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Spatial enhancement of EEG traces by surface Laplacian estimation: comparison between local and global methods

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Abstract

Objective: Surface Laplacian estimation enhances EEG spatial resolution. In this paper, we compare, on empirical grounds, two computationally different estimations of the surface Laplacian.

Methods: Surface Laplacian was estimated from the same monopolar data set with both Hjorth's method [local; Electroenceph Clin Neurophysiol 39 (1975) 526] as modified by MacKay [Electroenceph Clin Neurophysiol 56 (1983) 696] and with spherical spline interpolation [global; Electroenceph Clin Neurophysiol 72 (1989) 184].

Results: The grand averages computed with the two methods proved to be very similar but differed markedly from the monopolar ones. The two different computations were highly correlated, presented low relative errors and allowed to evidence comparable experimental effects.

Conclusions: These results suggest that Hjorth's method and spherical spline interpolation convey similar topographic and chronometric informations.

Significance: We provide empirical evidence that local and global methods of surface Laplacian estimation are equivalent to improve the spatial resolution of EEG traces. Global methods allow to explore the scalp topography and local methods allow to spare time in electrode setting that can be useful for studies on special populations (i.e. children, aged subjects) and for clinical purposes.

Keywords: ERP; Scalp current density; Current source density; Source derivation; Clinical applications

1. Introduction

Conventional monopolar electroencephalographic recordings (EEG) have a poor spatial resolution: The scalp potential distribution can be viewed as a 'blurred' copy of the original cortical potential distribution (Babiloni et al., 2001). This poor spatial resolution, roughly in the 6–10 cm range, can be enhanced up to 2–3 cm, provided that high spatial sampling is used (Nunez, 2000). One popular 'spatial deblurring' technique consists in estimating the surface Laplacian (SL). Under the assumption that the scalp is isotropic, one can demonstrate that the SL is proportional to the radial component of the gradient of the scalp current density (Nunez, 1981), also called more shortly 'scalp current density' (SCD; Perrin et al., 1989) or 'current source density' (CSD; Nunez et al., 1994). The SL is independent of the reference electrode (Nunez, 1981; Pernier et al., 1988) and, acting as a high-pass spatial filter, it removes the blurring effect of the diffusion of the currents through the highly resistive skull (Nunez, 1981). Finally, the SL is a good approximation of what would be the corticogram (Gevins et al., 1995). Moreover, by allowing to separately examine the time course of activities corresponding to different foci, the SL estimation

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secondarily enhances the temporal resolution of EEG (Law et al., 1993). Note, however, that SL is rather insensitive to deep sources (Pernier et al., 1988). Two kinds of SL estimation have been proposed; in what follows, we shall use the terms 'local' and 'global' (Babiloni et al., 2001) to refer to these two kinds of methods.

The goal of Hjorth (1975) method (local method) is to estimate directly the SL at selected sites. A local estimation is obtained by computing the difference between the potential at each electrode site and the average potential of its nearest four neighbours provided that the distances between electrodes are equal and the angles built by the electrodes configuration are equal. Hjorth's method and its following developments (e.g. MacKay, 1983) can be viewed as a method using a local reference based on the potentials recorded from neighbouring electrodes (Babiloni et al., 2001).

A global method for estimating the SL is based on the spline interpolation techniques (Nunez, 1995; Perrin et al., 1987a,b, 1989). The method is made of two steps: first, interpolation of the values of the potential recorded at each electrode, and second, computation of the spatial second derivatives of the interpolated function. Estimating the SL from spline techniques at a scalp site can be considered as a global method since the computation is based on the entire electrode array (Babiloni et al., 2001).

Although these two methods are based on very different computations, they should logically give similar results. However, to the best of our knowledge, no direct empirical comparisons have yet been done. The aim of the present study was to perform such a comparison. For this purpose, the SL was estimated with Hjorth's method (Hjorth, 1975) as modified by MacKay (1983) and with spherical spline interpolation (Perrin et al., 1989) from the same monopolar data set. Note that, although new methodological developments allowing to estimate the SL on realistic head models have recently been proposed (e.g. He et al., 2001), the spherical spline interpolation is nowadays more commonly used in research and clinical environments.

2. Methods

The data set stems from the experiment of Vidal et al. (2003) where a description of the experiment is available.

2.1. Subjects and task

Twelve right handed subjects participated in a reaction time task. The task was a variant of the Stroop color word task in which subjects either had to press the left or right button of a response pad, with their left or right thumb, or had not to respond, depending on the color of a response signal.

2.2. Electrophysiological recordings

EEG was recorded from 21 Ag/AgCl scalp electrodes The reference and ground were on the right and left mastoids, respectively. Impedances were kept below 5 kΩ (at 30 Hz). The brain structures underneath the electrodes were located on the basis of Homan et al. (1987) and Steinmetz et al. (1989) studies. In order to estimate the time course of SL by Hjorth's method (Hjorth, 1975), as modified by MacKay (1983), we used an electrode configuration that partly differs from the standard 10–20 electrode placement system. This configuration permitted the SL to be estimated at 13 electrodes-called 'nodal'-from the 21 electrodes. Note that the same electrode can be used as a nodal electrode and as an electrode involved in the computation of another nodal electrode. The inter-electrode distance was 3.7 cm on average, corresponding to a density of 64 electrodes if the whole head would be covered.

EEG and EOG signals were fed into Nicolet SM 2000 amplifiers, amplified (30,000 times), filtered and digitized (bandwidth: 0.1–100 Hz, 12 dB/octave, sampling rate: 256 Hz). EOG was recorded bipolarly between electrodes situated above the right eye and at its outer canthus. Neither selective 'notch' 50 Hz filter nor additional digital filtering was used.

EMG was recorded bipolarly from the flexor pollicis brevis of each hand by surface Ag/AgCl electrodes (6 mm diameter), amplified (5,000 times), filtered (high frequency cut-off: 1 kHz; low frequency cut-off: 1 Hz), full-wave rectified and integrated (integration window: 5 ms), and then, digitized on-line (sampling rate: 256 Hz).

2.3. Artifact rejection

The SL transformation is considered to remove ocular contamination (Law et al., 1993). Nevertheless, large ocular artifacts ($> 50\,\mu V$) and other artifacts were rejected by visual inspection of the monopolar recordings, considering the characteristic shape of these artifacts, EOG recordings, and the gradients of activity obtained at different locations. Because SL is very sensitive to them, artifacts present at single electrodes were also carefully rejected.

2.4. Recording periods and baseline

Brain activities were recorded continuously during the experiment. Response-related activities were averaged with respect to EMG onset. The time range of the epochs was 1000: 500 ms before and 500 ms after EMG onset. The onset of EMG activities was detected by visual inspection of each trial (Hasbroucq et al., 1999). Baseline was taken from 300 to 200 ms before EMG onset.

2.5. Surface Laplacian estimation

Hjorth's method: Each nodal electrode was surrounded by three other electrodes that formed the vertices of an equilateral triangle, so that the nodal electrode was at the center of that triangle. The estimation of the SL by Hjorth's method (Hjorth, 1975), as modified by MacKay (1983), consists in the following computation:

$$\{4/3[3V_N - (V_A + V_B + V_C)]\}/d^2$$

where V_N is the potential recorded at the nodal electrode, V_A, V_B, V_C are the potentials recorded at the surrounding electrodes, and d the distance between the nodal and the surrounding electrodes.

Spherical spline interpolation: We used the spherical spline interpolation algorithm of Perrin et al. (1989) as implemented in BrainAnalyzer© (the units are quoted for a notional sphere radius equal to 10 cm). The first step consists in computing an interpolation of the values of the potential. This is done by interpolating the potential values in a sphere reference and then in fitting, in the sphere reference, the best interpolation of the obtained values. The second step consists in deriving (spatial second derivatives) the obtained interpolated function. We chose three as degree of spline since this value minimizes errors (Perrin et al., 1987b); the interpolation was computed with a maximum of 15° of Legendre polynomial.

3. Results

Local and global estimations of the SL were computed for each of the 13 'nodal' electrodes from the 21 electrodes set. Fig. 1 presents monopolar (μV, top) and Laplacian ($\mu V/cm^2$) grand averages estimated from spherical spline interpolation (middle) and with Hjorth's method (bottom). Fig. 2 presents Laplacian maps (top) and Laplacian grand averages (middle) both computed from spherical spline interpolation, and Laplacian grand averages computed with Hjorth's method (bottom), for the right response at the three sites analysed in the previous study (Vidal et al., 2003): FCz, C3′ and C4′ (about 1 cm medial from C3 and C4).

The Laplacian waveforms computed with Hjorth's method (Fig. 2, bottom) revealed a negative wave at C3′ site, located over the primary sensorimotor cortex contralateral to the response, beginning about 100 ms before EMG onset and peaking about 10 ms after it. At C4′ site, located over the primary sensorimotor cortex ipsilateral to the response, a positive deflection developed in the same time range and was stopped by a negative-going bump at EMG onset. This contralateral negative/ipsilateral positive pattern was actually maximal over the primary sensorimotor areas. Furthermore, at FCz, located over the supplementary motor areas, a negative wave began approximately 200 ms before and peaked about 40 ms before EMG onset. This activity peaked about 50 ms earlier, on average, than that observed over the primary sensorimotor cortex contralateral to the response. Note that all these deflections were tested by slope analysis and were statistically reliable (Vidal et al., 2003). Concerning the Laplacian waveforms computed from spherical spline interpolation (Fig. 2, top), one can see that the deflections look very similar to those computed with Hjorth's method. Note that the waveforms of the two SL estimates were similar also for the other channels and differed markedly from the monopolar waveforms (see Fig. 1).

We attempted to quantify the similarity of the traces obtained with the two methods. In this aim, we computed relative errors and correlation coefficients (Bravais-Pearson r) from the traces (256 points) obtained with the two methods. Relative error, defined as the difference in amplitude between the two traces relative to the amplitude of the two traces, was computed as follows:

$$\sqrt{\left[\sum (H_i - S_i)^2\right]} \Big/ \sqrt{\left[\left(\sum H_i + \sum S_i\right) \Big/ 2\right]}$$

where H_i and S_i are each of the 256 points of the traces obtained, respectively, with Hjorth and Spline methods. These computations were done for each hand, for each of the 13 nodal electrodes, and for each of the 12 subjects, leading to a total of 312 relative errors and 312 r values. The probability of each relative error was plotted in the left part of Fig. 3 and the probability of each correlation coefficient was plotted in the right part of Fig. 3. From this figure, one can see that 89% of the relative errors are inferior to 0.20; moreover, more than 92% of the correlation coefficients are superior to 0.90, providing evidence that the two estimates are highly correlated. There are, however, a few high relative errors and low r values. To evaluate the potential discrepancy between the SL estimates corresponding to these marginal values, the Laplacians traces computed with the two methods were plotted for the two worse values (Fig. 3; insets). One can see that the gap between the two traces was due to amplitude differences occurring at limited parts of the traces.

In order to check that both SL estimations provide comparable effects, we tested the reliability of the deflections observed on the Laplacian traces computed from spherical spline interpolation and on the monopolar traces. We performed the same statistical analysis on the slopes as those performed in the Vidal et al. (2003) paper on the Laplacians computed with Hjorth's method. In successive time windows, we compared the slope values to a theoretical zero value by the one-sample two-tailed Student's t test. As the mean slope showed no effect of the responding hand for monopolar recordings ($F(1,11) = 1.41$, $P = 0.26$) and for SL estimated from spherical spline interpolation ($F(1,11) < 1$), data from both hands were

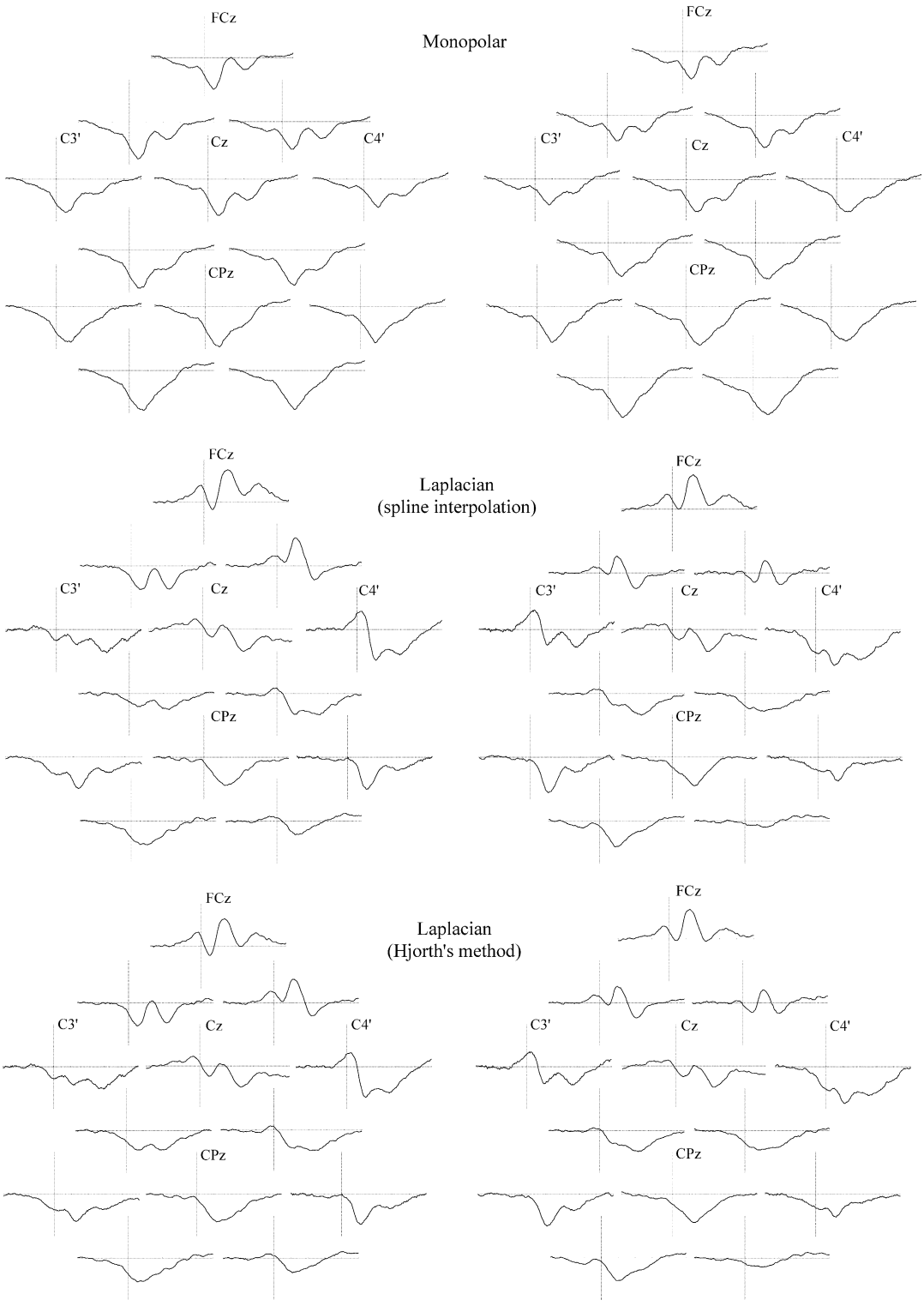

Fig. 1. Monopolar (μV; top) and Laplacian (μV/cm^2) grand averages computed from spherical spline interpolation (middle) and with Hjorth's method (bottom) for left- and right-hand responses (respectively, in left and right parts). Traces are averaged time-locked to EMG onset (zero of time, vertical bar); negativity is up. Time range: from −300 to +500 ms. Baseline: 300 to 200 ms before EMG onset.

merged and the activity recorded at C3′ and C4′ were labelled 'Contra SM1' and 'Ipsi SM1' for primary sensorimotor area contralateral to the responding hand and primary sensorimotor area ipsilateral to the responding hand.

Table 1 presents the measured slopes for the different time windows for monopolar traces and for Laplacian traces estimated from spherical spline interpolation as well as the *t* values for the comparison to zero of the slopes.

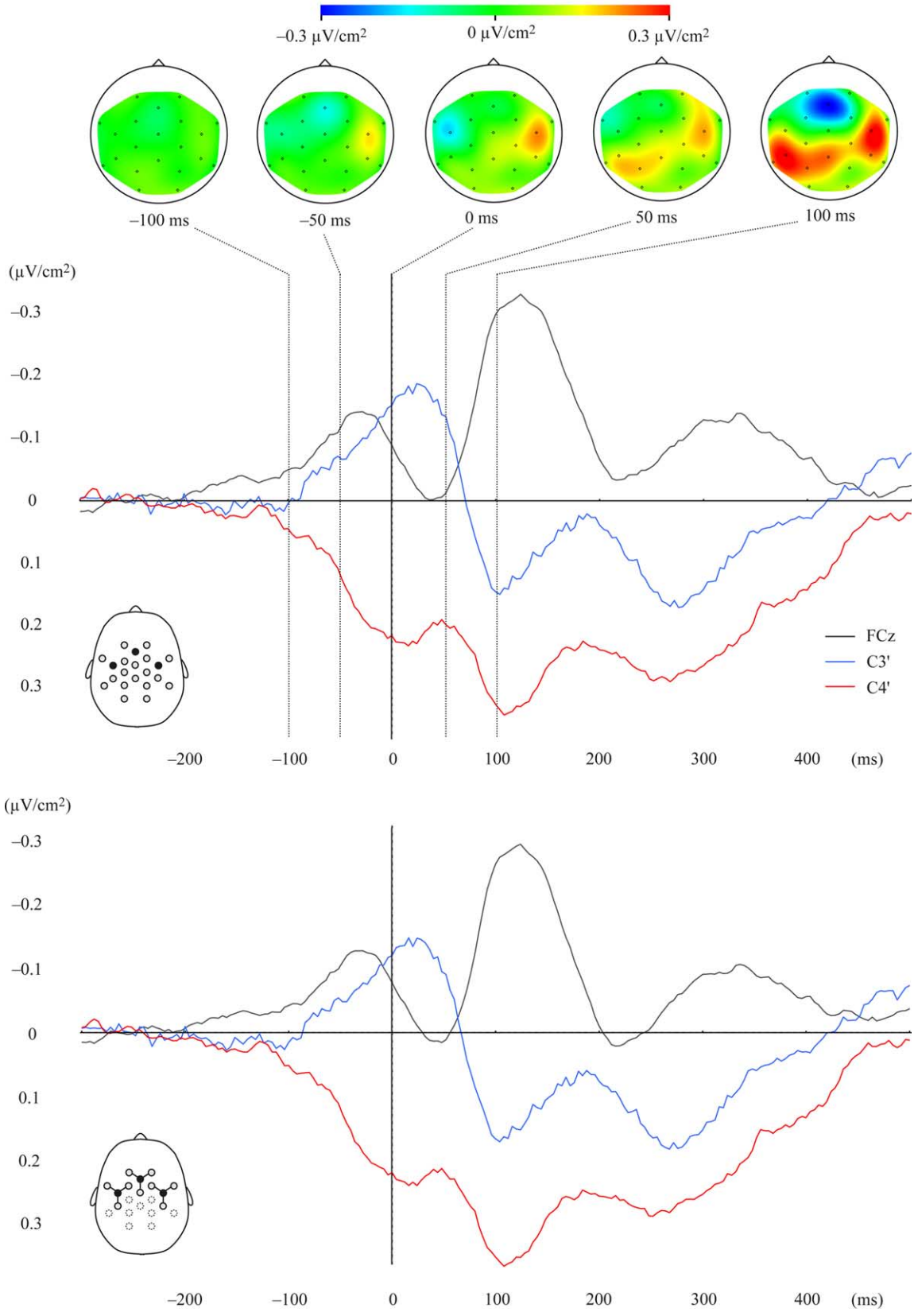

Fig. 2. Laplacian maps (top) and Laplacian grand averages (middle) computed from spherical spline interpolation and Laplacian grand averages computed with Hjorth's method (bottom) at FCz (in black), C3′ (in blue) and C4′ (in red; about 1 cm medial from C3 and C4). Traces are averaged time-locked to EMG onset (zero of time, vertical bar); negativity is up. Baseline: 300 to 200 ms before EMG onset. Top view of the head on the left bottom corner of the traces: Black dots symbolyzed the electrodes where surface Laplacian was estimated; grey dots symbolyzed the electrodes used in the computation.

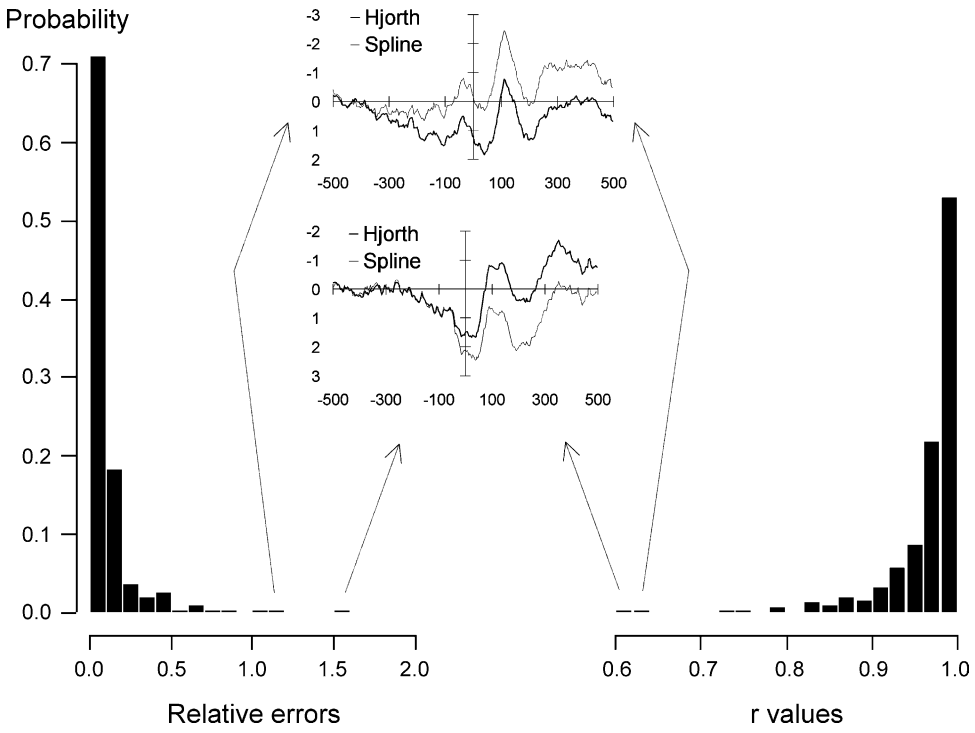

Fig. 3. Probability is plotted as a function of relative errors (difference in amplitude between the two traces relative to the amplitude of the two traces; left part) and correlation coefficients (Bravais-Pearson *r* values, degrees of freedom: 254; right part). Relative errors and correlation coefficients were computed for one hand, for one of the 13 electrodes, and for each of the 12 subjects. Insets: Laplacian ($\mu V/cm^2$) individual traces of two subjects plotted as a function of time (ms) for one experimental condition (left hand-response) computed from spherical spline interpolation (thin line) and with Hjorth's method (thick line). These two traces correpond to the two worse relative errors and correlation coefficients between the two surface Laplacian estimates: error relative of 1.14, $r=0.64$ (top), and error relative of 1.57, $r=0.60$ (middle). Traces are averaged time-locked to EMG onset (zero of time, vertical bar); negativity is up. Time range: from −500 to +500 ms. Baseline: 500 to 400 ms before EMG onset

This analysis reveals that the SL computed from spherical spline interpolation and with Hjorth's method provide comparable effects whereas monopolar recordings provide different ones.

4. Discussion

The results of this study show that Laplacians computed with Hjorth's method (Hjorth, 1975) and from spherical

Table 1
Values of the measured slopes at each tested electrode in each tested time period for monopolar (μV/s). Laplacian estimated from spherical spline interpolation ($\mu V/cm^2/s$), and Laplacian estimated with Hjorth's method ($\mu V/cm^2/s$; data stem from Vidal et al., 2003)

Period (ms)	Area		
	FCz	Contra SM1	Ipsi SM1
Monopolar			
−200/−100	16.44 [3.57] (0.01)	55.02 [5.60] (0.001)	30.66 [4.03] (0.01)
−100/−50	−8.65 [1.05] (ns)	−12.62 [1.94] (0.10)	17.51 [4.10] (0.01)
−50/0	56.67 [5.82] (0.001)	26.76 [3.53] (0.01)	61.07 [8.25] (0.001)
0/50		26.76 [5.60] (0.001)	61.07 [4.03] (0.01)
Laplacian (Spline interpolation)			
−200/−100	−0.50 [2.44] (0.05)	0.01 [0.08] (ns)	−0.03 [0.12] (ns)
−100/−50	−1.69 [2.67] (0.05)	−1.50 [3.19] (0.01)	1.46 [4.54] (0.001)
−50/0	1.69 [2.07] (0.06)	−2.04 [2.83] (0.025)	1.23 [4.20] (0.01)
0/50		2.01 [4.28] (0.01)	1.23 [1.73] (ns)
Laplacian (Hjorth's method)			
−200/−100	−0.39 [2.40] (0.05)	0.05 [0.39] (ns)	0.05 [0.19] (ns)
−100/−50	−1.42 [2.42] (0.05)	−1.24 [2.92] (0.025)	1.34 [5.24] (0.001)
−50/0	1.55 [2.204] (0.05)	−1.58 [2.41] (0.05)	1.24 [5.66] (0.001)
0/50		2.00 [4.60] (0.001)	−0.30 [0.81] (ns)

Zero of time period is EMG onset. As there is no effect of the responding hand, data from both hands were merged and labelled 'Contra SM1' and 'Ipsi SM1' for primary sensorimotor area contralateral to the responding hand and primary sensorimotor area ipsilateral to the responding hand. The $t(11)$ values for the comparison to zero of the slopes are in brackets and the corresponding level of significance is in parentheses.

spline interpolation (Perrin et al., 1989) were highly similar, suggesting that the two methods provide similar topographic and chronometric information, as predicted by theoretical developments (Babiloni et al., 2001; Nunez, 1995). The main difference between the two methods is that the SL cannot be estimated with Hjorth's method at each electrode of the array since the computation requires neighbouring electrodes (Nunez, 1981). Moreover, Hjorth's method is restricted to electrode spacing superior to 2.5 cm since the efficiency of the SL estimation with this method decreases sharply when the spacing between the nodal and the outer electrodes is inferior to 2.5 cm (Srebro, 1985). However, if, on the basis of a priori hypotheses concerning the generators of the measured activities, only a few sites are of interest, it is not necessary to compute interpolations that require a large number of electrodes. In other words, provided that the electrode density (number of electrodes and electrode spacing) remains the same, improvement of the spatial resolution of EEG can be obtained with a minimum number of electrodes. This is of interest for research focused on one particular cortical area. For instance, motor indices such as the Lateralized Readiness Potential (Gratton et al., 1988), or the recently shown Activation–Inhibition Pattern thanks to SL estimation (Tandonnet et al., 2003; Vidal et al., 2003), require only C3 and C4 sites. It could be also useful for studies on special populations (i.e. children, aged subjects) and for clinical purposes as time can be spared in electrodes setting without decreasing the accuracy of the SL estimation.

The present results provide an empirical evidence confirming that local and global methods of SL estimation are essentially equivalent to improve the spatial resolution of EEG traces. In conclusion, a global method is more suitable if the objective is to explore the scalp topography since this method give an estimation of the SL for all electrodes; a local method is more suitable if the objective is to study particular areas and spare time in electrode setting, like in clinical purposes, since this method necessitates a minimum number of electrodes.

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