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Polysomnographic and quantitative EEG analysis of subjects with long-term insomnia complaints associated with mild traumatic brain injury

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Abstract

Objective: The aims of this study were (1) to characterise the extent and nature of disrupted sleep in individuals with long-term sleep complaints subsequent to mild traumatic brain injury (MTBI), and (2) to determine whether sleep disturbances in MTBI subjects were more characteristic of psychophysiological, psychiatric, or idiopathic insomnia.

Methods: Nine MTBI patients (27.8 months post-injury; SD = 15.5 months) and nine control subjects underwent polysomnographic testing and completed self-report questionnaires on sleep quality. Power spectral (FFT) analysis of the sleep onset period was conducted, with both the power and variability in power being quantified.

Results: Individuals with MTBI exhibited long-term sleep difficulties, along with various cognitive and affective abnormalities. The MTBI group had 4% less efficient sleep ($p = 0.019$), shorter REM onset latencies ($p = 0.011$), and longer sleep onset latencies, although the latter were highly variable in the MTBI group (F-test: $p = 0.012$). FFT analysis revealed greater intra-subject variability in the MTBI group in sigma, theta, and delta power during the sleep onset period.

Conclusions: MTBI patients with persistent sleep complaints differ significantly from controls on a number of electrophysiological outcomes, but could not be easily classified into existing insomnia subtypes.

Significance: Sleep disturbances can persist well after the injury in a subset of patients with MTBI.

Keywords: FFT; Head injury; Insomnia; Mild traumatic brain injury; Post-concussion syndrome; Sleep disorders

1. Introduction

Mild traumatic brain injury (MTBI) affects approximately one in two hundred people every year (Bazarian et al., 2005) and is associated with various cognitive, affective and physical difficulties, which can persist well after the injury, and are often subtle and go unrecognised (Gronwall, 1989; Eide and Tysnes, 1992; Segalowitz and Brown, 1991; Segalowitz and Lawson, 1995; Wang et al., 2006). While there is some disagreement in terminology, mild head injury is defined as a loss of consciousness of 20 min or less with a Glasgow Coma Scale rating of 13–15, and a period of hospitalisation not exceeding 48 h (Levin et al., 1987). MTBI is defined herein as a blow to the head in the mild head injury range of severity, resulting in symptoms associated with post-concussion syndrome (PCS) at the time of injury. These symptoms include dizziness, fatigue, headaches, impairments in attention, poor concentration, sensitivity to noise, memory problems, depression, sleep difficulties, and others (Bigler, 1990).

Difficulty sleeping is the fourth most common symptom reported by MTBI patients, occurring in 43.9% of cases (Levin et al., 1987), and is still a complaint years after the injury in a subset of patients (Eide and Tysnes, 1992; Bigler,

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1990; Masson et al., 1996; Beetar et al., 1996). In general, individuals with MTBI report a variety of difficulties with initiating and maintaining sleep (Parsons and Ver Beek, 1982; Perlis et al., 1997; Mahmood et al., 2004; Ouellet et al., 2006; Parcell et al., 2006; Stulemeijer et al., 2006; Baumann et al., 2007). A number of polysomnographic (PSG) studies have examined the relationship between traumatic brain injury (TBI) or MTBI and sleep – with mixed results. These include more stage 2 (Lenard and Pennigstorff, 1970), less slow wave sleep (Lenard and Pennigstorff, 1970), less stage 1 (Prigatano et al., 1982), greater stage 1 (Ouellet and Morin, 2006), more awakenings (Prigatano et al., 1982; George and Landau-Ferey, 1986; Kaufman et al., 2001), and less REM (Ron et al., 1980; George and Landau-Ferey, 1986). Another study found no differences in overall sleep architecture, but found lower power in theta and alpha frequency bands during the first cycle of non-rapid eye movement (NREM) sleep, and lower delta, theta, and alpha power during the second cycle of NREM sleep (Parsons et al., 1997). These variable results may be partly attributed to the different age of subjects in each study, the length of time after the injury, and the severity and type of injury. Furthermore, sleep difficulties after MTBI may be due to variety of causes such as neurological damage to the sleep/wake system, learned associations to stressful or anxiety-inducing events associated with the injury that counteract sleep (psychophysiological insomnia), the result of chronic pain, or secondary to psychiatric symptoms such as anxiety or depression, which often develop after MTBI in both humans (Busch and Alpern, 1998) and animal models (Milman et al., 2005).

While some of the above studies included subjects with TBI in the mild range, none have specifically examined long-term polysomnographic measures subsequent to MTBI. In addition, the majority of studies have focused on overall sleep architecture and have not analysed micro aspects of sleep, which can discriminate between various types of sleep disorders and controls. For example, Lamarche and Ogilvie found that it was possible to differentiate psychophysiological insomniacs, psychiatric insomniacs, and controls using power spectral analysis of the sleep onset period (SOP) (Lamarche and Ogilvie, 1997). During wakefulness, the psychophysiological insomniacs had more beta (indicating higher physiological arousal) and less alpha power. In addition, alpha power did not show as dramatic a drop during the descent into sleep. Psychophysiological insomniacs also had less delta power during the latter stages of the SOP compared to psychiatric insomniacs and controls. In addition to examining mean power, the variability in power across the SOP has been shown to differentiate between normal and insomniac populations, with insomniacs having greater variability over the first 5 min of stage two sleep (McCartney et al., 1998). Such analyses have also been used to distinguish normal controls from subjects with narcolepsy (Alloway et al., 1999), and depression (Armitage et al., 1994), and were therefore included in this study. The FFT results were also used to determine whether sleep difficulties were more characteristic of psychophysiological or psychiatric insomnia, while standard polysomnographic measures were used to determine if MTBI subjects exhibit characteristics of idiopathic insomnia. This might provide clues to the aetiology of the sleep disturbance as well as suggest treatment strategies.

2. Methods

2.1. Overview of procedure

Subjects were recruited from a first year undergraduate psychology class, posters placed around the university campus, and an article in the local newspaper. After an initial telephone interview, subjects, who met the inclusion criteria (see below) for either the MTBI or control group, were scheduled for a 2.5–3 h interview and questionnaire session in the laboratory. A sleep log was given to subjects to take home for a two-week period. During overnight sessions, subjects were scheduled for three consecutive nights, the first two serving as adaptation nights.

2.2. Subjects

MTBI ($n = 9$) and control ($n = 9$) subjects were between 18 and 26 years of age. There were 6 male and 3 female subjects in the MTBI group, and 4 male and 5 female subjects in the control group. All subjects were university students except one, who was a recent graduate. A summary of demographic information is provided in Table 1. Subjects in the MTBI group were asked to come in for an interview and questionnaire period if they (1) were between six months and six years post-injury, (2) had symptoms of PCS at the

Table 1
Demographic and personality variables for the MTBI and control groups

Variable	MTBI	Control	*P*-value
N	9	9	–
Sex			
Male (*n*)	6	4	–
Female (*n*)	3	5	–
Age	21.4 (2.4)	20.7 (2.1)	–
Months post-injury	27.8 (15.5)	–	–
Personality Assessment Inventory			
Depression			
Cognitive	56.0 (7.4)	49.2 (13.5)	**0.030**
Affective	61.2 (14.0)	49.1 (15.2)	0.098
Physiological	66.0 (6.4)	38.8 (14.2)	**<0.001**
Total	60.8 (12.2)	46.8 (6.2)	**0.007**
Anxiety			
Cognitive	61.1 (9.2)	48.4 (7.1)	**0.005**
Affective	61.0 (13.1)	44.6 (3.7)	**0.002**
Physiological	63.3 (12.0)	47.1 (5.4)	**0.002**
Total	60.0 (11.7)	47.9 (7.2)	**0.017**

Values represent means (SD). Higher scores on the PAI indicate greater depression and anxiety, with scores above 59 considered elevated (Morey, 1991). Significant differences are in bold.

time of injury, (3) could clearly distinguish between sleep patterns before and after injury, (4) had sleep difficulties arise within a month post-injury, and (5) had sleep complaints characterised by sleep onset of greater than 30 min on four or more days in a given week. Subjects in the control group were asked to come in for an interview and questionnaire period if they (1) had no previous head injury, and (2) had no sleep difficulties. After the study had been completed, data from one control subject were not used for analyses because a normal night of sleep was not obtained over the three study nights.

All subjects in the MTBI group fell within the mild range, according to the definition described in the introduction, with a mean time post-injury of 27.8 months (range = 8 months to 4.5 years). Each subject was unconscious for 5 min or less, and spent 17 h or less in the hospital directly after sustaining the injury. The length of post-traumatic amnesia ranged from 5 to 60 min, and subjects experienced 0 to 90 min of retrograde amnesia. Most of the injuries were sports related, with ice hockey being the most frequently reported activity during injury. Non-sports injuries included a motor vehicle accident, a bicycle accident, and a fight. Injury-related information for each subject is summarised in Table 2. Self-reported sleep difficulty was not present in any subject prior to the injury. None of the MTBI or control subjects were taking any type of sleep medication, however two subjects were taking medication for asthma (one in each group). In addition, MTBI subjects were free from chronic pain.

2.3. Personality Assessment Inventory (PAI)

Several questionnaires were used in order to obtain descriptive information about the subjects. The PAI was used in order to acquire indices of depression and anxiety and is a standardised 344-item questionnaire in multiple choice format (Morey, 1991). Scores are standardised to have a mean of 50 and a standard deviation of 10, with higher scores indicating greater anxiety or depression. Test–retest reliability is 0.86 for depression and 0.88 for anxiety subscales, and validity was established by comparing the PAI with clinical judgements and existing measures of personality (Morey, 1991).

2.4. Brock Adaptive Functioning Questionnaire (BAFQ)

The BAFQ is a questionnaire comprised of 68 items which are rated on a five point Likert scale. The BAFQ was developed in order to provide self (and other) reports of cognitive functioning that may be prone to impairment subsequent to traumatic brain injury (Dywan and Segalowitz, 1996). Among the constructs assessed are planning, initiation, flexibility, excess caution, attention, memory, arousal, emotionality, impulsivity, aggressiveness, social monitoring, and empathy. The BAFQ has both a self-report section, and a section that a friend or family member completes; only the self-report section was used in this study. Self and family ratings in the areas of planning and initiation correlate with frontal event-related potentials (Dywan and Segalowitz, 1996).

2.5. Pittsburgh Sleep Quality Index (PSQI)

The PSQI is a 19-item questionnaire that assesses sleep quality for the preceding month and was used to obtain descriptive information about sleep (Buysse et al., 1989). It yields seven subscales which include subjective sleep quality, sleep onset latency, sleep duration, habitual sleep efficiency, sleep disturbance, use of sleep medication, and daytime dysfunction. Each subscale can have a score from zero to three, and the total score can range from 0 to 21, with higher scores indicating worse sleep quality. The PSQI has a 0.85 test–retest reliability for global sleep quality scores and range of 0.65 to 0.84 for the component scores (Buysse et al., 1989). Validity was established by comparing scores to a physician's diagnoses as well as polysomnographic assessment. The MTBI group completed the PSQI twice, once for the month preceding the injury (retrospective assessment), and once for the current month (post-injury).

2.6. Sleep Disorders Questionnaire (SDQ)

The SDQ is a self report, 175-item multiple choice questionnaire from which four subscales are derived: sleep apnoea, periodic leg movements, psychiatric insomnia, and narcolepsy (Douglass et al., 1994). The test–retest reli-

Table 2
Descriptive information relating to the head injury for MTBI patients

Variable	Subject								
	1	2	3	4	5	6	7	8	9
Sex	M	M	M	M	F	F	F	M	M
Months post-injury	36	14	8	36	40	54	18	12	32
Type	S	S	S	S	A	A	F	S	S
Unconscious (min)	<1	<1	<1	<1	1–5	5	<1	1	<1
Post-traumatic amnesia (min)	15	20	5	5	5	5	1–5	60	40
Retrograde amnesia (min)	0	90	0	1	0	1	0	0	10
Hospital time (h)	0	0	0	1	17	3	0	0	0

A, Accident; F, Fight/attack; S, Sports-related injury.

ability values for the four scales range from 0.75 to 0.84 and the questionnaire was validated against patient populations as determined by physicians' diagnoses (Douglass et al., 1994).

2.7. Brock Sleep and Insomnia Questionnaire (BSIQ)

The BSIQ is a mixed format, 125-item, self-report questionnaire. Its primary purpose is to distinguish among the American Sleep Disorders Association sub-types of insomnia (American Sleep Disorders Association, 1990). The following scales were calculated and used for descriptive purposes in the current study: sleep quality, psychiatric insomnia, and psychophysiological insomnia. To date, no study has been conducted to examine the psychometric properties of the questionnaire. It has primarily been used as a tool to define groups for research participation (Lamarche and Ogilvie, 1997), and thus does not have validity or reliability measures.

2.8. Sleep log and sleep questionnaires

A sleep log was given to subjects to take home in order to obtain information on normal sleep patterns (e.g. sleep duration, bedtime, etc.) for a two-week period and was used to schedule suitable bedtimes for overnight sessions. During the overnight sessions, questionnaires were used to gather sleep-related information on the day and night in question. For example, the Night-time Questionnaire contained items related to daytime activities such as the intake of medication, amount of physical activity, as well as sleepiness; the Morning Questionnaire required subjects to make subjective estimates of the time it took them to fall asleep, sleep duration, how typical (or atypical) the night's sleep had been. These questionnaires were used to document any events or activities that might affect the interpretation of the results for that night. These questionnaires do not have associated reliability and validity measurements and were not formally analysed.

2.9. Polysomnographic data collection

The Brock University sleep laboratory was used for the collection of polysomnographic data. It is equipped with two bedrooms that are electrically shielded, sound attenuated, and approximately 3×3 m in size. In order to make subjects feel more comfortable, the bedrooms were equipped with a dresser, mirror, and simulated window. A video camera (which operates in low light) recorded the participants continuously throughout the night, and the images were displayed in the monitoring room. Two-way communication was available via microphones and speakers placed in each room. Subjects spent three consecutive nights in the laboratory, the first two serving as adaptation nights.

Polysomnographic data, including electroencephalogram (EEG), electrooculogram (EOG), electromyogram (EMG), and electrocardiogram (ECG), were collected from each subject via 28 gold disc electrodes (Grass, West Warwick, RI). The scalp electrodes were fastened with collodion glue (Xenex Laboratories, Coquitlam, BC), and those placed on the skin were kept in place using micropore tape (3M, London, ON). Mark-easy 10–20 caps (Optimit, Tucson, AZ) were used to mark the standard electrode sites, with the following EEG sites used: Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, O2, and A2, referenced to A1. A ground electrode was placed on the forehead between Fp1 and Fp2. The ECG electrodes were applied to the chest below the left and right clavicle. The EMG electrodes were placed on the chin of each subject, and any electrodes with impedances greater than 10 Ω were reapplied.

Data were sampled at 200 Hz with a band-pass filter from 0.78 to 30 Hz and a notch filter of 60 Hz. Stellate Systems software was used to record (Harmonie, version 4.0, Montreal), score, and conduct power spectral analysis on the sleep data.

Bedtime procedures commenced as close to the subjects normal bedtime as possible. Once in bed, a bio-calibration procedure was conducted, followed by completion of the bedtime questionnaire. Subjects were allowed to sleep uninterrupted for the duration of the night and were allowed to sleep ad-lib within the constraints of the next day's schedule.

2.10. Polysomnographic and power spectral analysis

The PSG data from the third night were divided into 30 s epochs and scored according to Rechtschaffen and Kales criteria (Rechtschaffen and Kales, 1968) by a trained researcher. The records were scored blindly, without knowledge of which group the subject was in. Several sleep parameters were calculated: total recording time, total sleep time, sleep efficiency [(total sleep time ÷ total recording time) × 100], sleep onset latency, REM onset latency, wake time after sleep onset (WASO), and percentages of stage awake, 1, 2, 3, 4, REM, and percent movement.

Power spectral (FFT) analysis of the SOP was undertaken for the third night. The SOP (the period of time between lights out until the first spindle) was divided into nine stages (Hori et al., 1994) and power spectral analysis was conducted at each stage using the following frequency bands: delta (1.56–3.91), theta (3.91–7.81), alpha-1 (7.81–9.38), alpha-2 (9.77–11.33), alpha-3 (11.72–13.28), sigma (13.28–14.84), beta-1 (15.23–19.92), and beta-2 (20.31–29.69). Any artefacts (such as body movements or eye movements) recorded on EEG channels were eliminated manually and were not included in the analysis. The spectral record length was set to 5.12 s, and within each spectral record, two 2.56-s FFT analyses were performed and averaged together. A Hanning tapering window with 50% overlap was used. Mean log power was determined using C3,C4, Cz, O1, O2, P3, P4, Pz, T3, T4, T5, T6, Fp1, Fp2, F3, F4, F7, F8, and Fz electrode sites, with the data

re-referenced to the average of A1 and A2 prior to analysis. To calculate the variability in log power, a separate FFT analysis was conducted by dividing the sleep onset period into four quartiles and the standard deviation (SD) log power was calculated for the following frequencies: (1.0–3.9 Hz), theta (4.0–7.9 Hz), alpha (8.0–11.9 Hz), sigma (12.0–14.9 Hz), beta (15.0–29.9 Hz) using C4, F4, and O2 electrode sites. The FFT analysis for variability in power was identical to that for mean power.

2.11. Statistical analysis

For questionnaire and PSG data, an independent-samples *t*-test (two-tailed) was used to test for differences between the MTBI and control groups. Welch's correction was used if variances were not equal and a Wilcoxon rank sum test was used if outliers skewed the data; these are indicated in the text. Paired-samples *t*-tests (two-tailed) were used to test for differences in the MTBI group before and after the head injury. A linear mixed-effects model (Pinheiro and Bates, 2000; Kristensen and Hansen, 2004) was used to examine differences in power spectral analysis between conditions and across the sleep onset period (using either Hori's nine stages (Hori et al., 1994) or quartiles). Quadratic effects were included where necessary and log delta power was $\log_{10}$-transformed to normalise the residuals. Analysis was conducted with the open-source statistical program R (Ihaka and Gentleman, 1996; R Development Core Team, 2006) (version 2.3.1), available at www.r-project.org, and for all tests the Type I error rate (α) was set at 0.05.

3. Results

3.1. Questionnaire data

Data on depression, anxiety, adaptive functioning, and current and pre-injury sleep (MTBI group only) were collected via the PAI, BAFQ, and multiple self-report measures of sleep and sleep difficulty. The MTBI group had higher total depression scores on the PAI ($t(16) = 3.07$, $p = 0.007$), as well as higher scores on the physiological ($t(16) = 1.32$, $p < 0.001$) and cognitive ($W = 16$, $p = 0.030$) subscales, while there was no significant difference between groups on the affective depression subscale (Table 1). The MTBI group also had higher total anxiety scores ($t(16) = 2.65$, $p = 0.017$) as well as on all of the subscales: cognitive ($t(16) = 3.27$, $p = 0.005$), affective ($t(16) = 3.63$, $p = 0.002$), and physiological ($t(16) = 3.70$, $p = 0.002$). Scores above 59 are considered above average for all of the depression and anxiety scales (Morey, 1991).

There were significant differences between groups on the various scales of the BAFQ (Table 3). The MTBI group reported greater difficulty with cognitive flexibility ($t(16) = 5.81$, $p < 0.001$), planning ($t(16) = 3.25$, $p = 0.005$), excess caution ($t(16) = 3.44$, $p = 0.003$), attention ($t(16) = 3.39$, $p = 0.004$), memory ($t(16) = 3.59$, $p = 0.002$), and arousal level ($t(16) = 2.78$, $p = 0.013$). No group differences were found for initiation, emotionality, impulsivity, aggressiveness, social monitoring, or empathy.

Table 3
Mean (SD) scores on the Brock Adaptive Functioning Questionnaire for the MTBI and control groups

BAFQ	MTBI	Control	*P*-value
Flexibility	58.3 (13.0)	32.2 (3.6)	**< 0.001**
Memory	53.1 (13.0)	33.9 (9.4)	**0.002**
Excess caution	74.2 (18.4)	48.9 (12.1)	**0.003**
Attention	62.0 (19.8)	36.5 (10.7)	**0.004**
Planning	48.6 (13.8)	30.8 (8.8)	**0.005**
Arousal level	57.8 (13.1)	40.2 (13.6)	**0.013**
Aggressiveness	58.2 (21.4)	40.7 (19.9)	0.090
Social monitoring	43.5 (8.4)	38.4 (6.3)	0.167
Initiation	57.8 (12.3)	47.8 (19.4)	0.210
Empathy	38.2 (12.4)	33.3 (9.4)	0.358
Emotionality	52.2 (13.5)	47.2 (16.6)	0.493
Impulsivity	41.9 (14.6)	41.0 (15.7)	0.896

Higher scores indicate greater difficulty and significant differences are in bold.

Table 4
Mean (SD) scores on the Pittsburgh Sleep Quality Index, comparing pre-injury and current scores for the MTBI group, and current scores with the control group

PSQI	MTBI Group		*P*-value[a]	Control group	*P*-value[b]
	Pre-injury	Current		Current	
Sleep quality	0.8 (0.7)	1.9 (1.0)	**0.013**	0.9 (0.8)	**0.036**
Sleep latency	0.6 (0.5)	2.2 (1.0)	**< 0.001**	0.9 (0.9)	**0.009**
Sleep disturbances	1.0 (0.5)	1.7 (0.5)	**0.022**	1.1 (0.3)	**0.014**
Sleep duration	0.1 (0.3)	1.2 (1.1)	**0.021**	0.4 (0.5)	0.072
Sleep efficiency	0.1 (0.3)	1.0 (1.2)	0.086	0.2 (0.4)	0.092
Daytime dysfunction	0.9 (1.6)	1.6 (0.9)	0.219	0.9 (0.6)	0.079
Sleep medication	0	0	–	0	–
Global PSQI	3.4 (1.1)	9.6 (3.5)	**0.001**	4.4 (1.6)	**0.001**

Higher scores indicate greater dysfunction and significant differences are in bold.
[a] MTBI pre-injury vs. current.
[b] Current MTBI vs. control.

The PSQI was given to the MTBI group twice, once for the pre-injury condition, and once for the current post-injury condition (Table 4). Subjects in the MTBI group reported difficulty sleeping post-injury, with decreased sleep quality ($t(8) = 3.16$, $p = 0.013$), increased sleep onset latency ($t(8) = 5.77$, $p < 0.001$), decreased sleep duration ($t(8) = 2.86$, $p = 0.021$), and increased sleep disturbance (interruptions during the night; $t(8) = 2.83$, $p = 0.022$). There was also a significant difference on the global score ($t(8) = 5.44$, $p = 0.001$), but no difference between the pre-injury and current conditions for sleep efficiency or daytime dysfunction.

Group comparisons were conducted in order to determine whether the MTBI group reported greater difficulty sleeping than controls. The MTBI group had significantly higher scores on the PSQI than the controls (Table 4) for sleep quality ($t(16) = 2.29$, $p = 0.036$), sleep latency ($t(16) = 2.98$, $p = 0.009$), sleep disturbances ($t(16) = 2.77$, $p = 0.014$), and global PSQI ($t(16) = 3.99$, $p = 0.001$), indicating greater sleep difficulty among the MTBI group. Group differences

were also found on the narcolepsy ($t(16) = 3.10$, $p = 0.007$), psychiatric insomnia ($t(16) = 3.69$, $p = 0.002$), and periodic leg movements ($t(16) = 3.27$, $p = 0.005$) scales of the SDQ, and on the sleep quality ($t(16) = 9.03$, $p < 0.001$), psychiatric insomnia ($t(16) = 3.12$, $p = 0.007$), and psychophysiological insomnia ($t(16) = 4.30$, $p = 0.001$) scales of the BSIQ. All of these differences were indicative of greater sleep difficulty in the MTBI group compared to controls and are summarised in Table 5.

3.2. PSG measures reveal greater sleep difficulties in the MTBI group

Several standard measures of sleep were derived from PSG recordings in order to compare the MTBI group with normal sleepers on objectively measured variables. Subjects in the MTBI group had 4% lower sleep efficiency ($t(16) = 2.61$, $p = 0.019$; Fig. 1A) and longer sleep onset latencies ($t(16) = 2.25$, $p = 0.039$; Fig. 1B). The sleep onset latencies were extremely variable in the MTBI group with a standard deviation of 20.7 min (range 0.5–51.0), compared with a standard deviation of 4.6 min (range 1–14) in the control group (Levene test: ($p = 0.012$). When Welch's correction was used to account for the different variances between groups, the mean sleep onset latency was not significant at the 5% level ($t(8.8) = 2.25$, p = 0.052), despite being 2.3 times greater in the MTBI group. These results indicate that some individuals with MTBI have very long sleep onset latencies, while others had latencies similar to the control group. Differences in sleep onset latency between groups are also consistent with the subjective questionnaire data (Table 4). In addition, subjects in the MTBI group had shorter REM onset latencies ($t(16) = 2.88$, $p = 0.011$; Fig. 1C), with no significant differences between groups on the other PSG variables (Fig. 1D–K).

3.3. MTBI patients and controls have similar changes in mean power across the SOP

Mean power was examined in order to determine if there were any electrophysiological differences in the frequency domain between controls and the MTBI group. A linear mixed-effects model was used to examine differences between conditions and across Hori's nine stages. The values for all electrode sites were averaged together, and each frequency band (beta-1, beta-2, alpha-1, alpha-2, alpha-3, sigma, theta, and delta) was analysed separately.

The mean power of each frequency was significantly different across stages, with the faster frequencies generally decreasing, and the slower frequencies increasing (Fig. 2). There was no significant condition × stage interaction effect at any frequency, and the only significant difference between conditions was at beta-2, with the controls having greater power ($F(1,16) = 8.9$, $p = 0.008$, Fig. 2B).

Table 5
Mean (SD) scores on the Sleep Disorders Questionnaire and the Brock Sleep and Insomnia Questionnaire

Questionnaire	MTBI	Control	*P*-value
SDQ			
Psychiatric insomnia	23.7 (4.7)	16.3 (3.7)	**0.002**
Periodic leg movements	21.2 (6.6)	13.6 (2.4)	**0.005**
Narcolepsy	25.1 (5.40)	16.4 (6.4)	**0.007**
Sleep apnoea	21.8 (7.9)	18.4 (5.7)	0.321
BSIQ			
Sleep quality	42.7 (9.7)	10.3 (4.7)	**< 0.001**
Psychophysiological insomnia	45.7 (15.7)	21.3 (6.5)	**0.001**
Psychiatric insomnia	44.2 (18.6)	22.9 (8.7)	**0.007**
Delayed phase disorder	7.1 (4.5)	5.4 (4.0)	0.404

Higher scores indicate greater dysfunction and significant differences are in bold.

3.4. MTBI patients have greater variability in power across the SOP

The within-subject (or intra-subject) variability in power was examined in order to determine whether sleep difficulties associated with MTBI could be characterised by increased variability EEG power, similar to that seen in other sleep disorders (McCartney et al., 1998). The analyses performed were similar to those conducted for mean power above; the values for all electrode sites were averaged together, and each frequency band (beta, alpha, sigma, theta, and delta) was analysed separately.

There were no significant differences between conditions or quartiles for SD power in either the beta or alpha frequencies (Fig. 3A and B). In addition, there was no condition × quartile interaction effect at these frequencies. However, in the sigma frequency, the MTBI group had significantly more variability in power than the control group ($F(1,16) = 10.5$, $p = 0.005$, Fig. 3C), which was due to greater variability at later quartiles (condition × quartile interaction; $F(1,53) = 7.5$, $p = 0.008$), while the control group had similar levels of SD power in all quartiles. SD power increased linearly across quartiles in both the theta ($F(1,53) = 4.9$, $p = 0.031$, Fig. 3D) and delta ($F(1,53) = 30.4$, $p < 0.001$, Fig. 3E) frequencies. In addition, the MTBI group had significantly greater variability in power at theta ($F(1,16) = 6.8$, $p = 0.019$) and delta frequencies ($F(1,16) = 9.2$, $p = 0.008$).

4. Discussion

4.1. Questionnaire data

Consistent with previous studies, MTBI patients with persistent sleep complaints had impairments on a variety of psychometric measures, including, depression, anxiety, attention, and memory, which serves to validate the selection of subjects. These scores were only slightly elevated, and a number of patients were within the normal range. Patients also reported difficulties with initiating and maintaining sleep, which is not surprising since subjects in the MTBI group were selected based on the presence of sleep difficulties.

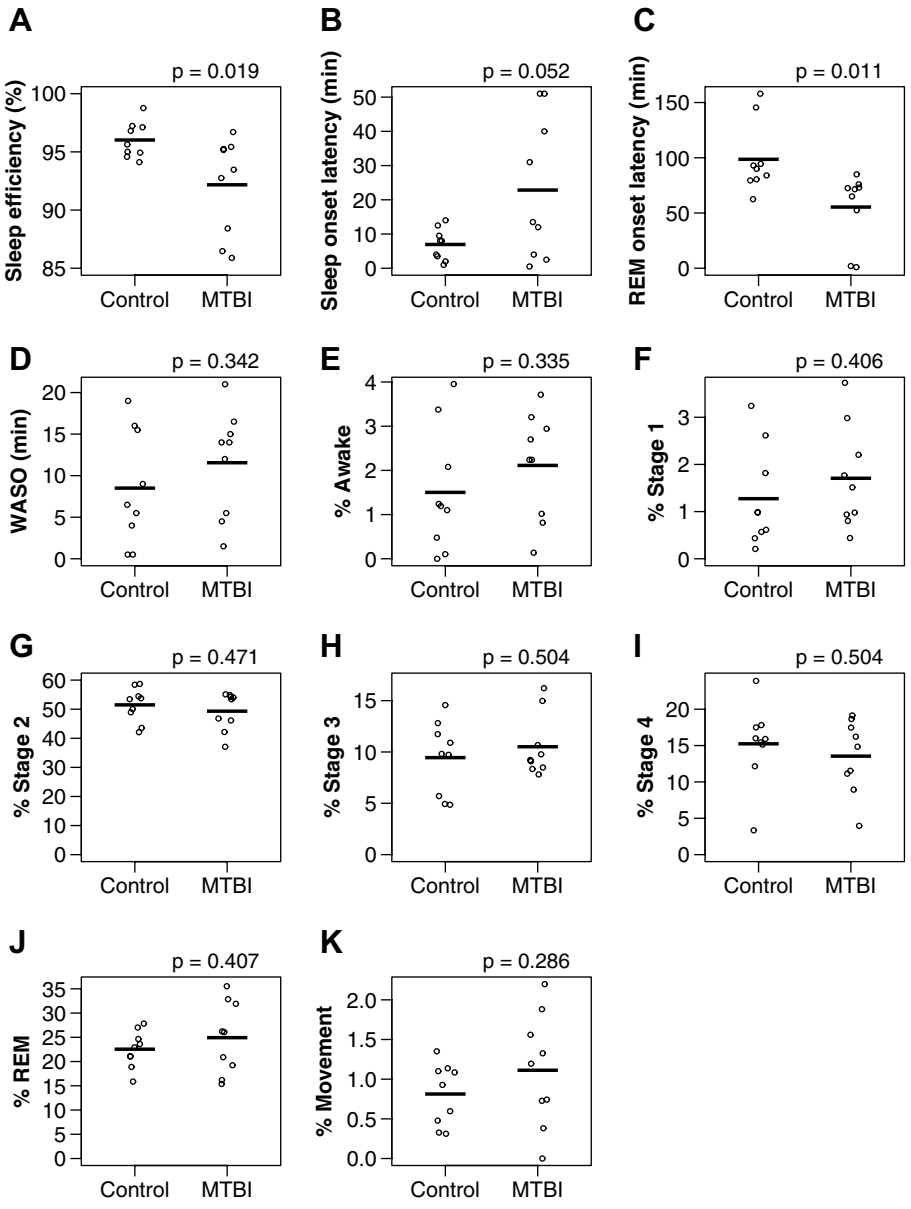

Fig. 1. Comparison of polysomnographic data between MTBI and control groups. Individuals with MTBI had less efficient sleep than controls (A). Sleep onset latencies were much more variable in the MTBI group (Levene test: ($p = 0.012$) and were, on average, 2.3 times longer, but this was not quite significant at the 5% level ($p = 0.052$; B). REM onset latencies were shorter in the MTBI group (C), and there were no significant differences on the other PSG variables (D–K). Bars represent means and data points are jittered slightly. Note: *y*-axis in A does not start at zero.

The MTBI group had higher scores on the periodic leg movements subscale of the SQD. This was an unexpected finding and leg movements were not recorded during PSG acquisition. However, given the results of the questionnaire data, future PSG studies should include an assessment of this in order to determine if they are present in subjects with MTBI, and the extent to which they disrupt sleep.

4.2. Polysomnographic data

A novel finding of this study is the confirmation of subjective self-reports with polysomnographic measures, demonstrating that patients' sleep difficulties persist well after the traumatic event. In particular, patients had less efficient sleep and longer sleep onset latencies, although latencies varied a great deal between subjects. Sleep efficiency in the MTBI group is consistent with a prospective study from Switzerland, where individuals with MTBI had a sleep efficiency of 92% (±6%) six months after injury (Baumann et al., 2007). The MTBI patients tended to be awake for longer during the night, consistent with previous reports (Prigatano et al., 1982; George and Landau-Ferey, 1986; Kaufman et al., 2001), but these differences were not significant in the present study. Subjects in the MTBI group also had shorter REM onset latencies, which was partly due to two subjects in the MTBI group entering REM sleep five minutes after sleep onset. Ouellet and

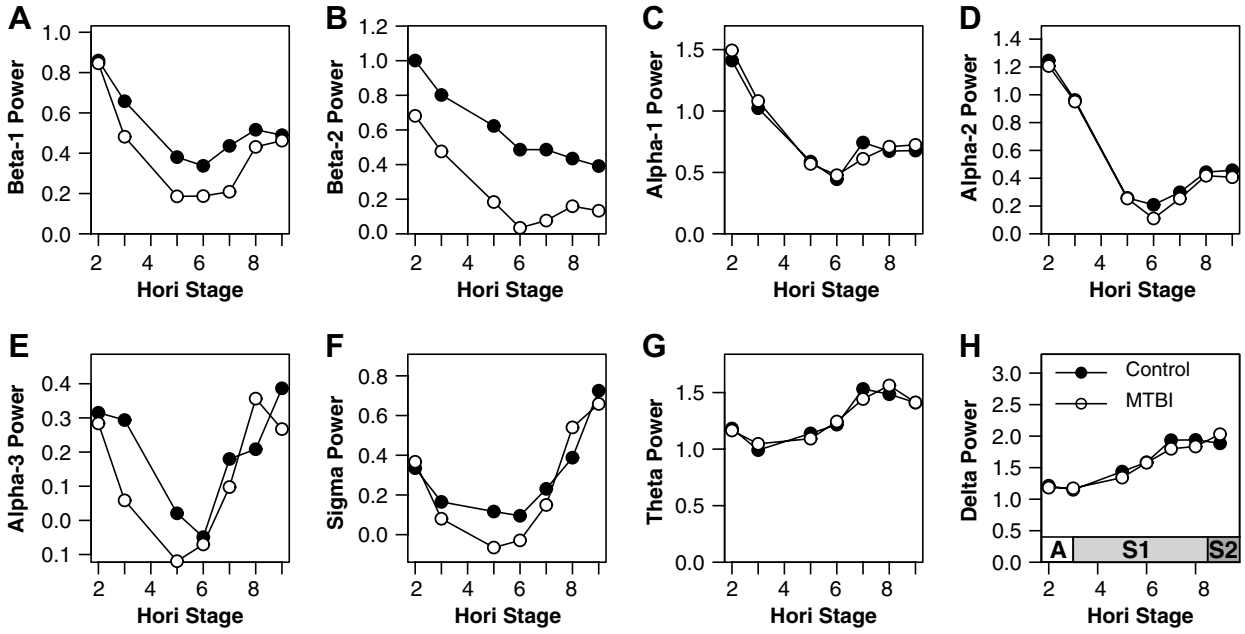

Fig. 2. Mean spectral power during the sleep onset period. The SOP was scored according to Hori's 9 stages (Hori et al., 1994) and power (μV^2/Hz) was calculated for eight frequency bands. The power of faster frequencies generally decreased from stage 2 to 9, while the power of the slower frequencies generally increased. The only significant difference between conditions occurred in the beta-2 frequency, with controls having greater power ($F(1,16) = 8.9$, $p = 0.008$, B). The standard R&K stages are overlaid in panel H. A, awake; S1, stage 1; S2, stage 2.

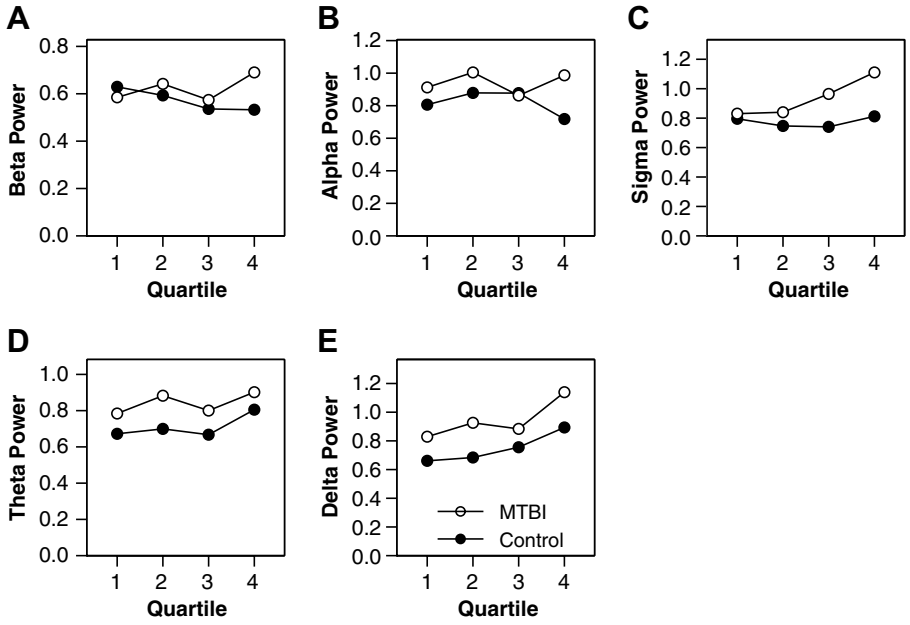

Fig. 3. Variability in power during the sleep onset period. The SOP was divided into four quartiles and standard deviation power (μV^2/Hz) was calculated for five frequency bands. Individuals with MTBI had greater sigma ($F(1,16) = 10.5$, $p = 0.005$, C), theta ($F(1,16) = 6.8$, $p = 0.019$, D) and delta ($F(1,16) = 9.2$, $p = 0.008$, E) SD power, indicating that they had a greater variability in power during the transition from awake to sleep. In addition, the SD power in the sigma band increased across quartiles in the MTBI group, while the control SD power did not (condition × quartile interaction effect, ($F(1,53) = 7.5$, $p = 0.008$). SD power also increased linearly across quartiles in the theta ($F(1,53) = 4.9$, $p = 0.031$) and delta ($F(1,53) = 30.4$, $p < 0.001$) frequencies.

Morin reported shorter REM onset latencies in a non-medicated subgroup of TBI patients (Ouellet and Morin, 2006). These sleep onset REM periods (SOREMPs) are characteristic of narcoleptic patients (American Sleep Disorders Association, 1990); however, these data should be put into context, and recent studies have indicated that SOREMPs have a prevalence between 3.9% and 13.1% in the general US population (Singh et al., 2006; Mignot et al., 2006). Of interest though, MTBI patients had significantly higher scores on the narcolepsy subscale of the SDQ (Table 5).

However, it is necessary to test for this directly using a multiple sleep latency test or maintenance of wakefulness test before conclusions can be drawn.

Idiopathic insomnia is thought to be the result of dysfunctional neurological control of the sleep–wake system, and is characterised by a decrease in percent stage 3 and 4, and an increase in percent REM (American Sleep Disorders Association, 1990). It was hypothesised that if insomnia was the result of damage to the sleep–wake system, then it would present with these characteristics; however, the percentages of these three stages were similar between the MTBI and control groups.

4.3. Power spectral analysis

Power spectral (FFT) analysis of the sleep onset period did not reveal any major differences in mean power between groups, with the only significant difference being in the beta-2 band. However, this was opposite to what was predicted, as it was the control group that had higher power. In a group of adolescents, Parsons et al. found a significant increase in mean power in the alpha-1, theta, and delta frequency bands 72 h after injury (Parsons et al., 1997). This study did not use a control group but measured power at 72 h, 6 weeks, and 12 weeks after injury. Therefore, these values represent changes in power within subjects shortly after injury, while the present study examined long-term differences between subjects, perhaps accounting for the different results. In addition, the MTBI subjects in the present study did not have a distinct mean power 'signature' across the SOP, as seen in psychophysiological and psychiatric insomnia (Lamarche and Ogilvie, 1997), perhaps indicating that changes after MTBI are distinct from those observed in these insomnia subtypes. The questionnaires also failed to distinguish between psychophysiological and psychiatric insomnia; the MTBI group had significantly higher values on both insomnia subscales of the BSIQ.

Lamarche and Ogilvie found greater within-subject variability in alpha and delta power in individuals with insomnia (Lamarche and Ogilvie, 1997), and therefore it was predicted that there would be greater within-subject variability in the MTBI group than the control group, with higher amounts of variability indicating greater disruption of the sleep onset process. MTBI patients did indeed exhibit greater standard deviation power than normal controls in a number of the standard frequency bands. Variability of this sort is associated with a greater magnitude of oscillation between movements away from, and towards sleep. As such, oscillations towards greater wakefulness might have a disruptive effect on the sleep onset process. High amounts of variability in arousal across the sleep onset period may account for the insomnia-like difficulties that are experienced by individuals with MTBI, in particular, it may explain the increase in sleep onset latency in some subjects. This suggests that SD power might be a useful measure for monitoring changes in recovery over time or the efficacy of experimental treatments, as it provides an objective neurophysiological measure that distinguishes groups; although, further work is required to establish the validity and reliability of such a measure. In addition, the inclusion of subjects with MTBI but with no reported sleep difficulties would be needed to establish whether increased SD power is associated with sleep dysfunction, or is a result of MTBI but not necessarily related to sleep.

Both the MTBI patients and control subjects were young adults, and therefore these findings may not generalise to paediatric, older adult, or geriatric populations. In addition, subjects in the MTBI group had elevated anxiety and depression scores, which are known to influence sleep parameters (Papadimitriou and Linkowski, 2005; Argyropoulos and Wilson, 2005). It should be noted however that the PAI uses questions about sleep dysfunction to determine emotional functioning scores, and since subjects were selected based on self-reported sleep difficulties, the questionnaire may have overestimated their actual level of emotional dysfunction. The design of the present study did not allow us to tease apart the relationship between MTBI, sleep, and emotional functioning, but it is worth studying more directly in the future. In addition, the existence of apnoea in the MTBI group was not assessed, but the apnoea score on the SDQ was not significantly different from controls.

In conclusion, a subset of individuals with mild traumatic brain injury exhibit long-term sleep difficulties, as determined by both self-report and polysomnographic measures, along with various cognitive and affective abnormalities. Sleep efficiency, sleep onset latency, and REM onset latency were the most affected PSG measures in the MTBI group. Power spectral analysis revealed differences in the variability of power during the sleep onset period, perhaps reflecting a general disruption of the process of falling asleep in patients with MTBI.

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