Surface Laplacian of Central Scalp Electrical Signals is Insensitive to Muscle Contamination

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***Abstract*—Objective: To investigate the effects of surface Laplacian processing on gross and persistent electromyographic (EMG) contamination of electroencephalographic (EEG) signals in electrical scalp recordings.**

Methods: We made scalp recordings during passive and active tasks, on awake subjects in the absence and in the presence of complete neuromuscular blockade. Three scalp surface Laplacian estimators were compared to left ear and common average reference (CAR). Contamination was quantified by comparing power after paralysis (brain signal, B) with power before paralysis (brain plus muscle signal, B+M). Brain:Muscle (B:M) ratios for the methods were calculated using B and differences in power after paralysis to represent muscle (M).

Results: There were very small power differences after paralysis up to 600 Hz using surface Laplacian transforms (B:M> 6 above 30 Hz in central scalp leads).

Conclusions: Scalp surface Laplacian transforms reduce muscle power in central and peri-central leads to less than one sixth of the brain signal, 2-3 times better signal detection than CAR.

Significance: Scalp surface Laplacian transformations provide robust estimates for detecting high frequency (gamma) activity, for assessing electrophysiological correlates of disease, and also for providing a measure of brain electrical activity for use as a 'standard' in the development of brain/muscle signal separation methods.

***Index Terms*—EEG, EMG, brain, paralysis.**

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I. Introduction

Interest in high frequency electroencephalographic (EEG) rhythms (above 20 Hz) has intensified since the recognition of the involvement of high-frequency beta (15-25 Hz) and gamma (>25 Hz) rhythms in cognitive processing [1]-[3]. It is well known that electrical activity from muscles (electromyogram, EMG) of the cranium and neck contaminates scalp recordings, and the spectrum of frequencies in the EMG overlaps the spectrum of the EEG particularly above 20 Hz [4], [5] and we have quantified the extent of the contamination [6]-[8].

Different referencing methods do not significantly attenuate and only marginally affect the distribution of EMG due to active muscle contraction [4]. Attempts have been made to identify EMG-free EEG components using blind source separation techniques, none of which have yet been demonstrably reliable [9]-[11].

Surface Laplacian transforms determine scalp current density using data from all active scalp electrodes [12]. As such, the method is sensitive to local sources and sinks located near to recording sites and insensitive to distant sources. There are no muscles underlying the central scalp, therefore, raw recordings from central channels should only be contaminated by potentials from distant muscles. These distant effects should be significantly attenuated in the surface Laplacian transforms. Here we report that, with certain restrictions, scalp surface Laplacian transforms substantially reduce muscle contamination in central scalp electrical recordings.

II. Methods

We used power spectra of electrical scalp recordings obtained from volunteers before and after the elimination of EMG activity by neuromuscular paralysis. We examined a variety of pre-processing methods to quantitate the amount of EMG contamination. In particular, we searched for any method that might sufficiently reduce EMG contamination in pre-paralysis recordings such that their power spectra matched the power spectra of recordings after paralysis (EMG-free).

EMG-free scalp recordings were obtained from volunteers who were pharmacologically paralyzed and artificially

respired while fully conscious. The procedure has been described in detail previously [6], [7] and was approved by The Clinical Research Ethics Committee of Flinders University and Flinders Medical Centre.

Five males (aged 28, 40, 48, 62, and 73) and one female (aged 47) participated in the experiment. They were studied in a Faraday cage, seated in a reclined position and required no change in posture after paralysis. They were recorded, first without paralysis, while undertaking a range of behavioral tasks. Cisatracurium (a curare-like agent) was then administered to achieve full neuro-muscular paralysis and intermittent positive pressure ventilation was initiated. When complete neuromuscular blockade was achieved, recordings continued and the subjects repeated the tasks.

A. EEG recording

EEG (115 channels) was recorded continuously (left ear reference, 5000 samples per second, 16-bit analogue to digital conversion, 1250 Hz low-pass filter) using a NeuroScan system (Compumedics, Victoria, Australia). Electrode impedances were less than 5kOhms. A 128-channel electrode cap with Ag-AgCl electrodes (Easy Cap Falk Minnow, Germany) was used to provide uniform scalp coverage.

B. Behavioral Tasks

All tasks were performed in both the un-paralyzed and paralyzed states. Tasks included resting with the eyes closed (eyes closed), left eye held open by a swab on a stick (left eye open), sub-maximal jaw-clenching (bite), frowning (frown), and strobe light stimulation to the held-open left eye at 40 Hz (strobe), amongst several other tasks not reported in this paper. Resting, baseline tasks were recorded for 10 seconds with both eyes closed and then for 10 seconds with the left eye held open and were recorded on three occasions in the un-paralyzed state (twice at the beginning and once at the end) and on two occasions in the paralyzed state (at the beginning and the end). Bite, frown and strobe were undertaken for 10 seconds.

C. EEG analysis

Recordings were edited by removing data from technically defective electrodes. All EEG data was retained except for those contaminated by electroencephalogram (EOG, blinks). Analysis was undertaken using in-house programs written in Matlab (The Mathworks, Natick, Massachussetts, USA). Data using five pre-processing methods were compared namely, left ear reference (L-ear - the original recording), common average reference (CAR) and surface Laplacian transforms [12], [13]. Three forms of surface Laplacian transforms were tested, a spline interpolation [14], Hjorth [15], and finite element [13]. Code for all estimators was obtained from the FieldTrip toolbox [16]. Power spectra were estimated using Welch's modified periodogram method, with blocks of 5000 samples (1 second). Contamination by 50 Hz (mains frequency signal) was removed by excision of 49-51 Hz power and its harmonics.

We estimated relative power spectra, obtained as the ratio of power spectra for the un-paralyzed condition (power due to brain activity plus power due to muscle activity plus power due to noise, B+M+N) over the power in the paralyzed condition (B+N).

To measure the quality of the output of a pre-processing method, we also estimated B:M ratios (viz. an SNR). The power due to brain activity B was estimated as the power spectrum during paralyzed recordings. The power due to muscle activity M was estimated as the difference in power spectra between un-paralyzed and paralyzed recordings. When M is small, noise significantly affects this estimate, and so two steps were taken to reduce its effect. First, all calculations were averaged within frequency bands. Second, we estimated the noise in scalp recordings as the difference in power spectra between two samples of baseline paralysis recordings (measured at the beginning of paralysis and at the conclusion of the mental tasks approximately 20 minutes later). Neither of these samples contained EMG. Estimates of muscle M less than the 95 percentile of the noise were regarded as unreliable and replaced by the threshold value. This conservative estimate of muscle activity was then used to calculate B:M ratios for a frequency band.

D. Statistical Analysis

The statistical significance of changes in power due to paralysis was evaluated using paired t-tests if normal and Wilcoxon signed rank test if not normal. The Lilliefors test was use to determine normality.

III. RESULTS

A. Resting tasks

Paralysis reduced spectral power compared to unparalyzed (due to muscle) over a broad range of frequencies during all tasks. During non-active tasks such as eyes-closed and left eye-open, the lower limit of power due to muscle varied in different regions of the scalp and with different methods of pre-processing. EEG traces, power spectra, and group-mean relative spectra, unparalyzed:paralyzed for the eyes-closed task, using the five methods are illustrated in Fig. 1. Relative to paralysis, EMG contamination was greatest in circumferential scalp areas (fronto-temporal, temporal and temporo-occipital) and least centrally, consistent with our previous reports in smaller numbers of subjects [6], [7].

Centrally, where contamination was least, both left-ear reference and common average reference EEG were still significantly contaminated by EMG (P-values all < 0.05 at Cz, Table I). In contrast, surface Laplacian transforms at central and para-central leads revealed small and non-significant contamination by EMG (P-values nearly all > 0.05 at Cz, Table I). The spline surface Laplacian was the only method for which residual muscle contamination was not significant at any frequency range.

Topographies of relative power for low gamma and higher frequency bands (selected according to [17]) demonstrate that there is very low central scalp muscle contamination using surface Laplacian tranforms (Fig. 2). These contrast to the considerable EMG contamination of EEG using left ear referencing or, to a lesser extent, using CAR. B:M ratios for these frequency ranges are given in Table II.

B. Muscle activation

The impact of active contraction, with frowning and jaw-clenching, as opposed to resting muscle tension, is illustrated in Fig. 3. Using CAR, EMG contaminated all electrodes albeit less at the central scalp. In contrast, spline surface Laplacian transforms exhibited a very small, albeit statistically significant, increase in relative power with ratios very close to 1. During bite, for Cz in the range 30-80 Hz, B:M ratios were 0.87 for CAR, and 8.1 for spline surface Laplacian. During frown, for Cz in the range 30-80 Hz, B:M ratios were 0.61 for CAR, and 9.1 for spline surface Laplacian.

C. Physiological responses

We evaluated the application of spline surface Laplacian in identifying brain responses in unparalyzed subjects, first using a low frequency response, alpha augmentation with eye-closure, and then using a high frequency response to sustained 40 Hz visual stimulation with strobe.

Examining the low frequency (alpha) response to the eyes-closed versus the left eye-open state, the finding with CAR and with spline surface Laplacian was similar. In the four subjects with good alpha activity, spline surface Laplacian revealed the expected posterior enhancement of alpha activity [18]. Although qualitatively similar, peak alpha frequencies were different, as were distributions, so that the group average was not informative and a single representative subject is shown in Fig. 4. In addition, spline surface Laplacian did not project spurious changes to more anterior sites that occurred with CAR (Fig. 4).

Examining the high frequency (gamma) response during 40 Hz strobe visual stimulation, spline surface Laplacian and CAR both revealed the expected posterior expression of 40 Hz steady-state visual evoked response, while the Laplacian did not project spurious 40 Hz changes to more anterior sites seen with CAR (Fig. 5).

IV. Discussion

By comparing scalp electrical recordings from normal (un-paralyzed) and paralyzed awake volunteers undertaking various mental and motor tasks, we have demonstrated that spline surface Laplacian transform of signals from central scalp positions have very high B:M ratios over all frequencies at which cerebral rhythms have been considered to be likely [17]. Particularly important is our finding that spline surface Laplacian transform is insensitive to EMG contamination centrally in the presence elsewhere of marked EMG-contaminated data (all Figs.). Blink artifact was the only biological contaminant actively excluded in our study. Sustained non-forceful muscle contractions in resting subjects (due to failure to fully relax) and non-intended transient movements were not excluded. Importantly, however, we also tested powerful contractions of jaw (temporalis) and forehead (orbicularis oculi) muscles. Activity in these muscles caused very slight, albeit significant, EMG contamination in the central scalp, an observation that provides, for the first time, evidence that useful data pertaining to all frequencies can be recorded in the face of sub-maximal scalp muscle contraction.

Concurrently with its resistance to EMG contamination in the central scalp region, application of the method, importantly, did not eliminate changes in power of cerebral origin, around 10 Hz posteriorly due to eye-closure, and the 40 Hz visual steady state response posteriorly due to 40 Hz visual stimulation. The focal expression of alpha with spline surface Laplacian compared to the broad expression with CAR is a good example of the spatial filtering properties of the Laplacian in which broad spatial activity (low spatial frequency) is attenuated [12].

The surface Laplacian approach transforms voltage EEG into a surface current density (SCD) space. Thus, the relationships between electrodes will change in both magnitude and phase and it cannot simply be assumed that standard EEG analysis will be suitable for SCD. Whilst there is evidence to suggest that surface Laplacian will benefit estimates of synchrony [19], [20] caution should be exercised to ensure that analyses, particularly phase analyses (e.g. phase coherence, phase-locking value, etc.) are appropriate for SCD and that the limitations of each approach are accommodated when interpreting results [20].

Our results, that spline surface Laplacian transforms provide the best pre-processing approach to avoiding muscle contamination of scalp signals, are consistent with the fact that there are no muscles underlying the central scalp so that central channels are only subject to the effects of potentials in distant muscles. As distant potentials affect closely located electrodes similarly they will largely be eliminated in the surface Laplacian transforms. In the earlier study of Goncharova and colleagues [4], next-nearest neighbor Laplacian transforms of 15% contraction of cranial muscles vs rest, performed worse than other referencing methods. Based on our findings, spline and, to a lesser extent, Hjorth Laplacians do appear to be more successful at identifying local current. Consistent with Goncharova and colleagues, however, we found high levels of EMG contamination with surface Laplacian transforms in peripheral locations (Figs. 1-3).

The results do not challenge the clinical use of EEG in the temporal domain in which, apart from epilepsy, rhythms with frequencies below 20 Hz are usually assessed. However, in the frequency domain, using left ear or common average referencing, it is clear that EMG contamination is extensive at frequencies close to and above those normally of clinical interest [4]-[6]. This is particularly problematic for investigators examining higher frequency activity associated with cognitive processes and cortical binding [1]-[3]. The surface Laplacian transform appears to provide a ‘window’ in the central scalp region for accessing high frequency cortical activity without significant muscle contamination. Based on CAR data, EMG contamination is apparent even when careful visual editing of scalp recordings has been attempted [6], [8]. In contrast, editing to excise EMG contamination appears to be unnecessary when using spline surface Laplacian transforms for the study of central scalp recordings.

It is widely accepted that new approaches are necessary for

extracting EEG from mixed EEG/EMG signals [9]-[11]. This view still remains relevant to channels circumferential to the central scalp. Evaluation of methods such as independent components analysis, principal components analysis and others require an EMG-free record to allow reliable evaluation. Until now it has not been clear that, in tasks not requiring forceful muscle contractions, central electrode data largely avoid muscle contamination when estimated with spline surface Laplacian transforms. Given this, the spline surface Laplacian approach provides an ideal source of signals for investigators to use in developing and testing algorithms to separate signals from brain and signals from muscle. An additional benefit of this observation is that a robust evaluation of possible relationships between neuro-psychiatric disorders and high frequency brain signals is feasible for the first time, at least in the central scalp 'window'.

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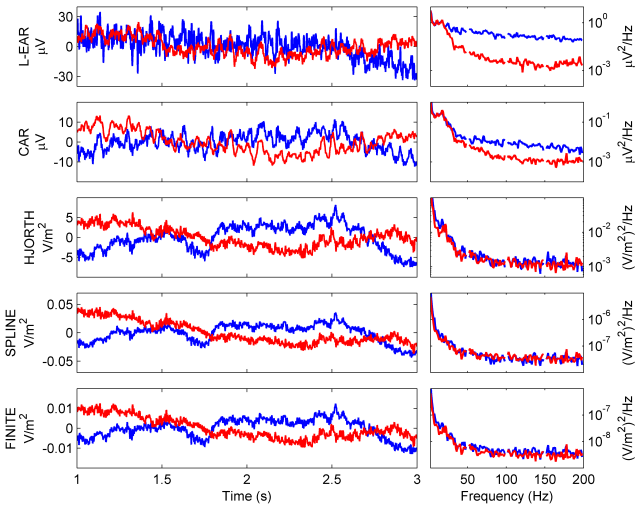

Fig. 1A. Illustrative EEG (left) at Cz from a single-subject for left ear (L-EAR), common-average reference (CAR), and nearest neighbor (Hjorth), spline, and finite element surface Laplacian transforms. EEG was recorded during the eyes-closed task in un-paralyzed (blue) and paralyzed (red) states. Power spectra for each segment is presented on the right.

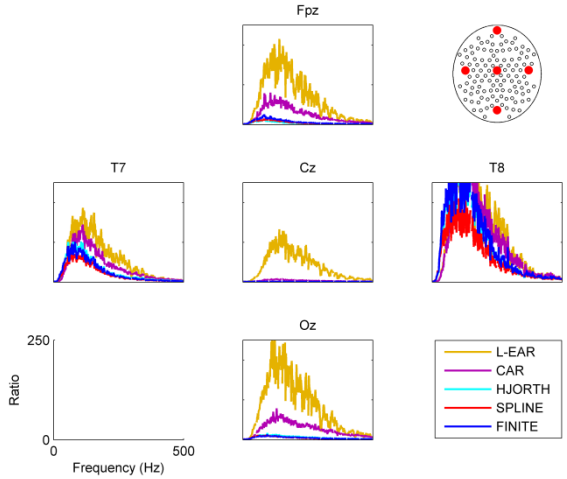

Fig. 1B. Illustrative mean (n = 6) relative power spectra of electrical scalp recordings for the five electrodes depicted in the scalp map (top right). The relative power is of eyes-closed un-paralyzed:paralyzed conditions, calculated using five methods. The detail of the central scalp electrode (Cz) is illustrated in Fig. 1C. Left=left; anterior=up.

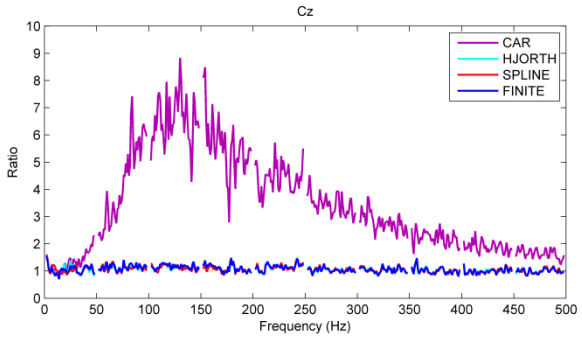

Fig. 1C. Detail of central scalp electrode (Cz) from Fig. 1B. Relative power (before vs after paralysis) for CAR (purple) and surface Laplacian transforms (cyan, red and blue). The surface Laplacian relative power centrally is close to a ratio of 1.

TABLE I
P-VALUES AT CZ OF RELATIVE POWER DURING EYES CLOSED FOR FIVE SPATIAL FILTERS, BY FREQUENCY BAND

Frequency Band (Hz)	Left Ear	Common Average Head	Hjorth Surface Laplacian	Spline Surface Laplacian	Finite Element Laplacian
25-35	0.009	0.060	0.727	0.950	0.77
35-45	0.017	0.044	0.381	0.450	0.33
30-80	0.021	0.031	0.123	0.309	0.13
80-200	0.031	0.031	0.013	0.063	0.02
200-600	0.026	0.031	0.155	0.308	0.25

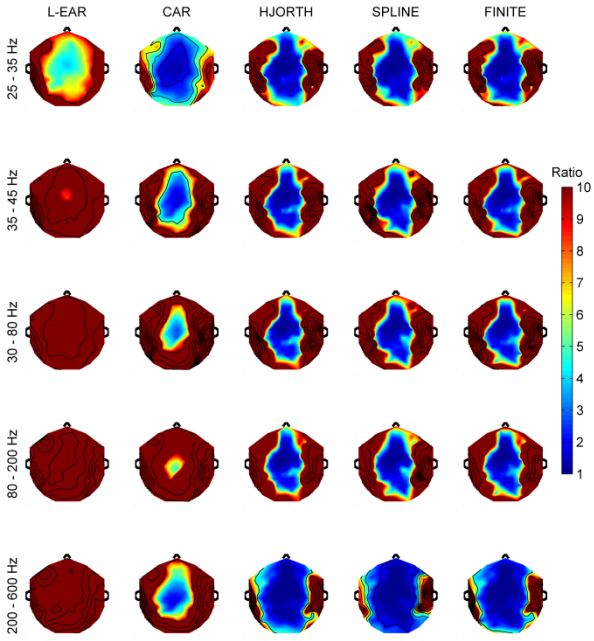

Fig. 2. Average topographies (n=6) of relative power for left ear, CAR and nearest neighbor (Hjorth), spline, finite element surface Laplacian transforms. The Laplacian methods provide an extensive central and paracentral area of signals barely contaminated by muscle.

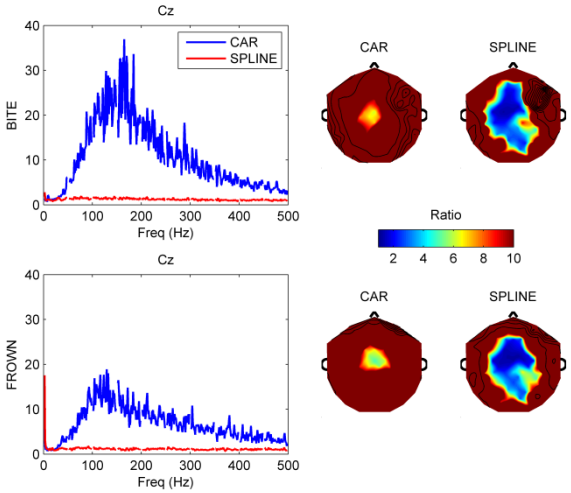

Fig. 3. Central (Cz) electrode mean (n = 6) relative power spectra of electrical scalp recordings illustrate the effect of strong muscle contraction on power in un-paralyzed vs paralyzed conditions, calculated using CAR and spline surface Laplacian transforms. Topographies display relative power averaged for 30-80 Hz for both methods, and illustrate the improved performance of spline surface Laplacian transforms in minimizing muscle contamination, even in the presence of strong muscle contraction.

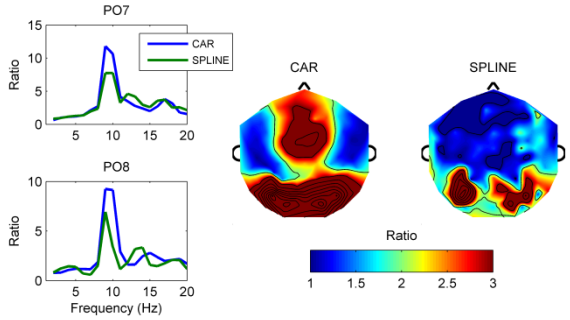

Fig. 4. Relative spectra of eyes-closed vs left eye-open (unparalysed), calculated with CAR and with spline surface Laplacian transforms, from electrodes on the left (PO7) and right hemisphere (PO8) posteriorly from one subject. Topographies display relative power for 9-10 Hz for the two methods. Both the spectra and the topographies reveal the expected increase in 9-10 Hz power due to eye-closure. The topographies also illustrate the improved localization of a source expected with spline surface Laplacian transformation.

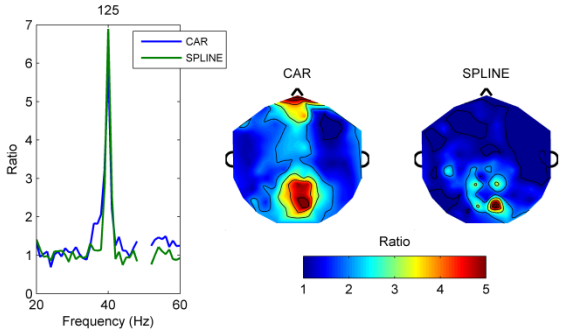

Fig. 5. Mean (n = 5) spectra from a right hemisphere posterior electrode (number 125, between POz and O2 in the extended 10-20 EEG system) illustrating the maximal relative increase in 40 Hz power due to strobe (unparalyzed) for CAR and spline surface Laplacian methods. Topographies display relative power at 40 Hz for the two methods. Both methods reveal the 40 Hz steady state responses due to strobe. The spline surface Laplacian transforms also improves the localization of the 40 Hz steady state response.

TABLE II
BRAIN:MUSCLE RATIOS DURING EYES CLOSED AT CZ FOR FIVE SPATIAL FILTERS - BY FREQUENCY BAND

Frequency Band (Hz)	Left ear	Common Average Head	Hjorth Surface Laplacian	Spline Surface Laplacian	Finite Element Laplacian
25-35	0.63 ± 0.15	3.3 ± 0.91	4.2 ± 1.53	5.9 ± 1.57	3.4 ± 1.16
35-45	0.27 ± 0.09	2.4 ± 0.51	3.4 ± 0.96	6.1 ± 1.99	3.4 ± 0.85
30-80	0.18 ± 0.05	2.0 ± 0.06	6.7 ± 1.43	9.9 ± 2.88	6.5 ± 1.37
80-200	0.03 ± 0.01	0.52 ± 0.23	8.5 ± 1.06	14.9 ± 3.05	7.1 ± 1.27
200-600	0.13 ± 0.06	1.4 ± 0.57	9.9 ± 0.5	20.3 ± 1.58	10.3 ± 0.64