (i.e., C4, P4) sites, and their spread due to volume conduction at ‘inactive’ sites (all other 65 sites of the EEG montage). Likewise, an identical pair of dipoles was placed at deep cortex locations directly under these scalp sites, 15 mm below dura.

2.2.2. Model 2

The second model probed the adequacy of the same transformations to separate and describe the amplitude and phase properties of contiguous generator regions at posterior areas of one hemisphere. It consisted of a series of superficial cosine generators distributed below six extended 10–20 scalp sites in the right posterior cortex (Pz, POz, P2, P4, PO4, P6), and sines below two adjacent scalp sites (P8, PO8).

2.2.3. Model 3

The third model was constructed to approximate minimal properties of posterior condition-dependent EEG alpha. Superficial generator regions were considerably larger, with dipoles distributed below 30-posterior electrodes spanning postcentral sites in both hemispheres.

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[1] It must be emphasized that while the complex FFT is a reversible linear transformation, a power or amplitude spectrum is not (cf Tenke and Kayser, 2005).

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