Power spectra and coherence in the EEG of a vegetative patient with severe asymmetric brain damage

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Abstract

Objectives: To examine differences in power spectra and intra-hemispheric coherence between the left and right hemispheres in the presence of severe asymmetric brain damage.

Methods: Power spectra and coherence functions were computed for a patient with severe damage to subcortical gray matter structures on the right side but relative preservation on the left.

Results: Power spectra differed modestly over the hemispheres, with greater low frequency power and less high frequency power over the more damaged right hemisphere. Coherence differed dramatically, with marked reduced coherence over the right hemisphere, particularly frontally where the damage was most extensive.

Conclusions: Damage to subcortical structures of one hemisphere may result in a marked reduction in coherence in the ipsilateral EEG with only a modest change in the power spectrum. We speculate that the physiologic basis of this selective change is damage to structures mediating communication between cortical areas. © 2000 Elsevier Science Ireland Ltd. All rights reserved.

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1. Introduction

Power spectrum and coherence analysis of the EEG has often been applied to the study of various forms of brain dysfunction (Hallett, 1999; Leocani and Comi, 1999). For example, the power spectrum in coma due to severe brain injury is of established prognostic significance. Kane et al. (1998) found that a favorable outcome for traumatic coma correlated with higher power over the left hemisphere, in particular beta band power in the fronto-central and centro-temporal regions, and with higher alpha band power in the centro-temporal region. Analyses of serial EEGs in the first week after head injury indicate that survival correlates with increasing power in the alpha and theta bands (Steudel and Kruger, 1979). Such changes may be provoked by the administration of thiopental (Klein et al., 1988). Thatcher et al. (1989) found that mild head injury was followed by reduced alpha power in the occipital EEG. In general, more

severe traumatic brain damage appears to correlate with decreased power, especially in the alpha range.

Coherence, a measure of cross-correlation in the frequency domain, may be more useful than power in prognostication of closed head injury (Thatcher et al., 1991). A high coherence is suggestive of a relationship between two signals, such as one driving the other, mutual driving, or both partly driven by a common input signal (e.g. Gersch, 1987). Since coherence is a ratio of coherent power to total power, changes in coherence cannot be simply the result of amplification or filtering of the power spectrum, but rather imply changes in functional connectivity.

Coherence has been found to vary with numerous disease states, but the direction of change is inconsistent across those states. Certain regions and frequency ranges show increases in coherence in multi-infarct dementia (Leuchter et al., 1992), AIDS (Newton et al., 1994) and mild head injury (Thatcher et al., 1989), while decreases are observed in Alzheimer's disease (Leuchter et al., 1992; Locatelli et al., 1998) and depression (Roemer et al., 1992). In some disease states the changes are more complex; for example, in schizophrenia the inter-hemispheric coherence is decreased (Hoffman et al., 1991) while the intra-hemispheric coherence is increased (Mann et al., 1997). The

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range of clinical variations in those studies and the possible confounding influences of state changes and artifacts associated with changing levels of activity make it difficult to interpret the effect of specific structural injuries on EEG coherence. Here we measure coherence in the left and right sides in simultaneously-recorded artifact-free records obtained from a patient with severe asymmetric brain damage. This allows us to directly assess the contribution of subcortical structures to intra-hemispheric coherence, with the above confounding influences minimized.

2. Materials and methods

The patient was a 49-year-old right-handed woman who 20 years ago suffered 3 successive hemorrhages from a deep central arteriovenous malformation of her brain. She was initially comatose but after several weeks regained her sleep–wake cycles. She has subsequently not shown any evidence of self-awareness or intentional behavior. Structural brain imaging using MRI showed destruction of the right basal ganglia and thalamus with relatively preserved but atrophied cerebral cortex of the right hemisphere (Fig. 1). There was also damage to the left posterior thalamus and left posterior parietal cortex and moderate atrophy of the rest of the left hemisphere. Further details have been published elsewhere (Schiff et al., 1999). Studies were done with informed consent obtained from the patient's legally authorized surrogate.

The data were recorded and digitized using the Telefactor Beehive EEG system (Telefactor Corporation, West Conshohocken, PA). The EEG was recorded for 3 sessions over 8 months, each session lasting at least 48 h. The recordings included 20 EEG channels placed according to the international 10/20 system with an average reference, and included simultaneous video recording of the patient. The sampling frequency was 200 Hz. Frequencies below 1 Hz and above 70 Hz were removed by digital filtering. The channels were recorded relative to an average reference.

EEG recording periods were excluded from analysis if: (1) video images of the patient suggested the presence of artifacts, such as the patient yawning or blinking; (2) the EEG contained discernible physiological artifacts such as eye movements, blinking, or muscular tension; (3) the EEG was of poor quality for any other reason (e.g. environmental or digitization artifact). EEG segments free of these artifacts were used in this analysis. This yielded EEG segments 12–120 s long, and most commonly 50–100 s.

Each segment provided one estimate of the power spectrum, and similarly one estimate of the coherence profile. A weighted mean of the estimates was constructed where the weighting of each estimate was proportional to the length of the corresponding recording. Error analysis was performed by calculating estimates derived from 50 s of data, averaging where necessary (e.g. taking the mean of the estimates from two 25 s periods). The standard error of the mean of these estimates is shown in Section 3. The errors are therefore approximate, but fairly reflect the range of estimates. The calculations were performed using Matlab (version 5.2) with 'psd' for computation of the power and 'cohere' for computation of the coherence. Each used Welch's averaged periodogram method (Percival and Walden, 1993) with NFFT of 256 and a Hanning window of the same size.

3. Results

The power spectra and intra-hemispheric coherence are shown in Fig. 2 for frontal, central and parieto-temporal regions. The power spectra, each averaged from a pair of electrodes in each region, show an attenuation in the 5–8 Hz range in the left frontal region. Otherwise, the left hemisphere and right hemisphere spectra are remarkably similar given the asymmetry of the brain damage. This finding was not altered by the use of another potentially more accurate method of estimation of the power spectra, the Thomson Multi-Taper Method.

Coherences were calculated from the same electrode pairs. The coherence in the right (more heavily damaged) hemisphere was lower overall than that of the left hemisphere in the frontal and parieto-occipital regions ($P < 0.001$). In the frontal channels, there was a two-fold difference in coherence across the entire frequency range examined. In the parieto-temporal channels, a similar difference was observed, but only above approximately 15 Hz. In the central channels a smaller but significant difference in coherence was present in the same range. In all channels, the differences in coherence between the hemispheres are much more striking than the differences in power.
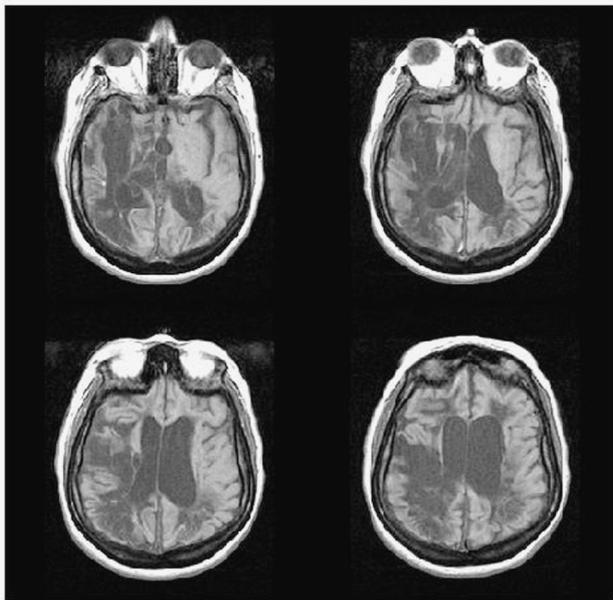

Fig. 1. Horizontal T1-weighted MRI images demonstrate marked asymmetry in the subcortical injury. Note loss of right thalamus and basal ganglia structures along with left posterior thalamic injury.
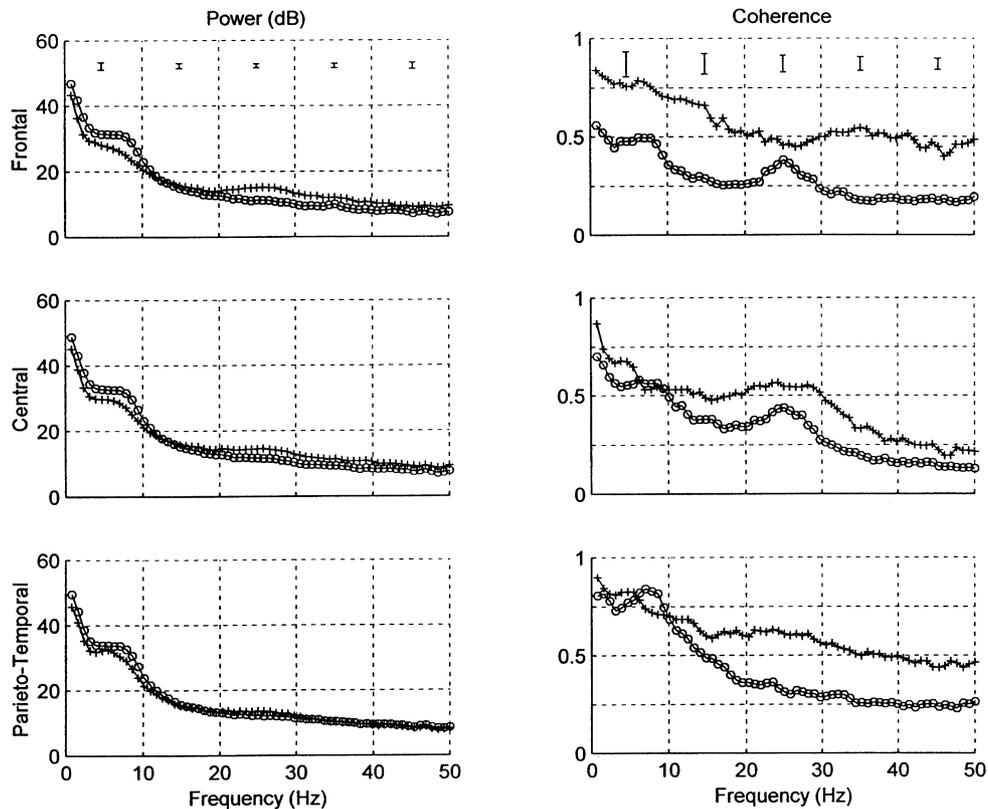
Fig. 2. The regional power spectra and coherence compared between the left (+) and right (o) hemispheres. 95% confidence limits are shown; these did not differ substantially between electrode pairs. Frontal region, electrodes F3/F7 (left hemisphere) and F4/F8 (right hemisphere); central region, electrodes C3/T3 and C4/T4; parieto-temporal region, electrodes P3/T5 and P4/T6.

Averaging across frequency bands provides an even more clear demonstration that the asymmetry in coherence is much greater than that in power (Fig. 3). The most dramatic asymmetry in coherence is in all 3 regions in the gamma and beta bands and frontally in the delta, theta and alpha bands.

Table 1 shows the statistical significance of each difference between the hemispheres in the spectral power of coherence. The number of 50 s segments used varied for each estimate. Each estimate of the power was derived from between 72 and 91 segments of 50 s, except for the frontal left which was derived from 43. The coherence estimates were derived from between 25 and 46 segments of 50 s, except for the frontal left which was derived from 10. Note that the greater number of significant differences in power than in coherence is due in part to these differences in the quantity of data in the estimates.

Fewer segments were used for the coherence estimates as these required both relevant channels to be free of obvious artifacts, whereas power could be calculated even when one channel did show artifacts. The power estimates did not change significantly when they were re-calculated using only the data contributing towards coherence estimates.

ANOVA analysis showed that the estimates of power did not differ significantly between sessions ($P > 0.01$) with the exception of F3/F7 ($P = 0.0003$) and P3/T5 ($P = 0.0005$). The 3 sessions, 5 frequency bands and 6 regions generated 180 comparisons; having two comparisons reaching $P < 0.01$ thus is within the range expected by chance. Coherence estimates for F4:F8 and P4:T6 during session 3 were clearly different from the other sessions. They show a fairly flat coherence across the frequency range. Anomalies were not evident in the relevant raw data. The analysis presented here included these data; discarding that data would only increase the asymmetry in estimated coherence. Coherence estimates in the other regions did not differ significantly between sessions ($P > 0.01$).

The clinical state of activity of the patient varied widely. The signals used for this analysis corresponded with periods in which the patient was observed not to be physically active. It would be interesting to compare these recordings to recordings during a more wakeful clinical state. However, the blinking, frequent chewing movements, facial muscle tension and small vocalizations that accompanied this state introduced frequent EEG artifacts that would confound a meaningful comparison.

4. Discussion

Quantitative analysis of this patient's EEG reveals a striking asymmetry in the coherence, and a more subtle asymmetry in the power spectrum. To understand this finding, we
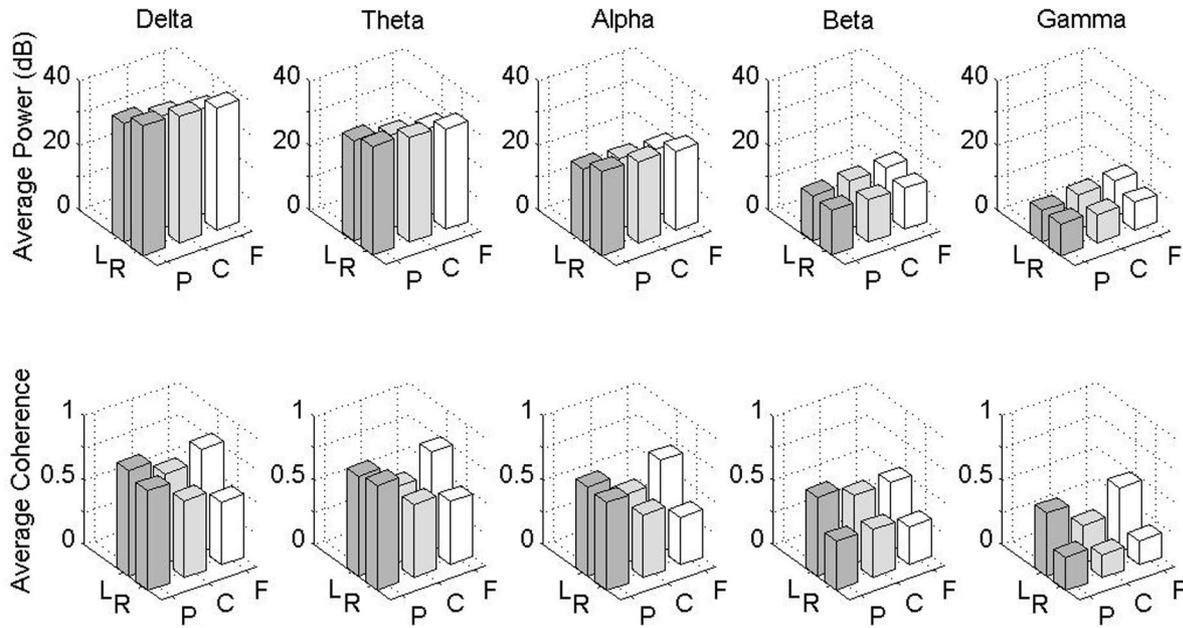
Fig. 3. Spectral power and coherence as for Fig. 2 averaged over frequency bands. Delta, 1–4 Hz; theta, 4–8 Hz; alpha, 8–13 Hz; beta, 13–30 Hz; gamma, 30–50 Hz. F, frontal; C, central; P, parieto-temporal.

consider what coherence may represent. It appears that coherence relates to communication among different neuronal populations, and that changes to those communications result in altered coherence (Newton et al., 1993; Besthorn et al., 1994; Dunkin et al., 1995). As reviewed above, several clinical studies indicate the complexity of changes in coherence associated with different patterns of brain injury. The

present studies offer a unique window into the possible role of subcortical structures in shaping the coherence architecture of the EEG. The parallel cortical-striato-pallidal-thalamo-cortical circuits (Alexander et al., 1990) are likely to be a strong source of EEG coherence (Contreras et al., 1996). It therefore seems likely that the coherence would be markedly lower in the right hemisphere of this patient given

Table 1
Power and coherence values with standard errors in the mean[a]

Band	Power					Coherence				
	Left	Right	L SEM	R SEM	Sig	Left	Right	L SEM	R SEM	Sig
Frontal										
Delta	32.59	37.66	0.31	0.77	***	0.786	0.483	0.013	0.026	***
Theta	26.94	31.30	0.26	0.80	***	0.767	0.489	0.010	0.029	***
Alpha	20.72	24.38	0.29	0.78	***	0.701	0.366	0.021	0.028	***
Beta	14.90	12.86	0.21	0.35	***	0.527	0.293	0.060	0.017	***
Gamma	10.90	8.53	0.59	0.34	***	0.489	0.186	0.083	0.035	**
Central										
Delta	34.71	38.96	0.71	0.87	***	0.694	0.592	0.009	0.021	***
Theta	28.93	32.45	0.60	0.79	***	0.593	0.564	0.021	0.031	
Alpha	21.66	24.94	0.45	0.80	***	0.533	0.482	0.016	0.025	
Beta	14.76	13.19	0.26	0.39	**	0.525	0.371	0.025	0.011	***
Gamma	10.55	8.68	0.38	0.34	***	0.296	0.175	0.031	0.007	***
Parieto-temporal										
Delta	36.71	40.05	0.79	0.80	**	0.823	0.768	0.008	0.026	*
Theta	31.36	33.61	0.72	0.75		0.778	0.809	0.012	0.022	
Alpha	22.55	25.80	0.47	0.72	***	0.695	0.679	0.020	0.024	
Beta	14.04	13.77	0.24	0.29		0.611	0.378	0.024	0.024	***
Gamma	9.66	9.83	0.27	0.29		0.490	0.258	0.038	0.037	***

[a] Sig indicates the statistical significance of the asymmetry: ***$P < 0.001$, **$P < 0.01$ and *$P < 0.05$.

the extensive damage to subcortical structures on that side. The difference in coherence between the two hemispheres is most dramatic frontally, where the damage to the subcortical structures is most asymmetric, with total destruction on the right side and some preservation on the left of the thalamus and relatively intact basal ganglia structures (Schiff et al., 1999). Coherence based on thalamo-cortical activation has been proposed to underlie integrative forebrain functions (Llinas and Pare, 1991) and damage to these connections is considered the primary basis of this patient's permanent unconsciousness (Schiff et al., 1999). The striking asymmetry of coherence in the context of our patient's pattern of injuries provides compelling evidence that subcortical structures, primarily the basal ganglia and thalamus, partly determine the coherence structure of the EEG.

Certain kinds of artifacts, such as surface EMG, are more likely to affect the high frequency bands and might result in a reduced coherence. This is not likely, however, to account for our results. While the reduced coherence was more prominent in the high frequencies, this reduction was specific to recordings over one hemisphere. Additionally, in view of the closely similar power spectra in corresponding channels between hemispheres, it is unlikely that there is a unilateral noise source that accounts for the inter-hemispheric difference in coherence. It should be noted that the low power at high frequencies does not diminish the reliability of those estimates: to a first approximation, the fractional error in a spectral estimate of a filtered Gaussian process does not depend on the frequency or amplitude, but only on the number of estimates.

It is tempting to compare the coherence levels found in this patient to those found in controls. One reason that such comparisons may not be reliable is that while the average reference potentials used here provide reasonable qualitative comparisons of coherence between lobes, volume conduction and reference effects limit the quantitative accuracy of those estimates (Nunez et al., 1999). A more fundamental problem concerns the confounding of coherence comparisons by differences in the level of arousal (Wada et al., 1996). The uncertainty in the level of arousal of this patient makes it unclear how to make a meaningful comparison of these coherence values with those of control subjects.

One study of coherence in patients with space-occupying brain lesions controlled for the level of arousal by excluding patients who had an impaired level of consciousness (Harmony et al., 1994). Similarly, they found that lesions of the forebrain were associated with reduced intra-hemispheric coherence in the damaged hemisphere. It would be most difficult to perform such a study on patients with lesions in the brainstem or diencephalon since most of these lesions will have major effects on the level of arousal. In this regard, the value of the results presented here is that there is an internal control. That is, the asymmetry of the brain damage allows us to compare the coherence in a heavily damaged hemisphere to that in a less damaged hemisphere recorded at the same time. We thus demonstrate

that the alteration of subcortical circuitry, rather than the altered level of global arousal, underlies the reduction in coherence.

Acknowledgements

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