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Scalp electrical recording during paralysis: Quantitative evidence that EEG frequencies above 20 Hz are contaminated by EMG

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Abstract

Objective: To identify the possible contribution of electromyogram (EMG) to scalp electroencephalogram (EEG) rhythms at rest and induced or evoked by cognitive tasks.

Methods: Scalp EEG recordings were made on two subjects in presence and absence of complete neuromuscular blockade, sparing the dominant arm. The subjects undertook cognitive tasks in both states to allow direct comparison of electrical recordings.

Results: EEG rhythms in the paralysed state differed significantly compared with the unparalysed state, with 10- to 200-fold differences in the power of frequencies above 20 Hz during paralysis.

Conclusions: Most of the scalp EEG recording above 20 Hz is of EMG origin. Previous studies measuring gamma EEG need to be re-evaluated.

Significance: This has a significant impact on measurements of gamma rhythms from the scalp EEG in unparalysed humans. It is to be hoped that signal separation methods will be able to rectify this situation.

Keywords: Neuromuscular blockade; Very high frequency; Gamma oscillations; EEG; Spectra; Auditory odd-ball

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1. Introduction

High frequency EEG rhythms above 30 Hz (gamma rhythms) can be recorded reliably in experimental animals using intracerebral and subdural electrodes. In preparation for epilepsy surgery, surface and depth EEG recordings are sometimes required for localisation of the epileptogenic zone. These recordings often reveal spontaneous high frequency EEG components (sustained gamma), which increase with visual, memory or sensorimotor tasks, (induced gamma) reviewed by Lachaux et al. (2000) and Tallon-Baudry (2003). Use of indwelling electrodes is not practical or ethical in the routine clinical setting, so assessing the ability of the scalp EEG to evaluate gamma EEG is important. There is debate as to whether or not information in human scalp EEG reliably follows animal brain recordings (Juergens et al., 1999). Many suggest that changes in the EEG/magnetoencephalography (MEG)

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with cognitive tasks, despite being in areas of the scalp prone to muscle activity, show task specificity and a different profile to perceived muscle activity (Tallon-Baudry et al., 1998). It has long been assumed that scalp EEG is heavily influenced by EMG activity and so methods that attempt to remove its influence have been devised, for example, evoked response methodology. Specifically, there are well-recognised time-locked responses to stimuli that, when averaged, eradicate the influence of spontaneous EEG and artefact. These evoked-responses frequently reveal components of synchronous time-locked activity within the gamma frequency range (Herrmann and Knight, 2001) (evoked gamma) as well as non-synchronous, loosely time-locked gamma range activity (induced gamma) occurring around the time of the P3 (Herrmann and Knight, 2001) though even here there are not widely concordant data. The former is believed to reflect attention to the task and the latter generated only when a degree of cognitive reflection on the task is required. Generally, the more complex the task, the larger the amplitude of the P3 (Senkowski and Herrmann, 2002).

The scalp EEG has not been completely evaluated for routine use in measurement of high frequency rhythms. We have previously reported that sustained or induced gamma rhythms in the EEG can be recorded via scalp electrodes (Fitzgibbon et al., 2004) and that there are changes in gamma EEG power in primary generalised epilepsies (Willoughby et al., 2003). Because it is non-invasive, the scalp recorded EEG will remain an important experimental, diagnostic and research methodology in humans. Given the established relationship of various forms of gamma oscillations to conscious and sub-conscious cognitive processing, it has become an area of intense interest in states where cognition and mentation are disturbed. However, it is not yet clear how reliably induced gamma EEG can be recorded from humans because recordings obtained from ‘relaxed’ humans may be confounded by low voltage EMG activity close to the scalp electrodes (Goncharova et al., 2003), or from high voltage EMG activity from distant muscles, for example in the neck. This possibility has more than just a theoretical basis because the spectrum of frequencies in the EMG overlaps the spectrum of gamma EEG frequencies (Goncharova et al., 2003; Kumar et al., 2003).

We aimed to identify the influence of EMG on EEG by taking scalp recordings from subjects before and after complete neuromuscular blockade, thus enabling a direct comparison to be made between recordings when EMG activity might be a significant confounding component of the EEG and recordings when all skeletal muscle activity was blocked. Given the view that valid gamma EEG can be extracted from time-locked signal averaging of EEG, eg during evoked responses, an auditory odd-ball task was also undertaken, so providing, under normal and paralysed conditions, a comparison of evoked and induced EEG changes during pre-cognitive and cognitive processing.

2. Methods

The study was approved by the Clinical Research Ethics Committee of Flinders University and Flinders Medical Centre. Two male individuals (one right-, one left-handed) associated with the EEG research group were subjects. They were familiar with the scientific background and purpose of the study and gave written, informed consent for the procedures.

2.1. Environment

The recordings were made in a room-sized Faraday cage in an EEG laboratory. The subject was seated on a chair, legs elevated, in a supported position that required no change after paralysis. Ventilator and monitoring equipment were located outside the cage and the existing Faraday cage ports were used for lines and airways. A neurologist and one anaesthetist remained in the cage throughout the experiment and a second anaesthetist, outside the cage, controlled the ventilator and undertook monitoring. The entire procedure was rehearsed until the protocol (Table 1) ran smoothly, including in one subject a session with paralysis, which had the aim of diminishing the novelty/expectation of paralysis by the subject. Communication was via a simple yes-no finger tapping routine that was utilised for both arms of the experiment (Gandevia et al., 1993).

2.2. EEG recording

One hundred and fifteen channels of EEG were recorded continuously (left ear reference, 5000 samples per second, 16-bit analogue to digital conversion, 1250 Hz low-pass filter) using a commercial EEG acquisition system (NeuroScan, Compumedics, Victoria, Australia). Given the clear expression in animals of gamma oscillations above 100 Hz (Siegel and Konig, 2003) and of very high frequency EEG in direct recordings (600 Hz) from brain surface (Baker et al., 2003), we chose the very high sampling rate of 5000 per second. A 128-channel electrode cap with Ag–AgCl electrodes (Easy Cap Falk Minnow, Germany) was used to provide uniform scalp coverage. The electrode distribution relative to the 10/20 system is illustrated at http://www.easycap.de/easycap/e/electrodes/11_M15.htm. Electrode impedances were kept below 5 kOhm. Some electrodes were removed from the EEG cap for use in recording EOG, ECG, respiration, left forearm (extensor indicis) EMG, left and right masseter EMG and left and right cervical para-spinal muscle EMG.

2.3. Mental tasks

Recordings were undertaken during different mental tasks listed in Table 1 in both unparalysed and paralysed conditions. Gamma correlates of the mental states are to be presented in separate paper, but for the purpose of

Table 1
Summary of tasks and procedure

Pre-paralysis study	Paralysis study
Finger tapping left and right	Sphygmomanometer cuff inflation, non-dominant arm
Sphygmomanometer cuff inflation, non-dominant arm	Paralyse (cisatracurium)
Deflate sphygmomanometer	Adjust ventilation
Rest 1 min	Check paralysis (measure motor action potential in extensor digitorum brevis)
Eyes closed	Eyes closed
Left eye held open	Left eye held open
Eyes closed – strobe	Eyes closed – strobe
Left eye held open – strobe	Left eye held open – strobe
Oddball paradigm	Oddball paradigm
Subtraction	Subtraction
AVLT	AVLT
Auditory discrimination	Auditory discrimination
Finger tapping non-dominant (actual) and dominant (fictive)	Finger tapping non-dominant (actual) and dominant (fictive)
	Deflate sphygmomanometer
	Rest 5 min
Head muscle contraction (masseter, frontalis, paraspinal)	Head muscle contraction (masseter, frontalis, paraspinal)
Eyes closed	Eyes closed
Left eye held open	Left eye held open
	Finger tapping left and right (actual attempted)
	Undertake experiential tests
	Sedate (propofol and fentanyl)

testing for contamination by EMG, each task was assumed to provide a different sample of EEG.

Baseline state. The subjects were recorded for 10 s with eyes closed, then with the left eye held open. This was repeated at the conclusion of each batch of tests.

Photic stimulation. Photic stimulation was undertaken at 16 Hz, and EEG recorded for 10 s with eyes closed, then with the left eye held open.

Oddball paradigm. Tones of low (500 Hz) or high pitch (1000 Hz) were presented randomly for 50 msec every second and the subject instructed to key press only in response to hearing high tones (25% of 180 stimuli over 3 min). The fewest targets deemed likely to generate an evoked response were used given the time restraints of the experiment (Lopes da Silva, 1999).

2.4. Paralysis

Intravenous glycopyrrolate (0.4 mg i.v.) was used to diminish oral secretions. This is a synthetic quaternary ammonium compound designed for peripheral anticholinergic effects and poor CNS penetration. Topical pharyngeal lignocaine was used to provide anaesthesia in preparation for insertion of a laryngo-pharyngeal mask airway. The paralysant was cisatracurium, 20 mg given by intravenous injection. Blood pressure, expired CO_2, finger oxygen saturation, ECG and respiratory movement were all monitored. Muscular paralysis was evaluated by right common peroneal nerve stimulation to extensor digitorum brevis. The motor action potential was fully abolished about 5 min after administration of paralysant; it was not until this point that the experiment was commenced, thus ensuring complete neuromuscular blockade and stabilisation of ventilation.

2.5. Sphygmomanometer cuff inflation

The non-dominant arm was isolated from the effects of paralysant by inflation of a manual sphygmomanometer cuff to 1.5 times resting blood pressure (∼220 mmHg). This allowed finger signalling for communication and task responses for up to 18 min, at which time anoxic paralysis of the arm began and the cuff was deflated. In the pre-paralysis session, the cuff was inflated for the control recordings only 2 min because, in practice sessions, a prior period of prolonged cuff inflation shortened the length of time the arm was able to function in the second period, compromising communication, which was essential for the paralysis session.

2.6. EEG analysis

Analysis was undertaken using programs written using Matlab (Matlab, The Mathworks, Natick, Massachussetts, USA). EEG recordings were recalculated to provide linked-ear referencing for all analyses and figures. All uncontaminated EEG for each task (usually around 10 s) was epoched into consecutive blocks ranging in size from 512 to 4096 samples (1/10–8/10 s approximately) providing close to 10–1.25 Hz resolution. Each epoch was transformed from the temporal domain to the frequency domain using fast Fourier transformation (1.25 Hz resolution, 4096 point block-size, Hamming window (default Matlab function, giving full weight to mid-point sample only, 1–2500 Hz)). The frequency spectra were averaged for each task to yield an averaged power spectrum. To ensure data were not contaminated by 50 Hz mains frequency, power values in the 50 ± 1 and harmonics were omitted from analysis. In figures illustrating raw EEG, 50 Hz contamination

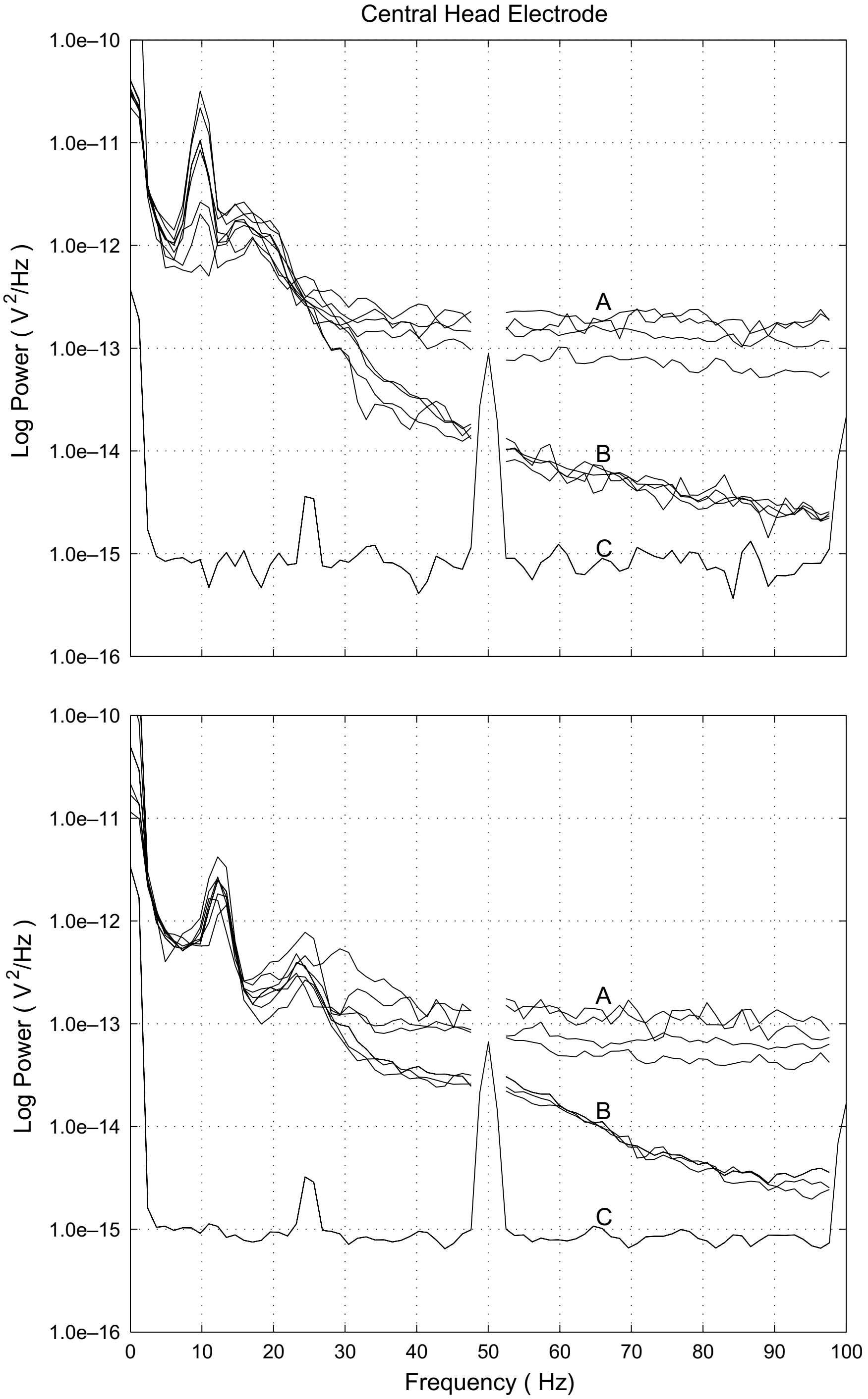

Fig. 1. Log power spectral density of unfiltered EEG from one electrode (right para-sagittal, between CPz and Pz), typical of all electrodes, in 3 conditions, in each of two subjects (upper and lower). (A) Unparalysed recumbent; (B) paralysed recumbent both showing results for tasks of modified AVLT, finger tapping, auditory discrimination and eyes closed; (C) recording of activity in Faraday cage with electrode cap in water, illustrating the electrical noise floor and 50 Hz (±1) plus harmonics.

of the signal has been removed by filtering using sequential median of 51 samples. In some instances, ‘relative power’ is illustrated. Relative power for a task was obtained by expressing EEG power for that task as a ratio to EEG power for a control task, ie the eyes-closed condition, or unparalysed vs paralysed conditions. No change in power from the control state returns a value of 1, and reductions relative to the control state return a value between 0 and 1.

Averaged evoked potentials were calculated for target (high tone) and non-target (low tone) stimuli from the recorded data, using a band filter of 0–25 Hz; averaged potentials were base-lined to the EEG of the preceding 100 ms. In addition, time frequency plots of the un-averaged, unfiltered, data were generated (EEGLAB Toolbox (Delorme and Makeig, 2004)) to visualise evoked and induced gamma frequencies with FFT of 512 samples of data and 90% overlap of consecutive epochs to provide temporally smooth images.

Analysis programming was shown to be robust, as the raw data subjected to independent analysis in another laboratory yielded the same results.

To provide a comparison for the current subjects, examples of high frequency measurements from other non-paralysed subjects are shown. Recording conditions were identical in most respects except that the unparalysed subjects were seated upright in the chair and EEG was collected at a sampling rate of 2000 samples per second.

3. Results

The subjects tolerated the procedure without adverse effects and experienced the procedure with feelings of alertness and anticipation. They felt muscularly relaxed and comfortable in both non-paralysed and paralysed phases of the experiment and there were no changes in posture or facial expression due to paralysis. All tasks were performed accurately in both phases of the experiment and the subjects found no perceived difference in the execution of the tasks in the presence of paralysant or antisialogogue, suggesting, there were no subjective central effects of these agents, as previously described (Smith et al., 1947; Topulos et al., 1993). There were increases in blood pressure from

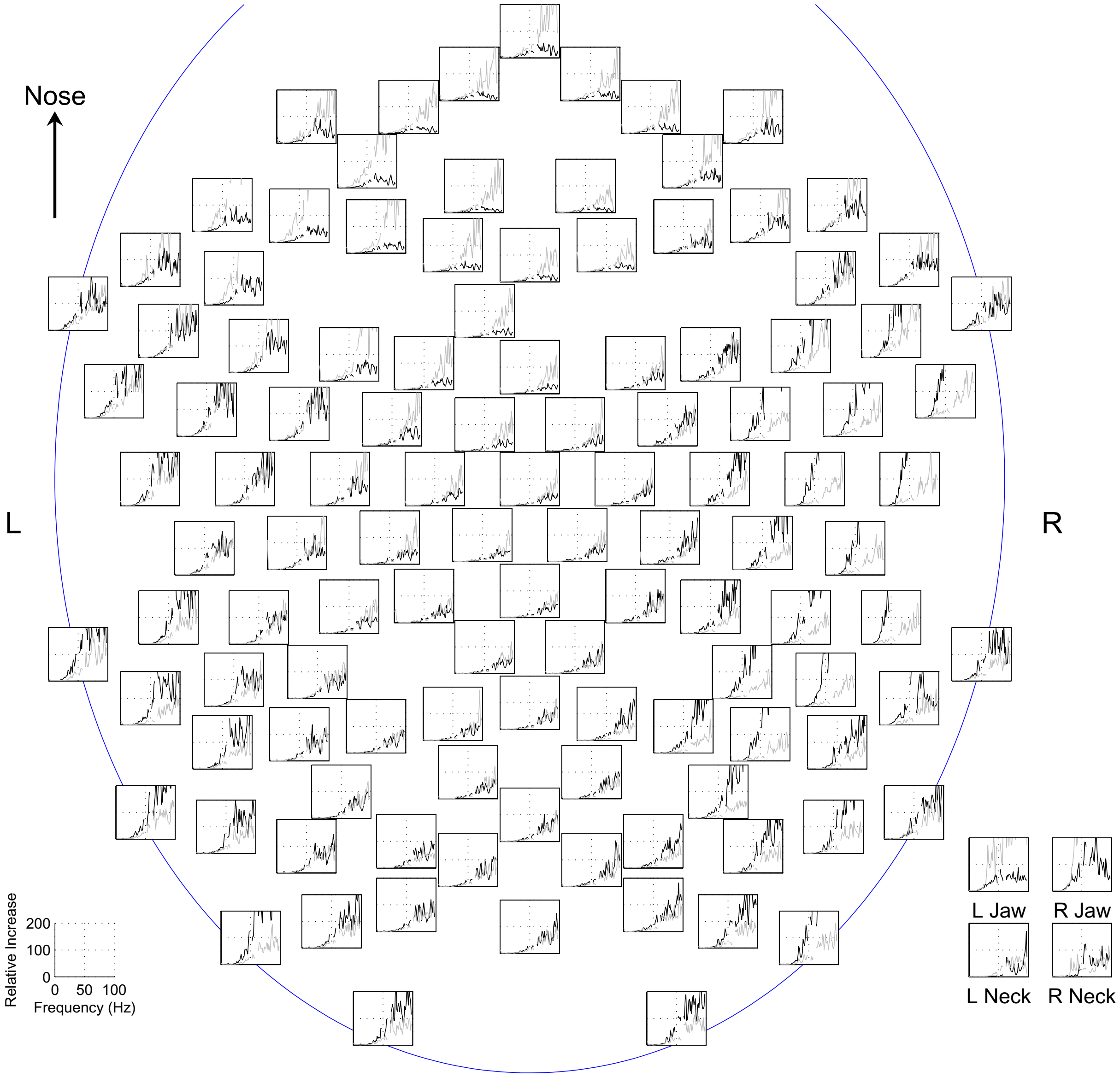

Fig. 2. Whole head montage of relative (unparalysed vs paralysed) spectral power of unfiltered EEG in two subjects (black and grey lines) in the condition of eyes-closed. The relative contribution of EMG activity to the spectra at high gamma frequencies is most striking in electrodes around the base of the scalp (up to or above 200-fold) and is least centrally (∼10- to 100-fold). Spectra from cervical and jaw muscles are shown below (right). These confirm cervical muscle activity even in the resting recumbent state and also the differential between left and right jaw activity due to the laryngeal mask position in one subject.

normal to around 200/100 in both subjects during both phases of the experiment. Ischaemic paralysis of the cuff-protected arm occurred after 18 min in one subject, allowing completion of only one cycle of the motor task during paralysis.

3.1. EEG

The EEG was contaminated by a 50 Hz (mains frequency) signal which, in separate testing studies, was shown to be present inside the Faraday cage even when all electrical equipment and power sources were inactivated and with the 128 channel Falk Minnow cap immersed in water. Recordings of this test situation provided the electrical noise floor for the experiment as shown in Fig. 1, graph C. The origin of the 50 Hz contamination was therefore located within the amplifiers or the hospital environment.

In every experimental condition, paralysis resulted in a marked reduction in the spectral power from 20 Hz to above 300 Hz, which reached a level of 100-fold in the 40–100 Hz range (Fig. 2). At 25–30 Hz, the lower boundary of gamma EEG frequencies, the reduction of power after paralysis is approximately 6-fold. Expressed differently, in this frequency range, 84% of the power in the EEG signal is derived from electrical activity which is abolished by paralysis ie, EMG.

A direct comparison of power at each electrode during a single task (eyes closed) in un-paralysed and paralysed states is illustrated in Fig. 2. The relative increase in power between the paralysed and un-paralysed state exceeds 200-fold in the basal areas of the scalp, adjacent to frontalis, temporalis and spinal muscles and, in one subject, worse on the right side where the pharyngeal tube rested. The appearances are representative of all tasks. In the central scalp region, surrounding the vertex, the effect of paralysis is least, but even here the power in the absence of EMG activity is different by 10- to 20-fold in the 50–100 Hz range. In the low gamma/high beta range of 25–30 Hz the contribution of muscle activity in the central scalp region varies from 1-fold (no increase) to 6-fold depending on the subject, the exact frequency and the location within the central scalp area.

Once the magnitude of the muscle artefact was appreciated, we examined selected subjects from an ongoing larger study. There was considerable inter-subject variability in the power of high frequency EEG/EMG contamination (above 20 Hz) (Fig. 3). When comparing other subjects, recorded in the upright position with eyes closed, with the paralysed results, it was clear that the majority of subjects have either intermediate or high amounts of what we suggest is EMG contamination (Fig. 3). There were a few subjects (three of 650 subjects) who under these conditions had a very similar spectral profile to the paralysed state, though this was only over the central head area. Interestingly, these subjects' power spectra increased to the higher levels when undertaking mental tasks (data not shown), indicating activation of scalp and neck musculature to levels seen in other subjects.

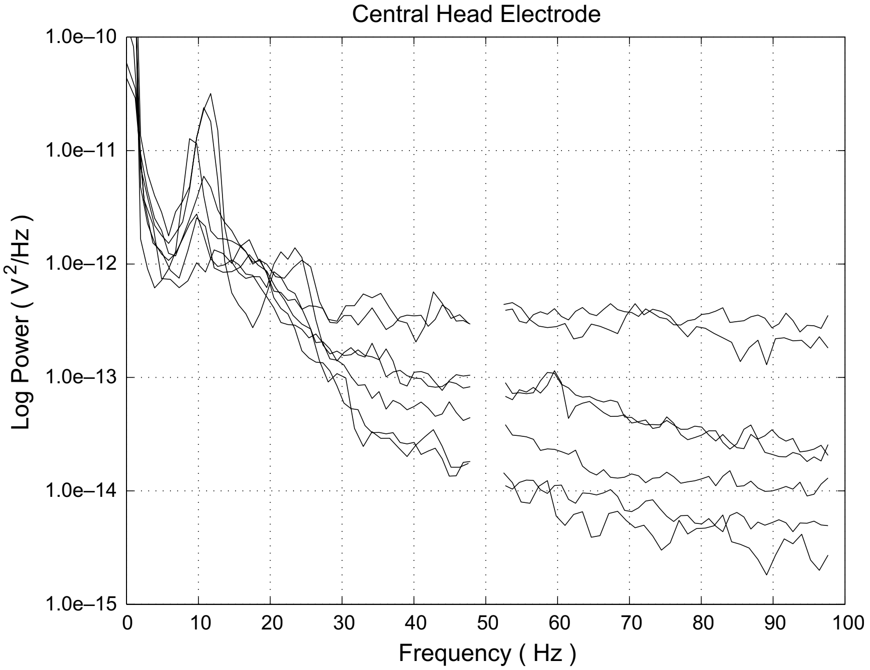

Fig. 3. Log power spectral density of unfiltered EEG from a representative electrode (right para-sagittal, between CPz and Pz) from several individuals recorded for a separate study. Each line indicates a power spectrum from different individuals in the eyes closed state, showing the variability between subjects. The two graphs with the lowest power spectra at high frequencies are from the paralysed subject and one of the three individuals whose resting spectra were virtually identical to the paralysed subject. 50 Hz (±1) and harmonics have been removed for clarity.

3.2. Time-locked EEG averaging

The oddball task was performed with 100% accuracy. The early components of the evoked response (N1, P2) were easily identifiable, but in one subject the ERP lacked a significant P3 component in the pre-paralysed state (Fig. 4). This was possibly a reflection of the heightened state of arousal of the subjects in the early part of the experiment, which then settled. We attempted to diminish this possibility with practice sessions, but it may be that arousal is unavoidable given the invasive nature of the pharyngeal intubation.

In all tasks performed during paralysis, increases of 1.5- to 3-fold were seen over relatively narrow band gamma frequencies (30–40 Hz), more on the left in the right-handed subject and *vice versa* including the oddball paradigm illustrated in Fig. 5 (full results to be published separately). To identify the distribution of the oddball response, we examined topographic plots of the time-frequency analysis, which showed that the only gamma response present in both subjects was most prominent in the non-dominant hemispheres posteriorly. Based on this observation we examined the averaged, 1.2 Hz resolution, relative spectral responses for this task and chose to display in Fig. 5 the spectra from electrodes that most clearly demonstrated a gamma change in these regions. Time frequency analysis showed this gamma increase to appear around 50 or 110 ms in the two subjects after the tone presentation and be maximal in the dominant anterior occipital area (see Fig. 6). Analysis of averaged time locked oddball data did not reveal any earlier gamma frequencies, contrasting with the findings of other groups in unparalysed subjects. Time frequency plots did not reveal changes in gamma power in the unparalysed state that had any similarity to findings in the paralysed state (Fig. 6). In other unparalysed subjects there were task-induced increases of broad

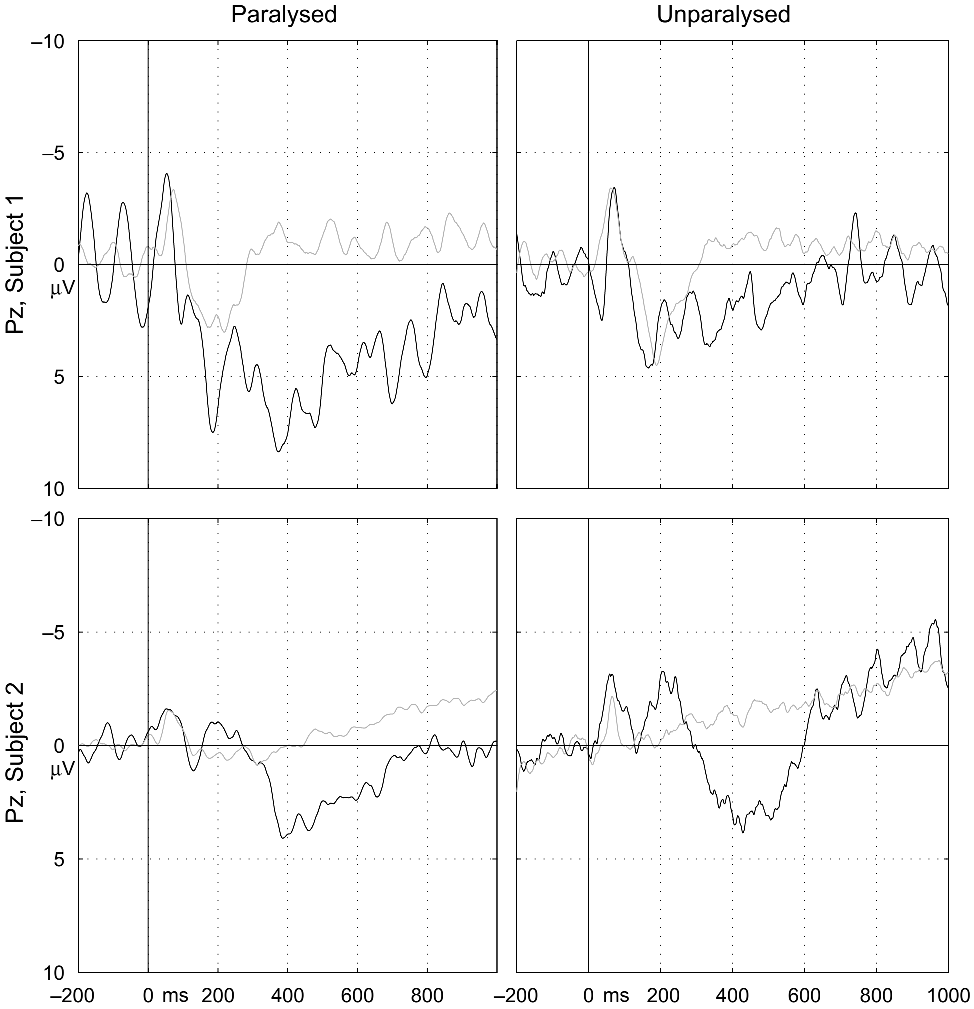

Fig. 4. Auditory evoked responses from electrode Pz (0–25 Hz filtered) to the oddball paradigm. The two traces on the left are in the paralysed state, those on the right unparalysed; upper two traces are subject 1 and lower two traces are subject 2. The black lines represent the response to the target tone (1000 Hz, $N = 45$) and the grey lines to the expected tone (500 Hz, $N = 135$). All responses are compared to the 100 ms preceding the tone. There is an evident N1 in all cases that is perhaps more prominent in the unparalysed state. In subject 1, there is a P3 to target tone only in the paralysed state from 300 ms not obvious in the unparalysed state.

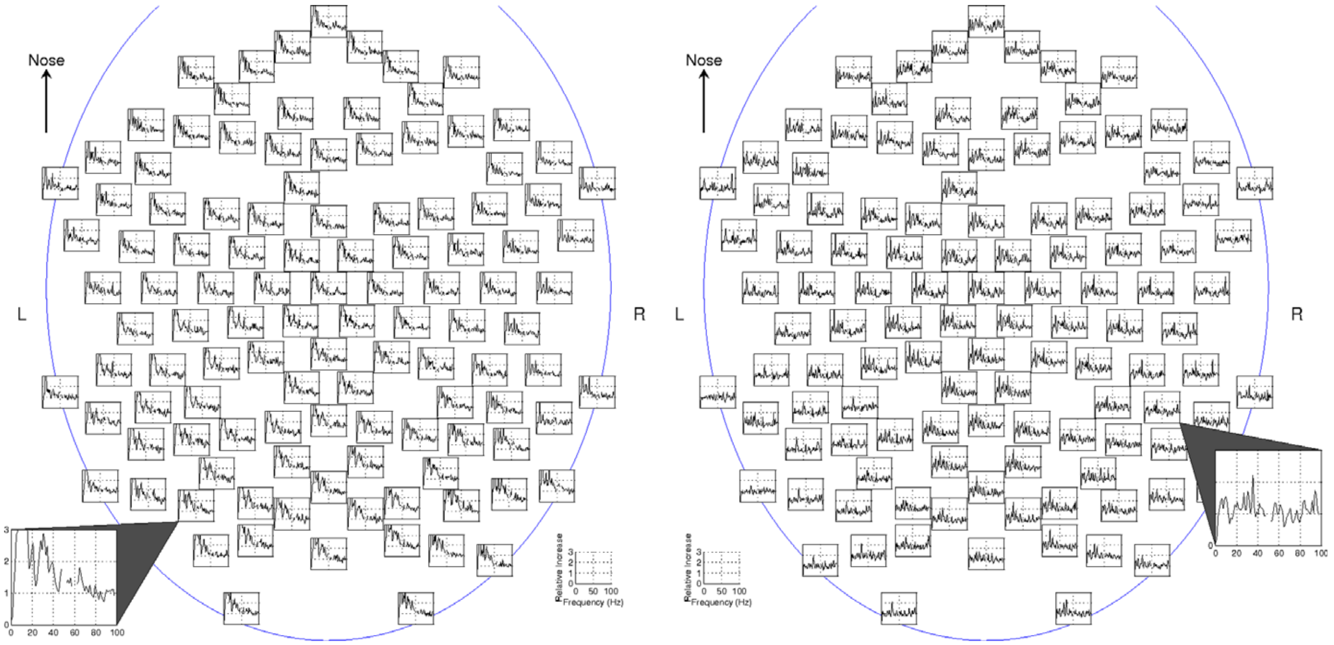

Fig. 5. Relative power increase in two subjects of unfiltered EEG during the odd-ball task in the paralysed state, in which spectra were calculated from 0.5 s before to 0.7 s after the tone; power relative to continuous EEG from the eyes-closed state. Figures are the average response of all tone presentations (similar results for target or expected tones – not shown). The insert shows a single electrode in magnification chosen to demonstrate the power changes in more detail.

band gamma frequencies (sometimes up to and beyond 100 Hz). This was especially the case for finger tapping, suggesting that the increases were due to EMG artefact, masking the much smaller narrow band EEG increase.

Given the contribution of EMG activity to the spectrum above 20 Hz, we examined the change in spectra caused by motor and other tasks, both in peripheral (forearm extensor) and cranial and cervical muscles. There was co-activation of non-dominant forearm muscles during tasks not related to forearm function. The power spectral densities during key presses (finger tapping), jaw clenching, frowning and neck extension are illustrated in Fig. 7. Activation to a greater or lesser degree can be seen in the forearm muscles during all four tasks, which is abolished by paralysis. The extent of this is illustrated in Fig. 7, where even fictive movement of the right finger (Fig. 7 line E) generates apparent EMG increases on the contralateral side. Similarly, scalp recordings adjacent to muscles show the capacity for mental tasks to activate cranial EMG activity (Fig. 8).

4. Discussion

This study reveals that EMG contaminates the majority of the routine scalp EEG at frequencies above 20 Hz. The most striking feature of the power spectrum after paralysis is the power reduction of frequencies above 20–30 Hz (Fig. 1). In the unparalysed state, high frequency power was most evident in lateral and posterior leads, consistent with a localisation close to cranial and cervical muscles. However, even centrally and frontally placed electrodes exhibited high power relative to the paralysed state, indicating a large muscle contribution to apparent EEG, approximating a minimum of a 10-fold of muscle over brain. Similar activity, relative to a relaxation condition, was demonstrated by Goncharova and colleagues (Goncharova et al., 2003) in subjects undertaking voluntary contraction of scalp muscles. However, here we demonstrate that even the relaxed state is characterised by some activity in scalp musculature. To emphasise this point, Goncharova and colleagues identified characteristic patterns of contaminating EMG activity in some scalp electrodes, which implies that meticulous techniques of EEG recording will minimise artefact (Goncharova et al., 2003), however, we demonstrate that even with the best practices, relaxed EEG is still significantly contaminated by EMG. The source of the myogenic signal in central electrodes is not obvious. EMG may be projected from cervical muscles, which are largely orthogonal to the central and frontal scalp and which can be seen to be active in the recumbent relaxed state (shown in Fig. 2). An aspect of the study that cannot be overlooked is the effect of high-alertness experienced by the subjects, a state associated with a sustained increase in blood pressure and pulse. It is feasible that the resting non-paralysed high level of gamma frequency activity ie EMG, is enhanced by the very alert state of the subject. Under more usual circumstances, resting EMG might not be so evident, so our findings may be on the high side of what might normally be expected. The wide range of findings in normals having regular EEGs supports this possibility, even so, in a small proportion of normal EEGs, high frequency spectral power is similar to that

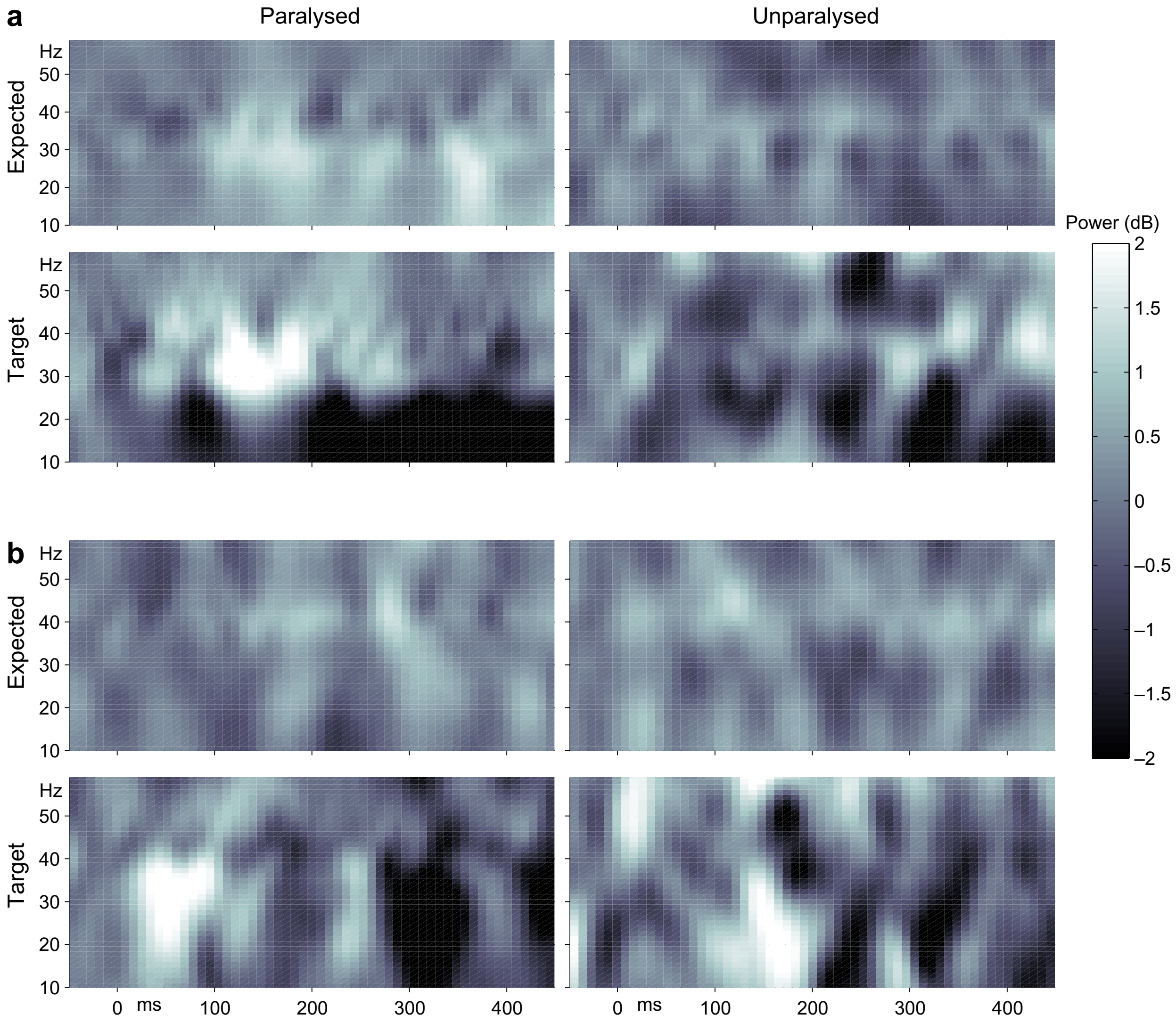

Fig. 6. (a) Time frequency plot of unfiltered EEG for the right-handed subject from a left anterior occipital electrode (highlighted in Fig. 5) for the oddball paradigm in the paralysed (left placed plots) and unparalysed (right placed plots) states. The grey scale colour is in dB with white representing a 2 dB (1.6-fold) increase in power. The upper two plots are results for low (expected, $N = 135$) tones and the lower plots for high (target, $N = 45$) tones only. Gamma increases are visualised at 110–200 ms in the paralysed state, but not for the unparalysed state, this is present for both target and expected tones and likely represents induced gamma, though not visualised in the presence of muscle. (b) Corresponding oddball study in the left-handed subject from a right occipito-parietal electrode. As in (a), gamma increases are visualised in the paralysed state, but not in the unparalysed state, although with a shorter latency of approximately 50 ms.

observed in the non-paralysed state in our subjects (Fig. 3). Divergence of unparalysed and paralysed spectra is demonstrable above 20 Hz, and not below, provides reassurance that EMG contamination is unlikely to be a problem in routine EEG. If there is a contribution of EMG to resting EEG below 20 Hz, a reliable estimate of this and its variance, will require more studies of this type.

It is theoretically possible that some of the changes seen are the result of central effects of the paralysant and not solely due to muscle paralysis. It is understood that cisatracurium effects are specific for the peripheral postsynaptic nicotinic receptor at the neuromuscular junction, with little effect on ganglionic receptors or the vagus and little carriage across the blood brain barrier. Cisatracurium, has several metabolites one of which, laudanosine has been reported to have cerebral excitatory effects in animals at high doses only (Kisor and Schmith, 1999). Certainly, paralysis experiments with vercuronium and curare have identified no subjective or objective effect on mental state (Smith et al., 1947; Stevens et al., 1976; Topulos et al., 1993). In the former experiment there was no effect of intravenous curare on visual blockade of alpha rhythm from the scalp EEG. Our subject's experience would concur with no subjective effect on mental state and certainly all the tests were completed with identical accuracy in both states and there were measurable narrow band gamma increases to mental tasks, suggesting responsiveness to the task at hand. The other possibility is of central effects

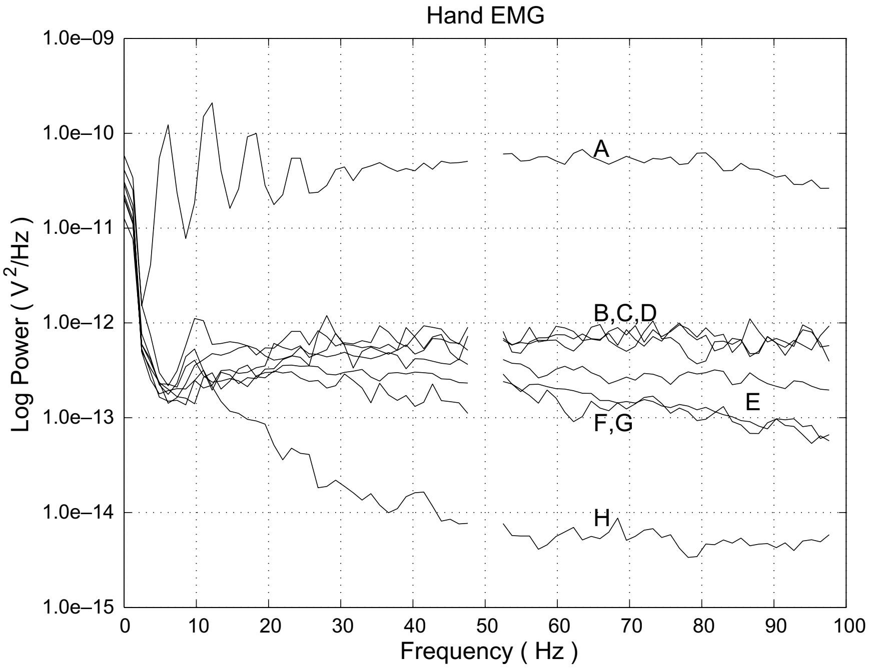

Fig. 7. Log power spectral densities from bipolar electrodes situated over the extensor indicis of the left arm in subject 1 during various motor tasks. Muscle activities are as follows; A, left finger tapping; B, bite; C, neck muscle contraction; D, frown; E, fictive right finger tapping; F, AVLT; G, pre-paralysis eyes closed; H, paralysis eyes closed. Again 50 ±1 Hz and harmonics are omitted for clarity. This figure illustrates that scalp muscle contractions and fictive movements of the contralateral finger influence EMG of forearm.

of the antisialogogue, anticholinergic agent glycopyrrolate, though this was present throughout both parts of the experiment and thus unlikely to contribute to differences between the arms of the experiment. Glycopyrrolate also was used in these procedures preferentially because it is a peripherally acting agent with poor CNS penetration. This fact is supported by an experiment of auditory evoked MEG responses (40 Hz) and effect of anticholinergics, where glycopyrrolate was used as control (ie without central effects) and failed to alter MEG evoked responses (Ahveninen et al., 2002), compared to scopolamine.

We were only able to detect gamma EEG changes to the oddball paradigm in the paralysed state and at different latencies of 50 and 110 ms. These did not appear in the usually reported frontal areas but were limited to areas much more posteriorly. Also, we were unable to reproduce this observation in the unparalysed state, which suggests that at least in our hands, using this oddball paradigm, that EMG obscures this aspect of information processing. Despite obtaining a reproducible P3 to the target stimulus in the paralysed state, we did not detect any increase in gamma frequencies around the 300 ms point. The early gamma increases at 50 and 100 ms are likely to represent some form of induced gamma. Given the variation in findings in two subjects, it remains unclear if these changes are typical of the oddball response. The gamma responses were found in somewhat unexpected brain regions. Given a 50 ms auditory signal, very short latent gamma increases (5–60 ms) might have been expected in posterior temporal locations and the later discrimination stage in pre-frontal regions. Neither of these was identified. A possible explanation for what was found may be that the concepts 'high' and 'low' may actually be 'visualised' and therefore gamma appears in non-dominant posterior parietal/occipital regions. We are not the first to report absence of ~300 ms induced gamma changes in the presence of measurable P3 to an oddball task (Juergens et al., 1999) and Sochurkova et al. were unable to detect gamma changes to a motor task with intracerebral recordings (Sochurkova et al., 2006). In the unparalysed condition, there were no corresponding increases in the time-frequency plot at gamma frequencies. We were not able to obtain time-locked evoked increases in gamma in either state.

Previously reported induced gamma is often seen over scalp areas where we have shown a high degree of muscle artefact, ie occipital and temporofrontal areas. It is often-argued that these gamma changes do not reflect muscle because passive tasks elicit no change (Tallon-Baudry et al., 1998). However, it is conceivable that tasks where cognitive effort is required actually manifest as muscle activity, hence when presented with the expected no response component of these tasks the subject remains "relaxed". In support of this has been our observation that there is a correlation of increasing power of high frequency scalp EEG with increasing task difficulty, evident throughout the whole of the scalp recording (data to be reported).

Reviewing the experimental data from our ongoing clinical study reveals how large a variation in high frequency activity there is between different individuals. Of 650 subjects, there were only a few subjects who, when at rest,

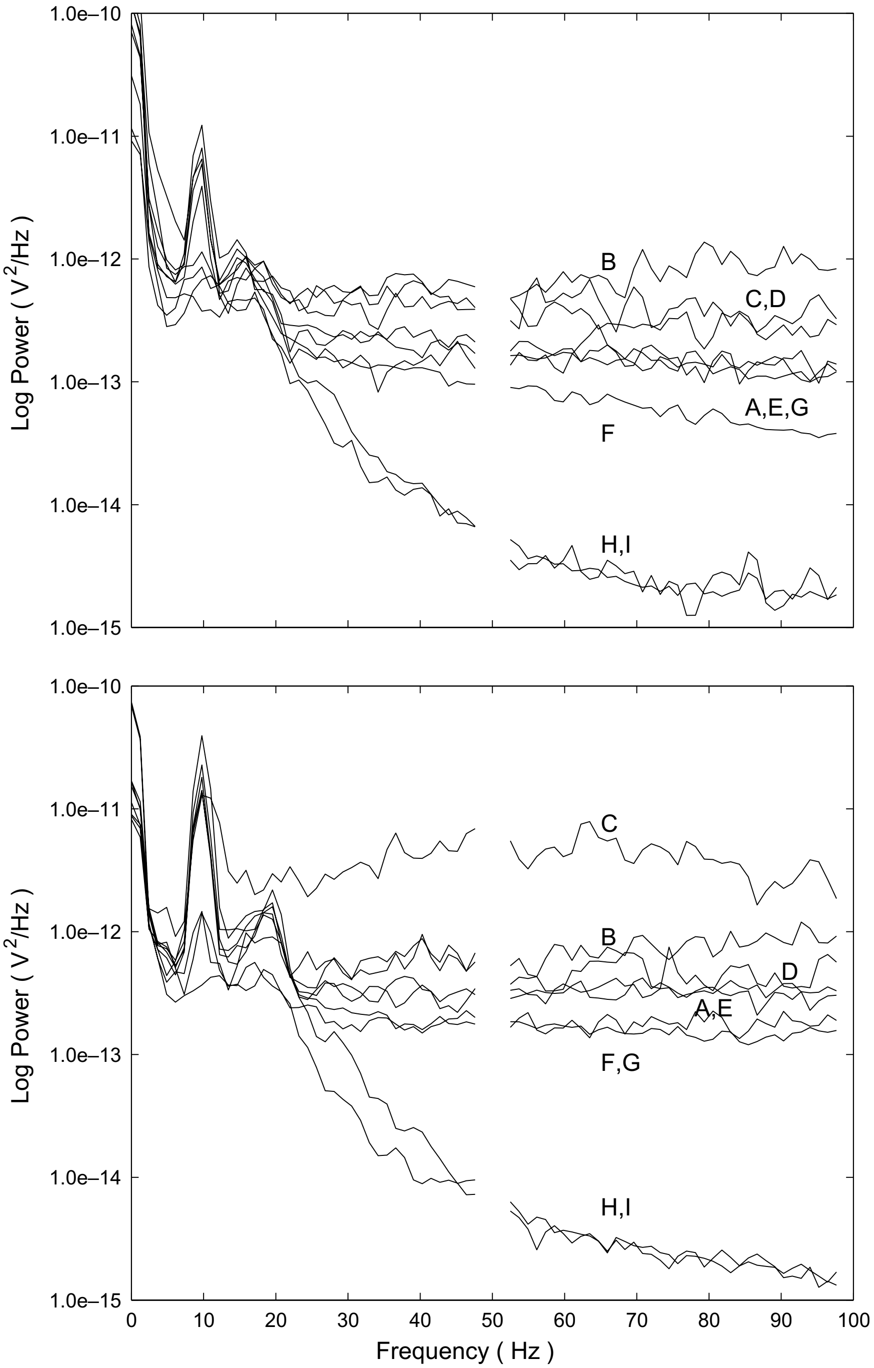

Fig. 8. Log power spectral density from scalp EEG in subject 1 shows the capacity for mental tasks and head/neck muscle activity to influence scalp muscle activity. Data are shown of spectra from two electrodes selected from EMG prone scalp areas from the left temple (upper plot) and from the right occiput (lower plot). Lines A–H are same as those illustrated for Fig. 7. Not only do the EMG activating-tasks influence the spectrum above 20 Hz but also the cognitive tasks are different from the eyes closed task, though similar in the occipital area.

exhibited a power spectrum almost equivalent to the paralysed subjects in the eyes closed state (Fig. 3). This tended to be in electrodes on the central head, ie removed from larger muscles. Also, high frequency power in the spectrum of these subjects increased during mental tasks, consistent with mental effort being associated with activation of muscle of the scalp, face and neck. We have shown that voluntary muscle contractions in the scalp are associated with muscle activity far removed from the scalp (Fig. 7) and vice versa (Fig. 8). It is a powerful observation that even fictive movement of the contralateral finger influences the activity of the ipsilateral muscles that are expected to be 'relaxed'. This may be in part explained by the complex perceptual mechanisms required to 'visualise' such a task. Even so, it is clear that there is widespread activation of distant muscles even during apparently simple motor tasks and also during mental activity. Perhaps such non-specific activation of muscular activity may be related to the expression of preparedness for primitive states of fight or flight, evolutionarily important states of mental activity.

This study highlights the limitations of scalp EEG for acquiring and measuring high frequency EEG rhythms, especially if interest is on sustained or induced gamma. The findings of this study indicate that our earlier studies (Willoughby et al., 2003; Willoughby et al., 2003; Fitzgibbon et al., 2004) have inappropriately relied on high frequency scalp recordings as a measure of EEG, a conclusion that may also apply to some studies of others. Our findings provide more evidence for Juergens and colleagues (Juergens et al., 1999) to support their view that "Minute task-dependent activations of head-muscles can, therefore, mask the very small gamma-components of cortical origin. Even worse, they may be misinterpreted as stimulus-modulated gamma-components." The underlying hypotheses relating to our papers remain to be evaluated using improved methodology. It is evident, though perhaps not surprising, that mental activity causes activation of scalp and neck muscles. Clearly it is not feasible to paralyse subjects for routine scalp EEGs, so we are now endeavouring to utilise optimal quantitative EEG methodologies (Tenke and Kayser, 2005) and signal extraction techniques to identify EEG at gamma frequencies, specifically using current source density methodology and amplitude spectra. We have already used data from the paralysed state in tests of blind signal separation algorithms to identify which are likely to be most robust in addressing this question (Fitzgibbon et al., in press). In particular, this evaluation does suggest the theoretical usefulness of principle components analysis when dealing with large amounts of EMG contamination.

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