Electroencephalographic coherence analysis in multiple sclerosis: correlation with clinical, neuropsychological, and MRI findings

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Abstract

Objective—To explore functional corticocortical connections in multiple sclerosis by means of coherence of the EEG, and to evaluate their correlations with the degree of cognitive impairment and with brain lesion load assessed by MRI.

Methods—EEG coherence was studied from 28 patients with clinically definite multiple sclerosis. Ten minutes of resting EEG were recorded with 20 scalp electrodes, with binaural reference. FFT power and coherence were calculated in artifact free epochs of 1 second and compared with values from 22 control subjects of comparable age and sex distribution. Patients also underwent MRI (n=27) and neuropsychological examination (n=21).

Results—Compared with controls, patients with multiple sclerosis showed increased 0 power in the frontotemporal-central regions (p<0.005). 0 Band coherence was decreased between homologous areas (p<0.02). a Band coherence was decreased both in the local and long distance connections (p<0.0005). These findings were most striking both in patients with high MRI subcortical lesion load and in patients with cognitive involvement. A significant correlation was found between interhemispheric 0 (p=0.02) and a (p=0.017) and anteroposterior a (p=0.013) coherence and subcortical MRI lesion load, but not with exclusively periventricular lesion load.

Conclusions—These findings support the hypothesis that cognitive impairment in multiple sclerosis is mostly dependent on involvement of corticocortical connections related to demyelination and/or axonal loss within the white matter immediately underlying the cortex.

Methods

PATIENTS AND CONTROLS

Twenty eight relapse free patients (17 men, 11 women; mean age 45.4 (SD 12) years, range 20–63; mean disease duration 12.7 (SD 8.9) years, range 2–30) affected by definite multiple sclerosis of the progressive form (16 primary progressive (PP), 11 secondary progressive (SP)), one transitional (T),) participated in the study. Neurological disability, measured using the Kurtzke expanded disability status scale (EDSS),25 was on average 5.3 (SD 1.6)
(range 2.5–8). Patients taking steroid treatment in the month before examination or under psychotropic drugs during the past 2 weeks were not included. Twenty two normal volunteers with similar age and sex distribution were also studied as controls. Patients also underwent MRI examination (except for one patient) and neuropsychological testing (except for seven patients). All patients and subjects gave their informed consent to participate in the study, which was approved by the local ethics committee.

**MRI**

Conventional spin echo dual echo (TR=2000, TE=30/80) brain MR scans were obtained using a 1.5 T machine (Siemens Magnetom SP63). Twenty four 5 mm thick axial contiguous slices were acquired, with a 250 mm field of view and a 256×256 image matrix. Patients were positioned in the scanner using published guidelines. For image analysis, multiple sclerosis lesions were counted on short echo, proton density (PD) weighted images (long echo T2 weighted images were used to increase the confidence in lesion detection). A scoring system weighted for lesion size was used to estimate the lesion loads; one point was given for each lesion with a diameter 1–5 mm, two points for 6–10 mm lesions, three points for lesions greater than 10 mm, and four points for extensive confluent lesions. Both total and regional (periventricular and subcortical) brain lesion loads were then calculated simply by multiplying the number of lesions by their individual scores. Patients were subdivided in two groups according to their median values of the total (cut off≥60) and of the subcortical (cut off≥10) lesion loads.

**NEUROPSYCHOLOGICAL EXAMINATION**

Patients underwent a comprehensive battery of neuropsychological tests: Wechsler adult intelligence scale (WAIS), Wechsler memory scale (WMS), digit span, Corsi span and Corsi supraspan, Raven, Weigl, Wisconsin card sorting test, short story, word pairs and word list, phonemic and semantic fluency, and attentional matrices. Patients were considered cognitively impaired if they failed in three or more of these tests. Nine patients out of 21 (42.8%) were classified as cognitively abnormal according to this criterion.

**EEG RECORDING AND ANALYSIS**

Ten minutes of eye closed EEG at rest were acquired using 19 Ag/AgCl electrodes, fixed to the scalp with collodion according to the 10/20 International System, with binaural reference (bp 1–35 Hz). The EEG signal was digitised (250 Hz sampling frequency) and stored for offline analysis. Artifact free epochs of 1 second were selected for calculation of fast Fourier transform power and coherence. Group comparisons of EFG absolute power were performed using the unpaired Student’s t test for frequencies between 2 and 20 Hz, in steps of 1 Hz. Coherence analysis for all electrode pairs was performed for the ì and í frequency bands (ì 4–8 Hz; í 9–12 Hz), as the major power differences between multiple sclerosis and control subjects were within these two bands (see Results section).

**STATISTICAL ANALYSIS**

We performed group comparisons of power and coherence using Student’s t test for unpaired data. Previous data from our group have shown that for each electrode pair the coherence values are distributed according to a gaussian function. The group average coherences of all patients with multiple sclerosis and control subjects were compared for each electrode pair except for the temporal electrodes, excluded from the analysis to avoid contamination from muscle artifacts. Bonferroni correction was applied to group comparisons of coherence values. Besides subdividing patients into two groups according to the presence of cognitive impairment neuropsychologically assessed, patients were also subdivided into two groups according to their total or, independently, to their subcortical MRI lesion score. For regression analysis between coherence and MRI data, coherence values for selected pairs were averaged to obtain, for each patient, a single value for anteroposterior and, separately, interhemispheric coherence. For
Each subject, anteroposterior coherence was the average of values from the midline pairs (FZ-CZ, FZ-PZ, CZ-PZ, CZ-OZ, PZ-OZ) and from pairs along the midline on the two sides (FP1-F3, FP1-C3, FP1-P3, FP1-O1, F1-C3, F3-P3, F3-O1, C3-P3, C3-O1, P3-O1, plus the homologous pairs). For interhemispheric coherence, non-homologous pairs were considered only within the distance of a single position in the anteroposterior direction according to the 10–20 system (for example, C3-F4, C3-P4); Non- homologous pairs with distance of more than two positions in the anteroposterior direction (for example FP1-C4) were not included in the average value of interhemispheric coherence, as it has been estimated that anatomical interhemispheric connections of this type are very scarce. Therefore, interhemispheric coherence was the average from the pairs FP1-FP2, FP1-F4, F3-FP2, F3-F4, F3-C4, C3-F4, C3-C4, C3-P4, P3-C4, P3-P4, P3-O2, O1-P4, O1-O2.

Results

Power

Considered as a group, patients with multiple sclerosis had a significant increase of power in the frontotemporal-central regions compared with normal subjects (p<0.05 in all frontal and central electrodes, T3 and T4; fig 1). In fig1, only patients who underwent neuropsychological evaluation were considered (n=21). A similar pattern was found in patients with cognitive impairment (n=9; five PP, four SP) if compared both with normal subjects (p<0.02 at all frontal, central, T3, and T4 electrodes; p<0.05 in all but occipital and T6 electrodes; fig 1) and to cognitively normal patients (n=12; seven PP, five SP) but the latter comparison did not reach statistical significance. Cognitively normal patients had no power difference from normal controls. No significant power difference was found when comparing patients with a high (n=17; nine PP, eight SP) versus a low (n=10; six PP, three SP, one Tr) total lesion load on

![Figure 2](image_url)

Figure 2  Group averages of absolute power maps. (A) patients with multiple sclerosis (n=12) with low subcortical lesion load (<10); (B) patients with multiple sclerosis (n=15) with high subcortical lesion load (>10); (C) group A v group B (p values; Student’s t test). Red shades in (C) represent significant power increase in group B.

![Figure 3](image_url)

Figure 3  Coherence maps. Lines represent significant (p<0.05) coherence decrease in the group of patients with multiple sclerosis who underwent cognitive tests (n=21) compared with normal subjects (n=22). Temporal electrodes were excluded from the analysis. (A) 6 (4–8 Hz); (B) a (9–12 Hz).
MRI, whereas a significant increase of δ (p<0.05 at electrodes FP1, FP2, F7, F8, T4) and θ (p<0.05 at all frontal, C3, C4, P4, T6, O1 electrodes) was present in patients with high (n=15; eight PP, seven SP) compared with low (n=12; seven PP, four SP, one Tr) subcortical lesion load (fig 2). Patients with memory impairment (n=4, two PP, two SP) had a higher power in the δ and θ bands over the left frontotemporal electrodes than normal subjects (data not shown; p<0.02 at electrodes F7, F3, Fz, T3, C3, F8, T4 for δ and at all but occipital electrodes for θ) and the other patients (p<0.05 at FP1, FP2, F3, C3, Cz for δ and Fz for θ).

**COHERENCE**

Compared with controls, patients with multiple sclerosis had reduced coherence of both θ and α bands (p between 0.05 and 0.002 for the θ band; p<0.0005 for the α band, significant if Bonferroni corrected; figure 3). In this figure, only patients who underwent neuropsychological examination were considered (n=21). θ Band coherence was reduced mostly between interhemispheric homologous electrodes or within the distance of a single position in the anteroposterior direction (P3-C4; P3-O1). α Band coherence was diffusely decreased both between interhemispheric and anteroposterior electrode pairs (figure 3). Cognitively impaired patients (figure 4) had a significant diffuse coherence decrease of the two bands compared with cognitively normal patients, in the anteroposterior and in the interhemispheric direction (p<0.0005, significant if Bonferroni corrected).

**CORRELATIONS BETWEEN COHERENCE AND MRI DATA**

No significant correlation was present between coherence and periventricular lesion load, whereas subcortical lesion load was significantly correlated with interhemispheric θ and α coherence (p=0.02 and p=0.017 respectively, figure 5) and with anteroposterior α coherence (p=0.013). The total lesion load had a correlation at the limit of statistical significance (p=0.05) only with the interhemispheric α band coherence.

Figure 4  Coherence maps. Lines represent significant (p<0.05) coherence decrease in the group of cognitively impaired (n=9) compared with cognitively normal (n=12) patients with multiple sclerosis. Temporal electrodes were excluded from the analysis. (A) θ (4–8 Hz); (B) α (9–12 Hz).

Figure 5  Regression of interhemispheric (I-E) coherence with periventricular (PV) and subcortical (SC) MRI lesion load in each patient with multiple sclerosis (n=27).
Discussion
In this study we evaluated computerised EEG spectral power and coherence in patients with multiple sclerosis, together with neuropsychological tests and brain MRI.

EEG POWER
We found a slowing of the background EEG activity in patients with multiple sclerosis compared with control subjects, together with a diffuse increase of slow oscillations in the anterior and temporal regions. Moreover, patients with memory impairment had an increase of slow components (δ and θ) in the left temporofrontal regions. Compared with normal subjects, power abnormalities were significant only in the group of patients with cognitive impairment and not in cognitively normal patients. Considering MRI, the groups of patients with high and low total lesion load had no significantly different EEG power from normal subjects and from each other. Conversely, patients with high subcortical lesion load had more θ and δ power compared with normal controls and with patients with low subcortical lesion load, who had normal EEG considered as a group. Other studies reported EEG abnormalities in multiple sclerosis, mainly increased slow frequencies and reduced α bands. Computerised spectral analysis showed a relation between disability and the amount of β activity in the frontocentral area and of θ activity in the temporal area. Moreover, after improvement due to immunosuppressive treatment, a marked increase of mean α frequency in the parieto-occipital region was present. Quattrini et al. in a 5 year follow up study, did not find a significant correlation between visual EEG abnormalities and neurological or psychiatric status, but there was a weak correlation between EEG and CT findings. Facchetti et al. failed to find a significant correlation between conventional or quantitative EEG and MRI findings or disability. Feng, at visual inspection of the EEG, found more abnormal records in active than quiescent patients with multiple sclerosis; moreover, patients with relapses had more frequent abnormalities than patients with a progressive course. In the present study, we investigated patients with a progressive form of multiple sclerosis, in which a higher prevalence of cognitive disturbances, compared with patients with relapsing-remitting disease, has been reported. Whether patients with secondary progressive disease are more affected by cognitive impairment than primary progressive ones is still a controversial issue, as this has been found by some authors and denied by others. Recent evidence, however, indicates that, when patients with primary or secondary progressive multiple sclerosis have similar disability and MRI lesion burden, the frequency and severity of cognitive disturbances do not differ significantly between these two multiple sclerosis phenotypes. This might explain why, in our study, the groups of patients with and without cognitive impairment were not clustered for either form of progressive multiple sclerosis. Our findings show that lesions immediately underlying the cortex, among other lesion locations, are the major determinant of the EEG power abnormalities encountered in multiple sclerosis. Several studies have shown a statistically significant correlation between the global cognitive impairment and the severity of white matter abnormalities of the hemispheres, of corpus callosum atrophy, and of ventricular dilatation. More strict correlation has been found between cognitive impairment and both subcortical lesion load and corpus callosum atrophy. Moreover, the analysis of regional cerebral lesion load showed significant relations with specific cognitive functions.

EEG COHERENCE
Our study has demonstrated a significant increase of frequency and severity of cognitive disturbances, compared with normal patients, both compared with normal subjects and with cognitively normal patients with multiple sclerosis, who showed no statistically significant coherence difference with normal controls. As coherence is considered as an indicator of functional neuronal connections between different cortical areas, a coherence decrease between two regions would indicate a decrease in their functional connections. Nevertheless, other factors could affect coherence estimates. Decreased coherence between O1 and O2 leads for the α-1 band and between F3 and F4 for the β-1 band has also been shown in normal subjects during light drowsiness compared with the awake state. In these findings, the decreased interhemispheric coherence for those bands was accompanied by increased coherence within the θ-1 and β-1 bands between C4 and O2. Even though we excluded through visual inspection EEG segments with signs of decreased arousal, it is possible that some decrease in interhemispheric coherence may be due to decreased arousal not evident at visual inspection of the EEG. Nevertheless, in our study the β band coherence was also decreased in patients with multiple sclerosis with cognitive impairment compared both with normal subjects and with patients with multiple sclerosis without cognitive impairment. Interhemispheric coherence for both bands was also inversely correlated with subcortical lesion load. Therefore, increased drowsiness in deteriorated patients cannot totally account for our findings. Another problem arising when interpreting coherence differences between groups is the reference used. Using a common reference (linked ears) a signal with high power (α oscillations) may produce an artificially high coherence between distant electrodes because of volume conduction. Moreover, the reference electrodes may record brain activity and project it to the EEG channels, thus artificially increasing the coherence estimates, as reported by Fein et al. If this were the case in our study, it could be possible that normal subjects, having a higher α power than patients with multiple sclerosis, display a higher α coherence.
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because of volume conduction of the oscillations. A method for reducing the signal introduced by the reference is the transformation of the data using the Laplacian operator5-55 although an agreement about the optimal computational algorithm is not completely reached56-59. For our coherence results, obtained using a common reference recording, if the finding of decreased α band coherence in patients with multiple sclerosis would be due to an artificially high α coherence in the control subjects (who had a higher α power), an increased θ coherence in patients with multiple sclerosis compared with controls would be expected, as θ power was higher in patients with multiple sclerosis. This was not the case in our findings, as both α and θ band coherence were lower in patients with multiple sclerosis compared with controls. Thus our results cannot be explained by an artifically high coherence caused by the use of a linked ear reference.

In the present study we found a significant correlation between anteroposterior coherence and the lesion load immediately underlying the cortex (“subcortical”). It has been reported that cognitive impairment is mostly related to lesions of the white matter immediately underlying the cortex, whereas no correlation between anteroposterior coherence and the lesion load immediately underlying the cortex (“subcortical”). It has been reported and the lesion load immediately underlying the cortex (“subcortical”) is the major correlate of slowed EEG activity and reduced coherence were present both in cognitively impaired patients compared with unimpaired patients and in patients with high compared with low subcortical MRI lesion load. Moreover, subcortical lesion load correlated highly with reduction of EEG coherence. Taken altogether, these data are consistent with the hypothesis that cognitive dysfunction in multiple sclerosis is dependent on the disconnection of cortical associative areas, produced by demyelination, or axonal loss, or both, in the subcortical white matter occurring in these patients.

We are grateful to Aldo Elia for the EEG recordings. This study was supported by a grant from the Istituto Superiore di Sanità (National Ministry of Health, Rome, Italy; protocol number 96J/T44).
