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On the benefits of using surface Laplacian (Current Source Density) methodology in electrophysiology

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The surface Laplacian (SL), also commonly referred to as current source density (CSD) or scalp current density (SCD), collectively denotes a group of mathematical algorithms that transform the scalp-recorded EEG into estimates of radial current flow at scalp. The sign of these estimates directly reflects the direction of the radial currents underlying an EEG topography, with positive values representing current flow from the brain towards the scalp (called sources), and negative values representing current flow from the scalp into the brain (called sinks; e.g., Nunez and Srinivasan, 2006). These two-dimensional estimates do not directly inform where in the three-dimensional brain the corresponding neuronal activity originates, a characteristic they have in common with the scalp-recorded EEG. However, they offer several critical advantages over surface potentials and over popular algorithms that try to infer the underlying neuronal brain sources in 3-D space (collectively referred to as inverse solutions). First, unlike surface potentials, SL estimates are reference-free, meaning that any EEG recording reference scheme will render the same SL estimates with unambiguous polarity. Second, compared to surface potentials, SL estimates have a sharper or more distinct topography, effectively reducing the negative impact of volume conduction, which widely blurs the scalp-recorded EEG signal. In this manner, SL enhances the spatial resolution (or specificity) of the EEG signal. Third, compared to inverse solutions, SL algorithms do not require any additional assumptions about functional neuroanatomy, tissue conductivity, brain volume, and geometry, number, orientation or independence of neuronal generators. All of these favorable characteristics of the SL have been known for decades (Hjorth, 1975, 1980; Nunez, 1981; Nunez and Pilgreen, 1991; Law et al., 1993a, 1993b; Pascual-Marqui et al., 1988). The SL has been carefully investigated in comparative simulation studies (Babiloni et al., 1995, 1996; Nunez et al., 1994), its advantages and disadvantages have been discussed controversially (Biggins et al., 1991, 1992; Nunez and Westdorp, 1994; Perrin, 1992; Perrin et al., 1987), and many researchers have employed SL

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methods for clinical applications (e.g., Cincotti et al., 2004; McFarland, 2015; see review by Kamarajan et al., 2015) and basic research questions (e.g., Burle et al., 2015; Cohen, 2015; Giard et al., 2014; Kayser and Tenke, 2015b; Rangel-Gomez et al., 2015; Vidal et al., 2015) alike.

If the topic of SL transformation of surface potentials has already been abundantly treated in the literature, why is a special issue on SL methods needed? What is the point of inviting contributions that merely showcase research exploiting the favorable properties of the CSD transform, particularly when directly compared to the conventional approach of using surface potentials?

There are several reasons that motivated this special issue. First and foremost, despite a broad recognition that a SL transform may be useful, the general view is that SL is applicable only to certain data scenarios, and even then only as an add-on or complement to the analysis of surface potentials. To counter this perception, the reports included in this special issue encompass a wide range of applications, including stimulus- and response-locked event-related potentials (ERPs) concerned with component topography and/or peak identification (Burle et al., 2015; Cohen, 2015; Kayser and Tenke, 2015b; Rangel-Gomez et al., 2015; Vidal et al., 2015), quantification of EEG spectra (Tenke et al., 2015), time-frequency analysis (Cohen, 2015; Kayser and Tenke, 2015b), removal of muscle-related artifacts in the EEG signal (Fitzgibbon et al., 2015), and brain-computer interface (BCI) research (McFarland, 2015). Despite these different contexts, all reports demonstrate the general applicability of SL measures, and most reveal their superiority over surface potentials. This sentiment is also expressed by Kamarajan et al. (2015) after reviewing the literature of SL studies conducted with neuropsychiatric populations.

Secondly, more recent developments for data analytic approaches, including not only inverse models but many sophisticated multivariate data reduction techniques, have paradoxically been embraced to a far greater extent than SL methods by the EEG research community, with more elaborate proposals emerging on an ongoing basis. Such an assiduous drive to innovation and trust in novel techniques seems strangely at odds with the tendency to ignore or reject a conservative and proven technique like SL, the full potential of which has yet to be determined. Carvalhaes and de Barros (2015) provide a comprehensive and mathematically-detailed account of the various SL approximation methods and their theoretical and computational facets, weighing in depth the pros and cons of frequently-used finite difference and spline techniques. This contribution complements other sources that discuss the relationship of surface Laplacian and the dura-surface potential (Nunez and Srinivasan, 2006) or intracranial and cortical current generators (Tenke and Kayser, 2012). However, it is unique in its scope of comparing existing SL methods and for offering practical suggestions that may lead to further improvements. Despite its formula-heavy content, their review is notably targeted to neuroscientists well-versed in EEG rather than to an expert biomedical engineering audience, making this contribution well-suited to the broad readership of this journal.

Third, while the shortcomings of reference-dependent surface potentials are widely acknowledged in the field, their direct implications are surprisingly not recognized. There appears to be a universal belief that as long as the same EEG reference scheme is applied consistently, reference-dependence is not a problem for the interpretation of an EEG data set, a notion even expressed during the peer review of this special issue. Kayser and Tenke (2015a) revisit the interpretational pitfalls that arise from volume conduction and the arbitrary choice of an EEG reference and explain in an intuitive fashion how a surface Laplacian transform resolves these ambiguities. Burle et al. (2015) highlight how volume conduction not only reduces the spatial resolution of field potential measures, but their temporal resolution as well, that is, the reliable representation of generator activity over time as inferred from prominent deflections in the ERP waveforms. Employing targeted forward simulations and selected examples from their previous work, the authors demonstrate convincingly that ERP research focused on ERP waveforms at selected scalp sites will yield misestimates of the timing of electrophysiological events that are of crucial importance to understanding cognitive functions. In contrast, a SL transform closely maintains the temporal properties of the underlying neuronal generator signal. Vidal et al. (2015) outline how the use of surface potentials may severely limit conclusions drawn from several cognitive paradigms, and may even result in erroneous data interpretation. The authors dissect the implicit and explicit assumptions generally made by the ERP research community to render deductions about functional processes, which are often exposed as fiction when analyzing the same SL-transformed data.

Fourth, several limitations of the SL transform have been stated, most notably the alleged insensitivity of the transformation to deep generator sources and/or broadly distributed dipole layers. This concern is directly addressed by Tenke and Kayser (2015) who detail EEG oscillations and phase in a simulation study using focal deep and shallow posterior generator sources as well as distributed posterior dipole layers. Contrary to what may have been expected given this objection, the comparison of reference-dependent EEG and corresponding SL topographies for amplitude, phase and coherence revealed a higher signal fidelity of SL estimates for both deep and distributed sources. As these simulations were modeled on posterior alpha rhythms, it may come as no surprise that Tenke et al. (2015) report similar results with real EEG data for several posterior alpha measures obtained during rest and task performance. Taking a pragmatic stance, Kayser and Tenke (2015a) compare a wide range of frequently-studied temporal and spectral ERP/EEG components to directly address and reject the common reservations against the universal use of SL. Their key argument relies on the versatility of the SL transform, which can be tailored to the targeted clinical or research objective by altering spline flexibility and regularization as key parameters of the SL algorithm, thereby maintaining its crucial reference-free property. A similar pragmatic rationale underlies the contribution of McFarland (2015), who discusses how SL spatial filtering can effectively reduce spatial noise and thereby enhance the identification of sensorimotor rhythm activity sources employed by BCI systems. The comparison of nearest neighbor versus next-to-nearest neighbor SL estimation revealed different favorable properties for either implementation, rendering both SL algorithms helpful for different signal aspects.

While the SL transformation has been recognized for its spatial filtering characteristics, multivariate data decomposition techniques, including principal components analysis (PCA) and independent components analysis (ICA), have been employed for accomplishing similar or related objectives. However, these multivariate approaches are not mutually exclusive of the SL transformation, as both can be successfully combined to take full advantage of their mutual strengths (e.g., Kayser and Tenke, 2006, 2015b). Rangel-Gomez et al. (2015) use SL and ICA methods to separate overlapping stimulus-related activity, both in space and time, during a stop- versus change-signal response paradigm to disentangle parietal and frontal sources involved in response inhibition. Fitzgibbon et al. (2015), employing EEG recordings from participants in the presence and absence of electromyogram (EMG) contamination due to pharmacologically-induced paralysis, demonstrate how the sequential application of ICA and SL can remove muscle-related artifacts from the EEG signal across the entire scalp and over a wide spectral range. Because EMG artifacts are not restricted to high frequencies above 60 Hz but also affect the spectral range of alpha and beta rhythms, this combined approach holds great promise for improving EEG and ERP signals of interest that are dominated by low-frequency activity (as most are).

A decisive strategy for evaluating costs and benefits of the SL transform is by means of direct comparison of known and specific effects. Cohen (2015) and Kayser and Tenke (2015b) employ real EEG data recorded during well-studied ERP paradigms for a targeted comparison of surface potentials converted to popular reference schemes and corresponding CSD estimates derived from spherical splines (Perrin et al., 1989). The beauty of these paradigms is that the underlying neuronal generators render a rather focal scalp activation, both in time and space, yielding a response-locked error-related negativity (ERN; Cohen, 2015) or a stimulus-locked N1pc contralateral to the stimulated hemifield (Kayser and Tenke, 2015b). Both reports include time-frequency measures and both assess how a reduced signal-to-noise ratio affects the stability of these measures undergoing these different spatial transformations. Together, these reports strongly suggest that CSD estimates compare favorably to surface potentials under these experimental conditions. While the SL superiority was remarkable in the Kayser and Tenke (2015b) study, a more complex picture is reported by Cohen (2015), who also studied frequency-specific inter-electrode connectivity. Clearly, more investigative work is required for the applicability of SL estimates for EEG oscillations, phase and coherence, but the simulations by Tenke and Kayser (2015) strongly suggest that SL estimates provide more accurate representations of oscillating sources than surface potentials for scenarios including deep and shallow as well as focal and distributed neuronal generators. Interestingly, SL methods have recently gained considerable use for studies of oscillatory EEG activity, a trend that is not evident for other areas of EEG and ERP research where the analysis of reference-dependent surface potentials are rarely challenged, including studies with psychiatric populations (Kamarajan et al., 2015).

In a joint symposium at the 2009 EPIC XV meeting held together with the Marseille research group of Boris Burle, Thierry Hasbroucq and Franck Vidal (Kayser and Tenke, 2009), we revisited the merits of the surface Laplacian. The feedback we received at that time suggested both a keen interest in these methods as well as the need for the field to become more familiar with them. This prompted us to provide a Matlab-based CSD toolbox (available at http://psychophysiology.cpmc.columbia.edu/Software/CSDtoolbox) as a convenient means to integrate the SL transform into an existing data processing stream and analysis pipeline, which has been increasingly used ever since. Our conclusions then were as valid and timely as they are now: CSD a.k.a. SL deserves a second look and an earnest opportunity to become mainstream for EEG/ERP research, which may ultimately alter the current practice of preferential analyzing reference-dependent surface potentials (Kayser and Tenke, 2015a). For EEG/ERP researchers to become globally familiar and comfortable enough with SL, it would be extremely helpful if CSD was a standard feature of commercial and open-source software packages intended to offer advanced EEG analysis. We hope that this special issue will be another step in this direction towards reference-free EEG analysis (Kayser and Tenke, 2010), stimulating new and exciting EEG and ERP research via CSD methods.

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