doi:10.1093/brain/awy348 BRAIN 2019: 142; 674–687 | 674

BRAIN
A JOURNAL OF NEUROLOGY

Brain white matter damage and its association with neuronal synchrony during sleep

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The restorative function of sleep partly relies on its ability to deeply synchronize cerebral networks to create large slow oscillations observable with EEG. However, whether a brain can properly synchronize and produce a restorative sleep when it undergoes massive and widespread white matter damage is unknown. Here, we answer this question by testing 23 patients with various levels of white matter damage secondary to moderate to severe traumatic brain injuries (ages 18–56; 17 males, six females, 11–39 months post-injury) and compared them to 27 healthy subjects of similar age and sex. We used MRI and diffusion tensor imaging metrics (e.g. fractional anisotropy as well as mean, axial and radial diffusivities) to characterize voxel-wise white matter damage. We measured the following slow wave characteristics for all slow waves detected in N2 and N3 sleep stages: peak-to-peak amplitude, negative-to-positive slope, negative and positive phase durations, oscillation frequency, and slow wave density. Correlation analyses were performed in traumatic brain injury and control participants separately, with age as a covariate. Contrary to our hypotheses, we found that greater white matter damage mainly over the frontal and temporal brain regions was strongly correlated with a pattern of higher neuronal synchrony characterized by slow waves of larger amplitudes and steeper negative-to-positive slopes during non-rapid eye movement sleep. The same pattern of associations with white matter damage was also observed with markers of high homeostatic sleep pressure. More specifically, higher white matter damage was associated with higher slow-wave activity power, as well as with more severe complaints of cognitive fatigue. These associations between white matter damage and sleep were found only in our traumatic brain injured participants, with no such correlation in controls. Our results suggest that, contrary to previous observations in healthy controls, white matter damage does not prevent the expected high cerebral synchrony during sleep. Moreover, our observations challenge the current line of hypotheses that white matter microstructure deterioration reduces cerebral synchrony during sleep. Our results showed that the relationship between white matter and the brain's ability to synchronize during sleep is neither linear nor simple.

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Received July 4, 2018. Revised October 22, 2018. Accepted November 19, 2018. Advance Access publication January 28, 2019

Keywords: white matter; sleep; NREM sleep; traumatic brain injury

Abbreviations: DTI = diffusion tensor imaging; NREM = non-rapid eye movement; TBI = traumatic brain injury

Introduction

When the brain departs from wakefulness to enter into deep sleep, it shifts from a state of desynchronized EEG activity to an avalanche of spontaneous slow (<1 Hz) and large amplitude (>75 μV) waves. These epiphenomena reflect slow oscillations that occur at a cellular level where intense and synchronized neuronal firing alternates with a period of silent state. Although cortically generated, slow waves are thought to emerge from the dynamic interplay between thalamic nuclei and the cerebral cortex (Murphy *et al.*, 2009; Crunelli *et al.*, 2015). They play crucial roles in the restorative properties of sleep, being notably essential to synaptic plasticity underlying learning and memory consolidation (Marshall *et al.*, 2006; Steriade, 2006; Tononi and Cirelli, 2006; Diekelmann and Born, 2010). Recent studies also implicate them with the clearance of neurotoxic waste products accumulated during wakefulness, a process thought to be compromised in some neurodegenerative diseases (Xie *et al.*, 2013; Mander *et al.*, 2015; Morawska *et al.*, 2016).

Current hypotheses suggest that the structural properties of white matter tracts affect how brain networks will synchronize themselves to produce slow oscillations during non-rapid eye movement (NREM) sleep. In one study, interindividual differences of the corpus callosum volume explained 38% of NREM EEG slow-wave activity variability (Buchmann *et al.*, 2011). More specifically, larger volumes were associated with higher slow-wave activity power, supporting the hypothesis that large interhemispheric white matter tracts increase EEG synchronicity. In a second study, a steeper rising slope of the sleep slow waves, suggestive of a better cortical synchrony, was associated with a higher axial diffusivity in major frontal bundles, which the authors associated with better white matter integrity (Piantoni *et al.*, 2013). Taken together, these results support the idea that healthier white matter tracts correlate with higher cerebral synchronicity during sleep.

However, these previous studies on cerebral white matter and sleep slow waves have been performed in young, healthy adults who probably have very little interindividual variability in their white matter tracts. The question remains as to whether a brain can properly synchronize its networks to produce large sleep slow waves and a restorative sleep when it undergoes massive white matter damage, as seen in some neurological conditions. This question can be answered by testing patients with extensive white matter damage months after a moderate to severe traumatic brain injury (TBI). In fact, this population is particularly interesting to study, as most of these patients have visible white matter damage on MRI and up to 70% of them develop severe fatigue and chronic sleep disturbances, including increased sleep needs and reports of non-restorative sleep (Duclos *et al.*, 2014; Ouellet *et al.*, 2015). The inability of the brain to synchronize its local neuronal networks during sleep could be a key element to explain these complaints.

Here we investigated morphological characteristics of NREM sleep slow waves in individuals with various degrees of white matter damage secondary to moderate to severe TBI compared with healthy controls. We also performed correlational analyses between white matter structural properties in TBI subjects and sleep slow wave characteristics that are typically associated with neuronal synchrony. We tested the hypothesis that more severe white matter damage is associated with reduced neuronal synchrony during sleep (e.g. reduced slow wave amplitudes and slopes), which could impede the restorative function of sleep, and in doing so, generate the often observed fatigue and sleep disturbances.

Patients with chronic TBI and controls completed daily sleep diaries and wore an actimetric device the week preceding testing to monitor total sleep time the week before the MRI scanning and the polysomnography recording. All participants underwent a 3 T MRI followed by a full night of in-laboratory polysomnography the same day. The next morning, a comprehensive neuropsychological assessment was performed, and participants filled out questionnaires on mood, fatigue and sleep. To characterize white matter structure, we used diffusion tensor imaging (DTI), a technique that measures the diffusion of water molecules in the brain. Because of the clear directionality of white matter tracts, water diffusion is greater along the axis of the fibres and lower perpendicular to them, which allows inference on axonal and myelin damage. We used four diffusion metrics namely fractional anisotropy, mean, axial and radial diffusivities to infer whole-brain voxel-wise white matter structure. In the case of severe damage to the white matter, as seen in patients with chronic TBI, it is expected to observe an increased diffusivity along axial and radial axes and a reduced fractional anisotropy (Kraus *et al.*, 2007; Kennedy *et al.*, 2009; Kumar *et al.*, 2009; Pitkonen *et al.*, 2012; Haberg *et al.*, 2015). To characterize NREM sleep slow waves, we used an automatic detection on a full night of polysomnography recording. We measured slow wave density and morphological characteristics, including amplitude, frequency, slope, and phase duration. We hypothesized that the extent of white matter damage (reflected by increased diffusivities and reduced fractional anisotropy) predicts lower neuronal synchrony during sleep (reflected by waves of lower amplitude and slopes).

Materials and methods

Participants

Twenty-three participants aged between 18 and 56 years old and diagnosed with a moderate to severe TBI were recruited for this prospective study and were compared to 27 age- and sex-matched healthy controls. All TBI patients were previously admitted to the Hôpital du Sacré-Coeur de Montréal, a tertiary trauma centre, in the acute stage of their injury and they were all recruited based on their hospital chart. During testing, TBI patients were in the chronic phase of the injury, at least 11 months following the trauma (average: 23.4 months, range 11–39 months; see Table 1 for demographic and clinical characteristics). Diagnosis of TBI, defined as an alteration in brain function, or other evidence of brain pathology, caused by an external force (Menon *et al.*, 2010), was performed by a licensed neurosurgeon according to standard established criteria for moderate to severe TBI (Teasdale and Jennett, 1974): a Glasgow Coma Scale (GCS) score between 3 and 12, a post-traumatic amnesia longer than 1 h, a loss of consciousness longer than 30 min, and positive brain scans. All participants presenting any of the following conditions were excluded from the study: (i) a history of psychiatric, neurologic, sleep (before the injury), or substance use disorders; (ii) sleep medication and inability to cease medication use prior to testing; (iii) history of single (for control subjects) or multiple TBI (for TBI patients); (iv) quadriplegia; (v) obesity, defined by a body mass index over 30; (vi) pregnancy; (vii) jetlag due to a recent trans-meridian trip; (viii) night shift work leading to an atypical sleeping schedule; or (ix) MRI contraindications (often in the form of metallic implants left by surgeries). Eight TBI participants were taking psychoactive medication prior to recruitment (see Supplementary Table 1 for detailed data). Of those, three ceased the intake several days before the testing. The medicated patients, when compared to the rest of the group, showed no significant differences in either slow waves, sleep quality, or fatigue scores and were therefore included in analyses. The study was approved by the Hôpital du Sacré-Coeur de Montréal Research Ethics Board and written consent was obtained

Table 1 Demographic characteristics, questionnaires, neuropsychological assessment and sleep macro-architecture

	TBI *n* = 23	Controls *n* = 27	*t*-value (*P*-value)
Age, years	30.5 (11.1)	30.3 (13.4)	0.1 (0.95)
Sex, male/female, *n*	17/6	21/6	0.3 (0.75)
Education, years	13.0 (3.3)	15.2 (2.1)	2.9 (0.006)
GCS at hospital admission	8.5 (3.3)	-	-
Length of post-traumatic amnesia, days	17.0 (17.6)	-	-
Time after injury, months	23.4 (9.4)	-	-
Return to work/school, %	60	-	-
Questionnaires			
Fatigue Severity Scale	40.1 (16.1)	30.7 (11.1)	2.4 (0.02)
Epworth Sleepiness Scale	8.4 (5.7)	6.5 (4.1)	1.3 (0.19)
Pittsburgh Sleep Quality Index	6.7 (3.2)	4.2 (2.5)	2.9 (0.005)
Beck Anxiety Inventory	9.3 (10.0)	4.6 (6.3)	2.1 (0.04)
Beck Depression Inventory II	17.4 (10.7)	4.9 (6.0)	5.2 (<0.001)
Neuropsychological assessment			
Trail Making Test A time, s	30.8 (13.1)	25.6 (9.2)	1.6 (0.13)
Trail Making Test B time, s	84.0 (35.0)	63.8 (26.3)	2.2 (0.03)
Color-Word interference 1 time, s	31.6 (6.1)	27.4 (4.6)	2.6 (0.01)
Color-Word interference 2 time, s	24.0 (4.8)	19.1 (3.2)	4.1 (<0.001)
Color-Word interference 3 time, s	60.0 (13.4)	50.0 (12.6)	2.7 (0.01)
Color-Word interference 4 time, s	68.5 (19.7)	50.3 (8.3)	4.3 (<0.001)
Hopkins Verbal Learning Test, total learning	23.6 (5.3)	26.1 (3.7)	1.9 (0.07)
Sleep macro-architecture on PSG			
Sleep latency, min	16.1 (16.7)	20.3 (29.1)	0.6 (0.53)
REM sleep latency, min	106.0 (90.7)	114.1 (62.6)	0.4 (0.72)
Total sleep time, min	465.7 (59.4)	441.0 (59.5)	1.5 (0.15)
Number of awakenings	33.8 (13.3)	27.8 (10.8)	1.7 (0.09)
Wake after sleep onset, min	57.8 (46.1)	48.0 (33.7)	0.8 (0.41)
Apnea-hypopnea index, events/hour	2.6 (3.5)	2.2 (2.5)	0.5 (0.63)
Sleep efficiency, %	88.6 (9.7)	90.2 (6.8)	0.7 (0.52)
Stage N1 sleep, %	11.7 (6.2)	10.5 (5.2)	0.7 (0.48)
Stage N2 sleep, %	53.7 (7.1)	52.5 (6.4)	0.6 (0.53)
Stage N3 sleep, %	16.4 (9.7)	17.9 (8.9)	0.6 (0.56)
REM sleep, %	18.3 (4.4)	19.1 (5.4)	0.6 (0.55)

Data are presented as mean (standard deviation), when applicable. GCS = Glasgow Coma Scale; PSG = polysomnography.

from each participant or the immediate family (for inapt participants), compliant with the Declaration of Helsinki.

Overview of the protocol

One week before the lab visit, participants wore an activity monitor device (Actiwatch-L or Actiwatch-Spectrum, Philips Healthcare) and filled out a daily sleep diary to document their sleep-wake cycle. Participants then underwent a brain MRI followed by a full night of in-laboratory polysomnography the same day. A comprehensive neuropsychological assessment was performed the morning after polysomnography to measure executive functions, processing speed, attention, language, working memory, and global functioning. We collected clinical data related to the injury from their hospital charts. Participants also filled out several questionnaires: the Pittsburgh Sleep Quality Index (Buysse *et al.*, 1989), the Fatigue Severity Scale (Krupp *et al.*, 1989), the Epworth Sleepiness Scale (Johns, 1991), the Beck Anxiety Inventory (Beck *et al.*, 1988), and the Beck Depression Inventory-II (Beck *et al.*, 1996).

Polysomnography

Bedtime and wake time were determined according to the participant's usual schedule. The recording montage comprised 19 EEG derivations (FP1, FP2, Fz, F3, F4, F7, F8, Cz, C3, C4, Pz, P3, P4, O1, O2, T3, T4, T5, T6), bilateral electrooculogram, chin and tibia EMG, and ECG. Nasal and oral airflows were measured using a pressure transducer, a thoracic belt, and an abdominal belt. Blood oxygen saturation was measured with a pulse oximeter on the finger. Sleep stages and events were scored according to criteria from the American Academy of Sleep Medicine scoring manual and sleep cycles according to the criteria of Aeschbach and Borbely (1993).

Slow wave detection and analysis

Slow waves were detected automatically on selected frontal and central derivations (F3, F4, Fz, C3, C4, Cz) during NREM N2 and N3 sleep stages for all sleep cycles. Epochs containing artefacts were excluded by automatic and visual detection. These data were analysed using an in-house software package combined with an acquisition software (Harmonie Stellate Systems, Montreal, Canada). EEG data were initially band pass filtered between 0.3 and 4.0 Hz with a linear phase finite impulse response filter (−3 dB). The criteria used for slow wave detection were: (i) negative peak lower than −40 μV; (ii) peak-to-peak amplitude higher than 75 μV; (iii) negative phase duration between 125 and 1500 ms; and (iv) positive phase duration lower than 1000 ms (Carrier *et al.*, 2011). The following morphological characteristics were then identified for each slow wave detected: amplitude (voltage difference between the negative and positive peaks in μV), frequency (oscillation speed in Hz), slope (velocity of the change between the negative and positive peaks in μV/s), negative phase duration (in s), positive phase duration (in s), and density (number of slow waves per min). A visual representation of these characteristics can be seen in Supplementary Fig. 1.

Slow-wave activity power

Quantitative EEG analysis was performed on the frontal derivations during NREM N2 and N3 sleep stages of the entire night and for sleep cycles 1 to 3 separately. Epochs containing artefacts were excluded by automatic and visual detection. These data were analysed using an in-house software package combined with an acquisition software (Harmonie Stellate Systems, Montreal, Canada). Fast Fourier Transform was carried out on epochs of 5 s, and the absolute and relative [*delta* / (*theta* + *alpha* + *beta*)] power for the delta frequency band (0.5–4 Hz) was then calculated.

MRI acquisition

Magnetic resonance imaging of the brain was performed on a 3.0 T scanner (Siemens Magnetom Trio) at the Unité de Neuroimagerie Fonctionnelle of the Institut universitaire de gériatrie de Montréal. The MRI protocol consisted of a pulsed spin echo diffusion-weighted imaging sequence (echo-planar imaging) (64 non-collinear directions, image resolution = 2 × 2 × 2 mm^3, 72 slices, repetition time = 9500 ms, echo time = 93 ms, b-value = 1000 s/mm^2, duration = 648 s) with additional gradient field maps and AP/PA b0 sequences, a T_1-weighted sequence (image resolution = 1 × 1 × 1 mm, repetition time = 2530 ms, echo time = 1.64 ms, duration = 363 s), a T_2-weighted sequence and a FLAIR sequence. A licensed neuroradiologist inspected all MRI.

DTI preprocessing and analysis

Diffusion data were preprocessed using the Toolkit for Analysis in Diffusion MRI (http://unf-montreal.ca/toad/). The pipeline involves the following steps: (i) parcellation using the Freesurfer (https://surfer.nmr.mgh.harvard.edu/) recon-all pipeline v5.3.0; (ii) denoising; (iii) motion and distortion correction; (iv) upsampling and registration with the parcelled anatomical images and atlases; (v) FSL tensor reconstruction; and (vi) extraction of tensor metrics including fractional anisotropy and mean, axial and radial diffusivity.

Data were then prepared for the voxel-wise statistical analysis using tract-based spatial statistics (TBSS) (Smith *et al.*, 2006) from the FSL diffusion toolbox (https://fsl.fmrib.ox.ac.uk/) (Smith *et al.*, 2004). First, all subjects' fractional anisotropy data were affine-aligned to the MNI152 1 mm standard space using the non-linear registration tool FNIRT. Next, the mean fractional anisotropy image was created and thinned with a threshold of fractional anisotropy > 0.2 to create a mean fractional anisotropy skeleton which represents the centres of all tracts common to the group. Each subject's aligned fractional anisotropy data were then projected onto this skeleton. Similar steps were subsequently performed to project the mean, axial, and radial diffusivity data onto this skeleton as well.

Statistical analyses

The TBI and control groups were first compared on demographic characteristics, questionnaires, neuropsychological tests, and sleep macro-architecture using two-tailed Student *t*-tests or χ^2. For slow wave analysis, in order to reduce the number of variables and because no hemisphere effect was observed, we pooled frontal electrodes together (frontal

cluster: F3, F4, Fz) and central electrodes together (central cluster: C3, C4, Cz). For three participants, one electrode had to be removed because of artefacts, and we therefore used the two remaining electrodes only. One participant had all central electrodes removed, and was excluded from this analysis. To characterize slow waves in TBI and control subjects, we performed repeated measure ANOVAs with one inter-subject factor (group: TBI versus control) and one repeated measure (electrode: frontal and central clusters), with age as a covariate to account for its effect on slow waves. These statistical analyses were carried out with SPSS Statistics version 20 (IBM Corp., 2011), with statistical significance set at $P < 0.05$.

DTI statistics were performed using Randomise (Winkler *et al.*, 2014), a tool from the FSL diffusion toolbox. It uses non-parametric Monte Carlo permutation inference to perform voxel-wise statistics on the white matter images processed previously by TBSS. For each contrast of interest in our models, 10 000 permutations were done, giving us a confidence limit of ± 0.0044 for $P = 0.05$. Threshold-free cluster enhancement was used as a thresholding method (Smith and Nichols, 2009; Winkler *et al.*, 2014). This method takes the raw statistic image and produces an output image in which the voxel-wise values represent the amount of cluster-like local spatial support. The family-wise error rate was accounted for by the Monte Carlo permutation test and the threshold-free cluster enhancement. Group comparisons were performed for fractional anisotropy, as well as for mean, axial, and radial diffusivities. Group correlations were performed on all four diffusion metrics for the following regressors with age as a confound variable: injury severity (Glasgow Coma Scale score, length of post-traumatic amnesia), slow wave characteristics from the frontal pool of electrodes (amplitude, slope, negative phase duration, positive phase duration, frequency, density), slow-wave activity power for F3 electrode (both relative and absolute, for sleep cycles 1 to 3 separately) and questionnaire scores. Regression analyses were performed in the TBI and the control groups separately. The significant clusters were labelled according to the ICBM-DTI-81 white matter atlas (Mori *et al.*, 2008). T-values of significant clusters were presented in the figures by masking the original t-value images to only show significant clusters ($P < 0.05$ corrected for multiple comparisons). While all analyses were performed on the mean fractional anisotropy skeleton, significant clusters in the presented figures were filled from the thin fractional anisotropy skeleton to the mean fractional anisotropy image to better represent actual white matter.

Data availability

Relevant data that support the findings of this study are available from the corresponding author upon reasonable request.

Results

Participant characteristics

Demographic characteristics as well as questionnaire, neuropsychological and sleep macro-architecture results for both groups are presented in Table 1. The TBI group reported significantly more fatigue and worse sleep quality than controls. Additionally, these patients presented impairments in several cognitive domains, as evidenced by poorer performances than controls on neuropsychological tests. TBI patients' sleep macro-architecture was not different from controls despite their subjective evaluation of poor sleep quality and daytime fatigue. No group difference was found in the total sleep time measured with sleep diaries and actigraphy in the week preceding the polysomnography.

A voxel-wise statistical analysis (using TBSS from the FMRIB Software Library diffusion toolbox) of the preprocessed DTI scans showed extensive white matter damage in the TBI group (Fig. 1). Decreased fractional anisotropy and increased mean, axial and radial diffusivities were evident across almost all major white matter tracts in the brain, from the cerebral hemispheres to the brainstem. Furthermore, the TBI group was heterogeneous in terms of white matter damage, with some individuals showing no difference from controls and others showing important sequelae. This extensive white matter damage was strongly correlated with markers of TBI severity, most notably the Glasgow Coma Scale scores upon hospital admission and post-traumatic amnesia duration (Supplementary Fig. 2).

Sleep slow waves in TBI participants compared to healthy controls

First, we performed ANOVAs with Group and one repeated measure (EEG electrodes: frontal and central clusters) with age as a covariate on slow wave characteristics. We found no Group × EEG electrode interaction for any of the slow wave characteristics, but we observed several significant group effects (Table 2). TBI participants had slightly longer negative and positive phase duration than control participants. As expected by the latter result, slow wave frequency was lower in TBI compared to control subjects. Finally, the negative-to-positive slope was lower in the TBI group compared to the control group. No significant main group effect was found for either slow wave amplitude or density.

Sleep slow waves and white matter damage

The analysis of white matter with voxel-wise statistics (using TBSS and Randomise from the FSL diffusion toolbox) revealed a pattern of strong associations with slow waves' morphology involving the amplitude, slopes, and negative phase duration. While no relationship was found in the control group, DTI metrics generally associated with a more damaged white matter predicted higher cortical synchrony during sleep in the TBI group.

Higher slow wave amplitude correlated with more severe white matter damage in TBI patients (Fig. 2), and more specifically with higher axial diffusivities in multiple voxel clusters in the frontal and temporal regions, involving the

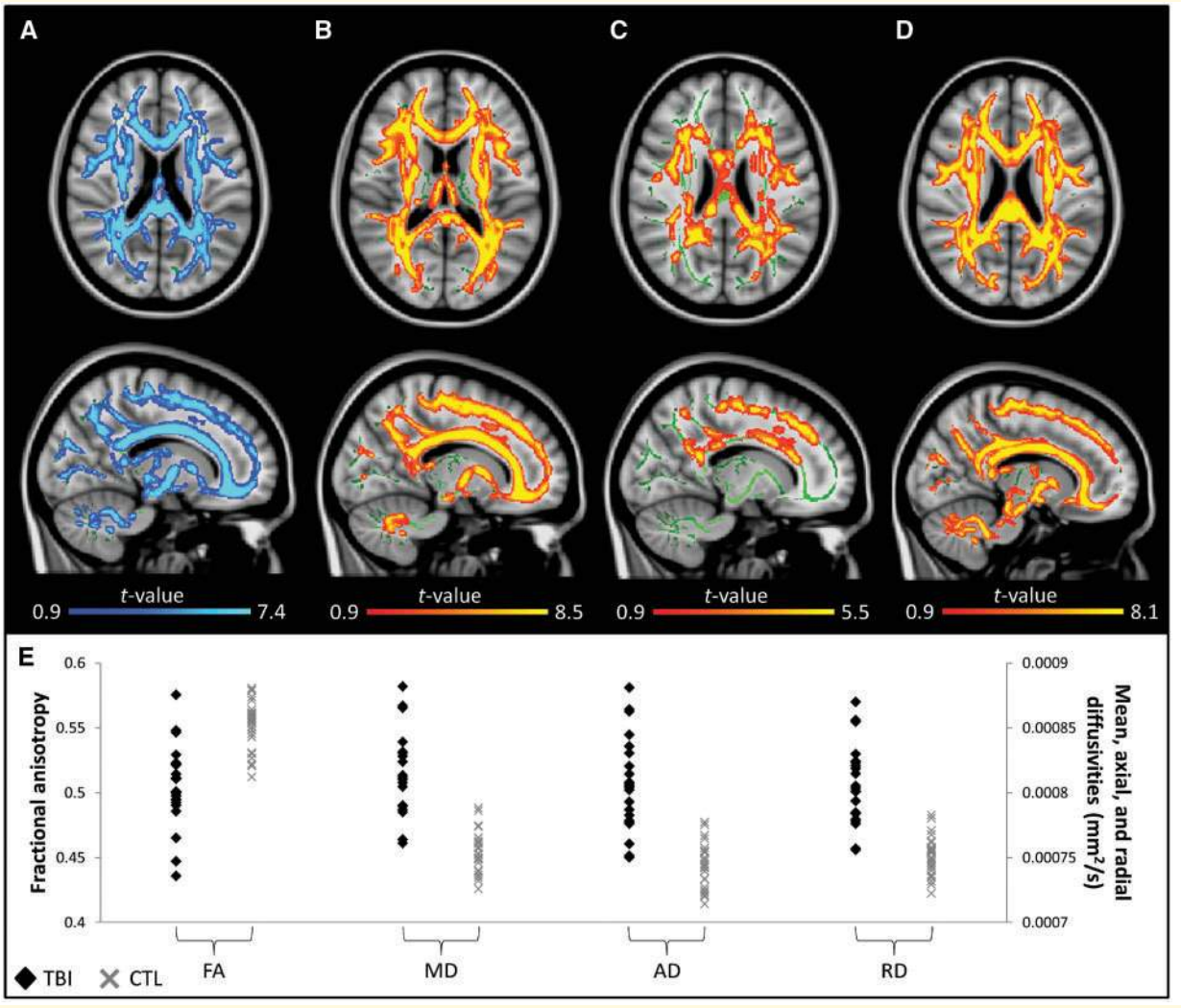

Figure 1 Group differences on diffusion metrics. TBSS voxel-wise contrasts between TBI and control (CTL) groups (blue, TBI < CTL; red to yellow, TBI > CTL) for (**A**) fractional anisotropy (FA), (**B**) mean diffusivity (MD), (**C**) axial diffusivity (AD), and (**D**) radial diffusivity (RD). Significant results are overlaid over the MNI152 T1 1 mm brain and the mean fractional anisotropy skeleton (in green). Significant increases in the TBI group compared to the Control group are shown in the red to yellow scale and significant decreases are shown in light blue. The mean value of all significant clusters is represented on the graph for each subject. Significant results were thresholded at $P < 0.05$ controlled for age and corrected for multiple comparisons.

Table 2 Results of the Group × Electrode cluster ANOVAs on slow wave characteristics

	TBI (n = 23)		Controls (n = 27)		Main group effect
	Frontal cluster	Central cluster	Frontal cluster	Central cluster	
Peak-to-peak amplitude, μV	130.7 (13.4)	122.4 (13.4)	135.7 (20.1)	123.0 (16.7)	F = 1.2; P = 0.28
Negative duration, s	0.487 (0.048)	0.478 (0.047)	0.456 (0.040)	0.457 (0.049)	F = 4.0; P = 0.05
Positive duration, s	0.538 (0.052)	0.531 (0.056)	0.500 (0.051)	0.497 (0.054)	F = 8.0; P < 0.01
Frequency, Hz	1.09 (0.11)	1.12 (0.13)	1.17 (0.12)	1.20 (0.13)	F = 6.9; P = 0.01
N-to-P slope, μV/s	340.9 (59.4)	315.0 (56.3)	380.2 (87.5)	339.7 (74.8)	F = 4.8; P = 0.03
Density, n/min	9.0 (5.0)	7.0 (4.3)	10.3 (5.0)	7.9 (4.3)	F = 1.4; P = 0.25

No interaction or cluster effects were observed. Data are presented as mean (standard deviation). N-to-P = negative to positive.

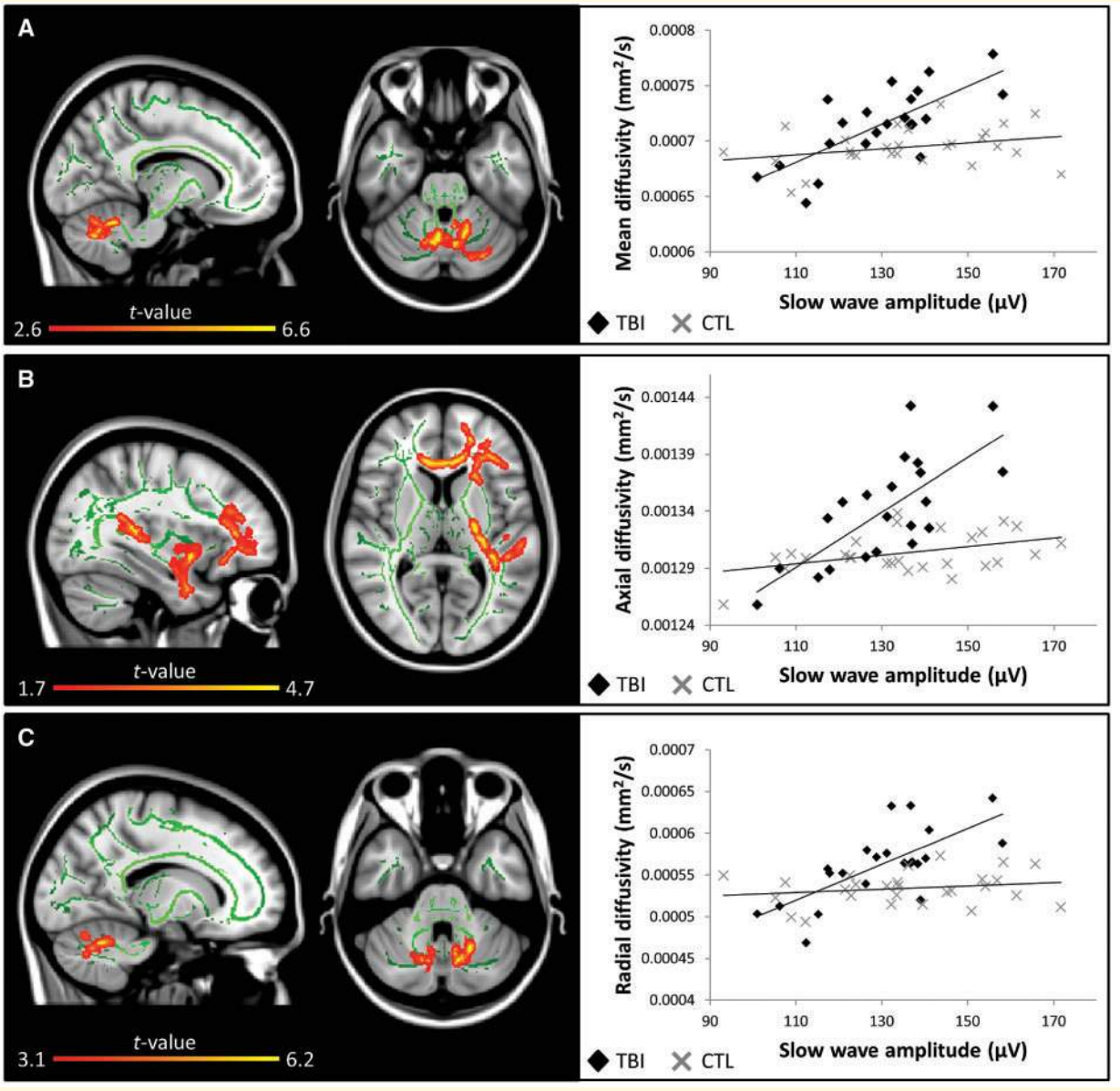

Figure 2 Slow wave amplitude and white matter damage. Areas in the TBI group where slow wave amplitude is positively correlated (red to yellow coloured areas) with (**A**) mean diffusivity (r = 0.81), (**B**) axial diffusivity (r = 0.74), and (**C**) radial diffusivity (r = 0.78). Significant results are overlaid over the MNI152 T_1 1 mm brain and the mean fractional anisotropy skeleton (in green). The correlation between the mean value of all significant clusters and slow wave amplitude is represented on the graphs. No area of negative correlation was found in the TBI group and no significant correlation was found for the control group (CTL). Results are thresholded at $P < 0.05$, adjusted for age and corrected for multiple comparisons.

genu of the corpus callosum, the anterior and posterior limbs of the internal capsule, the retrolenticular part of the internal capsule, the anterior, posterior, and superior corona radiata, the posterior thalamic radiation, the inferior longitudinal and fronto-occipital fasciculus, the external capsule, the fornix, and the uncinate fasciculus (Fig. 2B). Higher slow wave amplitude also correlated with both higher radial diffusivities and higher mean diffusivities in the inferior, middle, and superior cerebellar peduncles (Fig. 2A and C).

Steeper slow wave slope was also correlated with more severe white matter damage in TBI patients. Namely, the negative-to-positive slope was steeper when axial diffusivity was higher in clusters located over the frontal and temporal regions that were previously detailed (Fig. 3).

The negative phase duration of the slow wave was also positively correlated with white matter damage in TBI patients (Fig. 4). More specifically, longer negative phases correlated with lower fractional anisotropy in multiple voxel clusters once again scattered in a fronto-temporal

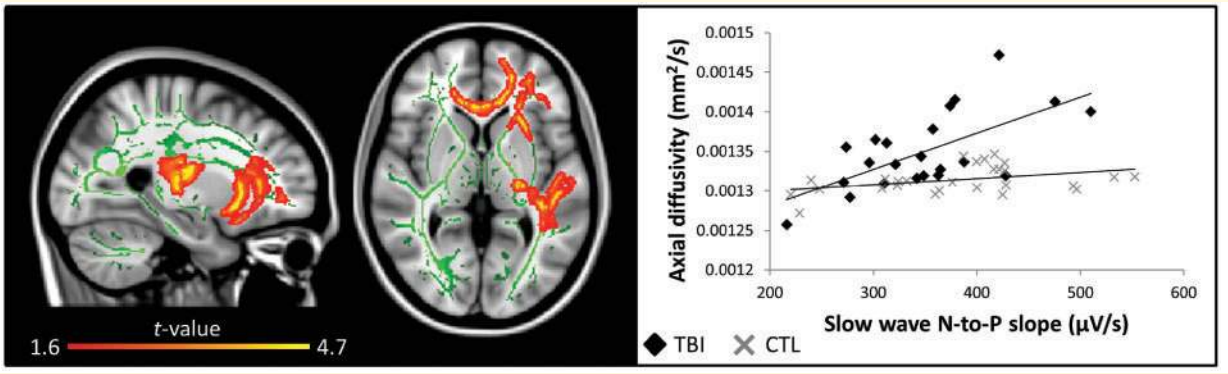

Figure 3 Slow wave slope and white matter damage. Areas in the TBI group where slow wave negative-to-positive slope is correlated (red to yellow, positive correlation) with axial diffusivity (r = 0.64). Significant results are overlaid over the MNI152 T_1 1 mm brain and the mean fractional anisotropy skeleton (in green). The correlation between the mean value of all significant clusters and slow wave N-to-P slope is represented on the graph. No area of negative correlation was found in the TBI group and no significant correlation was found for the control group (CTL). Results are thresholded at $P < 0.05$, adjusted for age and corrected for multiple comparisons.

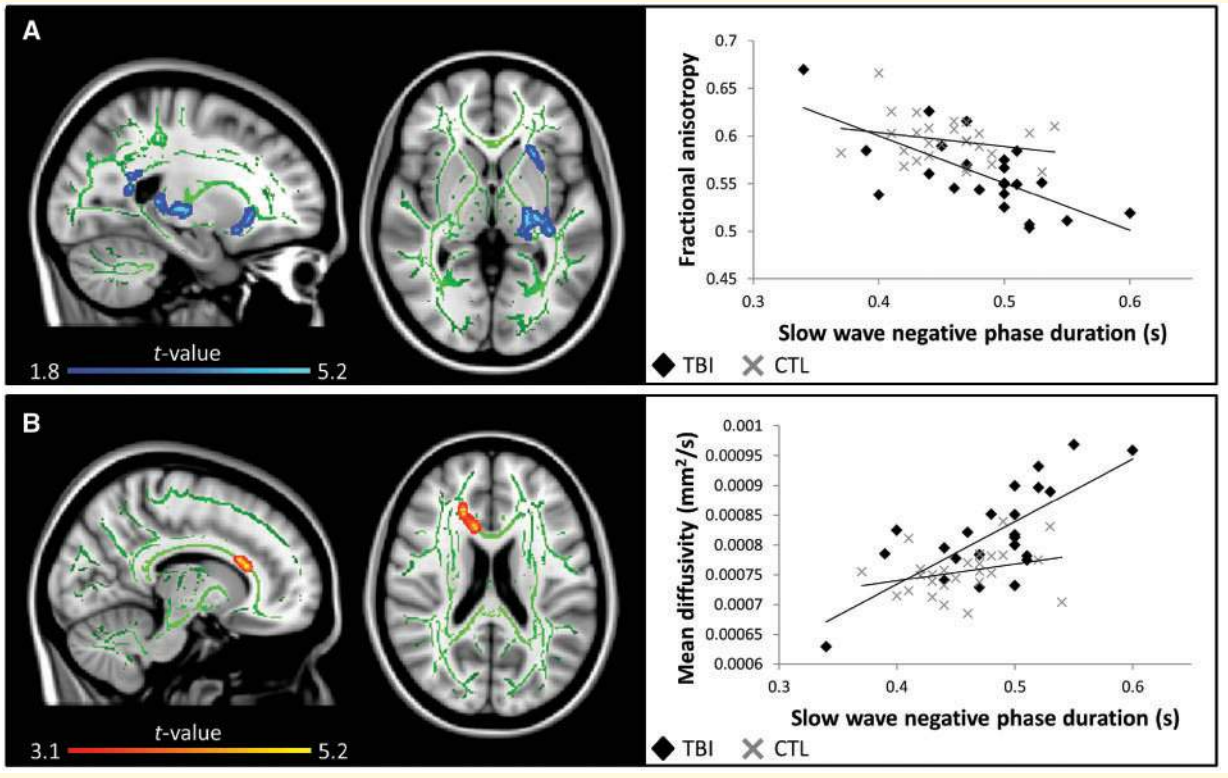

Figure 4 Slow wave negative phase duration and white matter damage. Areas in the TBI group where slow wave negative phase duration is correlated (blue, negative correlation; red to yellow, positive correlation) with (**A**) fractional anisotropy (r = −0.69) and (**B**) mean diffusivity (r = 0.73). Significant results are overlaid over the MNI152 T_1 1 mm brain and the mean fractional anisotropy skeleton (in green). The correlation between the mean value of all significant clusters and slow wave negative phase duration is represented on the graphs. No significant correlation was found for the control group (CTL). Results are thresholded at $P < 0.05$, adjusted for age and corrected for multiple comparisons.

manner and involving the splenium of the corpus callosum, the cerebral peduncle, the posterior limb of the internal capsule, the retrolenticular part of the internal capsule, the anterior and posterior corona radiata, the posterior thalamic radiation, the inferior longitudinal and fronto-occipital fasciculus, the external capsule, the fornix, the uncinate fasciculus, and the tapetum (Fig. 4A). Longer negative phases were also associated with higher mean diffusivities in the genu and body of the corpus callosum, and the anterior corona radiata (Fig. 4B).

In summary, in TBI patients, widespread white matter damage in various regions containing short and long-range white matter tracts was associated with a pattern of higher neuronal synchrony in which the sleep slow waves are of higher amplitude and steeper slopes. Longer negative phase duration was also associated with the same observed white matter damage.

Sleep slow-wave activity and white matter damage

To investigate the association between cortical synchrony during sleep and white matter structure further, we analysed the NREM slow-wave activity power (0.5 to 4 Hz frequency band). We measured the absolute and relative slow-wave activity power for each sleep cycle. No group difference was found for NREM slow-wave activity power between TBI patients and controls for any of the sleep cycles. However, the voxel-wise correlations with DTI metrics showed very strong associations in the TBI group only, similar to what was found with slow wave voxel-wise analyses. More specifically, white matter damage was positively correlated with relative slow-wave activity power in the first sleep cycle only (Fig. 5) and with absolute slow-wave activity power in the second (Supplementary Fig. 3) and third sleep cycles (Supplementary Fig. 4). In these cases, higher relative and absolute slow-wave activity power correlated with higher mean diffusivities, higher radial diffusivities, and lower fractional anisotropy in regions mostly overlapping with what was found with the slow wave morphology analysis.

Subjective sleep quality, fatigue, and white matter damage

Finally, we set out to see if the variability in white matter structure had any relationship with self-reported measures of sleep and fatigue. In the TBI group, while sleep quality and daytime sleepiness did not correlate with white matter characteristics, fatigue was positively correlated with white matter damage. Indeed, higher self-reported fatigue strongly correlated with higher axial diffusivities in the same pattern of voxel clusters mentioned previously (Fig. 6). No such associations were found for the control group. For both groups, no significant associations were found between any of the self-reported measures of sleep and fatigue and slow wave characteristics.

Discussion

In the present study, patients with moderate to severe TBI had widespread white matter damage throughout the brain, from all cortical tracts to the brainstem, which is consistent with the literature showing white matter damage in chronic TBI (Benson *et al.*, 2007; Kraus *et al.*, 2007; Kennedy *et al.*, 2009; Kinnunen *et al.*, 2011; Spitz *et al.*, 2013; Haberg *et al.*, 2015). Our DTI results suggest significant demyelination, axonal injury and white matter degeneration consecutive of moderate to severe TBI. Not surprisingly, the extent of white matter damage correlated with more severe TBI in our sample. Our most important result was that this white matter damage was strongly associated with signs of better neuronal synchrony during NREM sleep: EEG slow waves were of higher amplitude and had steeper slopes in participants with more damaged brains. These results are in opposition with our hypotheses, as we expected that a loss of white matter would have decreased neuronal synchrony and consequently, decreased slow wave slopes and amplitudes. Our results also showed that white matter damage correlated positively with longer slow wave negative phase, higher NREM sleep slow-wave activity power and more severe fatigue during the day. These results challenge our understanding of what represents healthy NREM sleep slow waves.

The complex relationship between cortical synchrony during sleep and white matter integrity

During NREM sleep, the brain is highly synchronized locally and spontaneously produces slow waves on the EEG. These epiphenomena reflect slow oscillations that occur at a cellular level, where periods of silent state (negative phase) alternate with intense synchronized neuronal firing (positive phase). The slow wave negative to positive (N-to-P) slope represents the rate of transition between the negative and the positive phases; steeper slopes are the result of a more synchronous transition from the silent phase to the depolarization phase. Slow wave amplitude, on the other hand, most likely represents the extent of the synchronal neuronal firing. The more cortical neurons are simultaneously depolarized, the larger the measured amplitude should be on the EEG. Slow oscillations occur across the cortex, originating mostly near the insula and the medial cingulate gyrus (Murphy *et al.*, 2009) from the dynamic interplay between thalamic nuclei and the cerebral cortex (Crunelli *et al.*, 2015), and propagate along the anterior-posterior axis of the brain through the cingulate pathways and parts of the default-mode network (Massimini *et al.*, 2004; Murphy *et al.*, 2009). Short- and long-range connections are therefore considered crucial for slow wave generation and propagation, and as such, a strong association with white matter is to be expected.

In line with this hypothesis, a previous study found that a steeper rising slope of slow waves was associated with higher axial diffusivity in major frontal bundles and temporal lobe fascicles (Piantoni *et al.*, 2013). This was found in 15 young, healthy adult males with little variability in their white matter characteristics. In the present study, we failed to replicate these findings in our healthy control group. Factors explaining the discrepancy between studies could be sex difference in the control groups [77% males in

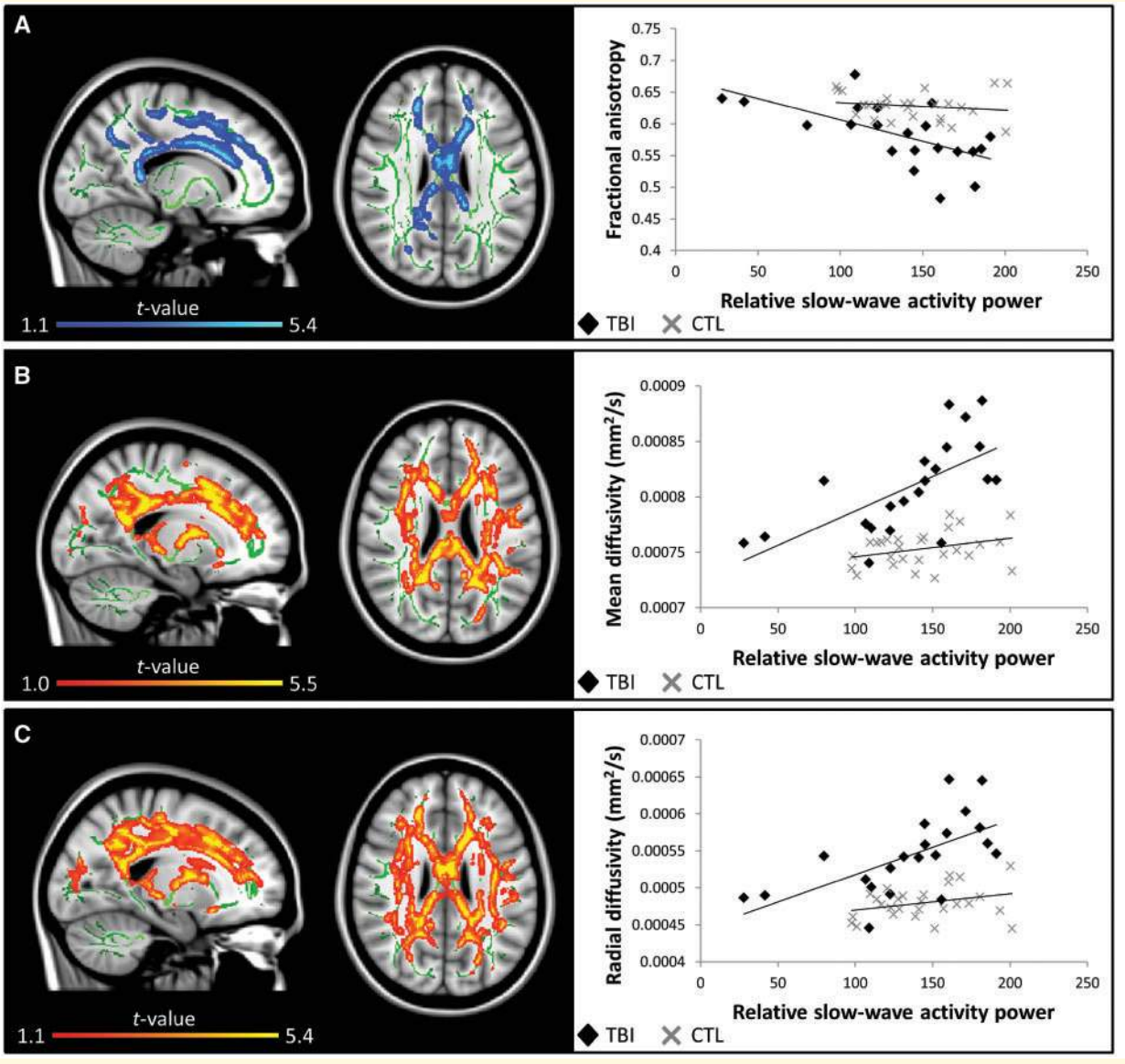

Figure 5 Relative slow-wave activity power in the first sleep cycle and white matter damage. Areas in the TBI group where slow wave activity power is correlated (blue, negative correlation; red to yellow, positive correlation) with (**A**) fractional anisotropy ($r = -0.63$), (**B**) mean diffusivity ($r = 0.70$), and (**C**) radial diffusivity ($r = 0.65$). Significant results are overlaid over the MNI152 T_1 1 mm brain and the mean fractional anisotropy skeleton (in green). The correlation between the mean value of all significant clusters and relative slow-wave activity power is represented on the graphs. No significant correlation was found for the control group (CTL). Results are thresholded at $P < 0.05$, adjusted for age and corrected for multiple comparisons.

the present study versus 100% males in the study by Piantoni *et al.* (2013)], the age difference in the control groups (30.3 ± 13.4 years versus 25.4 ± 4.8 years, respectively), and the age-correction applied to our analyses. However, further studies with a larger sample of healthy control subjects are necessary to clearly identify the association between individual differences in healthy white matter and slow wave characteristics.

Slow wave morphology has also been studied in ageing. Older adults show a decline in slow wave amplitude and slope (Carrier *et al.*, 2011). These modifications in slow wave characteristics could be linked with the white matter loss observed with advancing age (Peters, 2002; Yap *et al.*, 2013) and were found to be associated with the thinning of specific cortical regions (Dube *et al.*, 2015).

In opposition to these previous studies in healthy young and older adults, our patients with widespread white matter damage had higher slow wave amplitudes and steeper slopes. Although we may have expected to see changes mirroring those seen in ageing individuals, due to the documented loss of white matter in the ageing brain, we did not find such results. Our results combined with these previous observations raises the possibility that the relationship between sleep slow waves and white matter structure is neither linear nor simple.

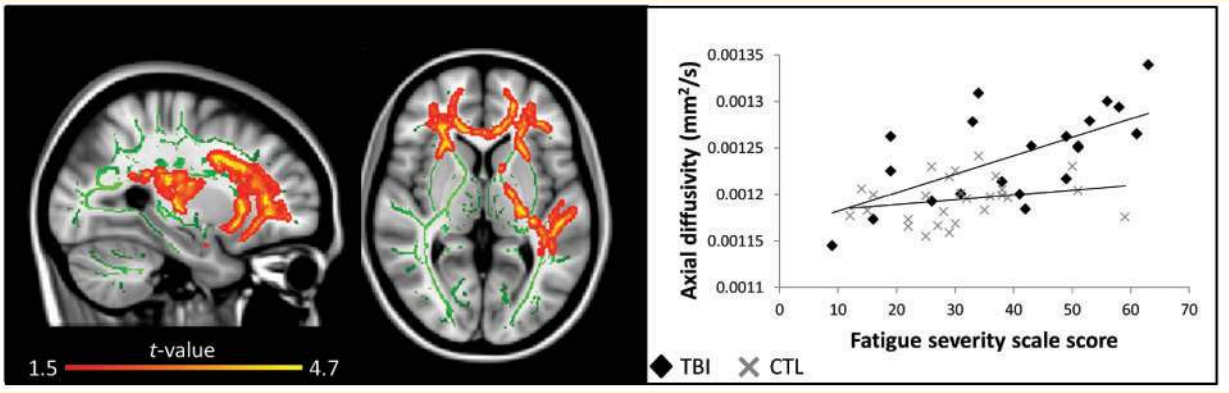

Figure 6 Self-reported fatigue and white matter damage. Areas in the TBI group where fatigue is correlated (red to yellow, positive correlation) with axial diffusivity (r = 0.66). Significant results are overlaid over the MNI152 T_1 1 mm brain and the mean fractional anisotropy skeleton (in green). The correlation between the mean value of all significant clusters and fatigue is represented on the graph. No area of negative correlation was found in the TBI group, and no significant correlation was found for the control group (CTL). Results are thresholded at $P < 0.05$, adjusted for age and corrected for multiple comparisons.

To understand the association between white matter loss and slow waves observed in our TBI participants, we may refer to studies on partial cortical deafferentation. *In vivo* cat experiments in which a portion of the cortex is undercut have been performed to study the mechanisms of trauma-induced epilepsy (Avramescu and Timofeev, 2008; Avramescu *et al.*, 2009; Timofeev *et al.*, 2013). In these studies, the authors recorded enhanced slow-wave activity in the undercut hemisphere up to 16 weeks after the injury (Timofeev *et al.*, 2013). They hypothesized that this increased synchrony was caused by the increased network excitability observed chronically after partial deafferentation. Indeed, homeostatic plasticity in the brain works to maintain network excitability through changes in the balance of excitatory and inhibitory synapses and regulation of intrinsic neuronal excitability (Turrigiano *et al.*, 1998; Turrigiano, 2011). After partial deafferentation, network activity is acutely decreased, which engages upregulatory mechanisms to increase cortical excitability (Avramescu and Timofeev, 2008; Avramescu *et al.*, 2009). This concept is evidenced by another study in which they showed an acute reduction of slow-wave activity power in partially deafferentated cats, followed by a time-dependent recovery of slow-wave activity along with cortical excitability (Lemieux *et al.*, 2014). Although the models used in these studies are more crippling than what is observed in human TBI, these observations may partly explain the association we observed between white matter and NREM sleep slow waves in the present study. Diffuse white matter damage may acutely engage these homeostatic mechanisms to upregulate network excitability in the long term and cause part of the increase in neuronal synchrony we described. One study in humans has investigated cortical excitability changes after mild to moderate TBI (Nardone *et al.*, 2011). They found that a subset of patients, more specifically those with excessive daytime sleepiness, presented patterns of motor cortex hypoexcitability when compared to controls. However, the large majority of patients showed no such hypoexcitability. These measures were also taken during wakefulness and on patients with minor brain damage only 3 months following the TBI. As such, this question remains open until more comprehensive experiments are performed.

On the other hand, it may also be that physical disconnection by diffuse white matter damage in TBI brings the cortex closer to its default state. Many argue that the default emergent activity patterns of the cortical network are highly synchronous slow waves (Sanchez-Vives *et al.*, 2017). Indeed, spontaneous slow waves emerge in states where the cortex is either physically or functionally disconnected from outside stimulation, such as deep sleep (Steriade *et al.*, 2001), anaesthesia (Chauvette *et al.*, 2011), or *in vitro* cortex slices (Sanchez-Vives and McCormick, 2000). Thalamo-cortical connections are especially vulnerable to TBI in humans, effectively bringing the cortex slightly closer to an isolated state. This may also play a role in the large slow waves we observed in patients with important white matter damage.

Finally, we cannot exclude that this association between white matter damage and slow wave characteristics is due to homeostatic sleep pressure (Borbely, 1982; Borbely and Achermann, 1999). An increase in slow-wave activity power at the beginning of the sleep period is the standard physiological marker of homeostatic sleep pressure (Borbely, 1982). Our TBI subjects with more severe white matter damage had higher slow-wave activity for all sleep cycles. Furthermore, steeper slow oscillation slopes and higher amplitude, the pattern observed in our TBI participants who had more white matter damage, were previously associated with a rise in homeostatic sleep pressure (Riedner *et al.*, 2007; Vyazovskiy *et al.*, 2007, 2011; Bersagliere and Achermann, 2010; Rodriguez *et al.*, 2016). Chronic white matter damage may cause TBI patients to accumulate need for sleep faster. Indeed, white

matter damage due to TBI has consistently been associated with impaired cognition (Kraus *et al.*, 2007; Kumar *et al.*, 2009; Palacios *et al.*, 2013; Spitz *et al.*, 2013; Arenth *et al.*, 2014; Kim *et al.*, 2014), and TBI patients have been shown to exert more mental effort for the same task than healthy subjects (Belmont *et al.*, 2009). A study using functional MRI has also observed that while performing a cognitive task, TBI patients have increased brain activity compared to healthy subjects in several brain regions believed to be involved in mental fatigue, which is thought to represent higher mental effort (Kohl *et al.*, 2009). In the present study, we found that TBI patients with more white matter damage also had more severe subjective fatigue. Similar results were observed in other studies (Clark *et al.*, 2017; Schonberger *et al.*, 2017). Taken together, these findings suggest that chronic white matter damage causes TBI patients to accumulate mental fatigue faster during the day, which may increase homeostatic sleep pressure and enhances sleep synchrony during subsequent sleep. A valid concern would be that these patients were under sleep deprivation, causing the aforementioned phenomena. However, as mentioned previously, all patients completed daily sleep agendas and wore an activity monitor device the week preceding testing, all of which confirm that these patients had similar total sleep time when compared with controls. Nevertheless, protocols specifically assessing the evolution of fatigue throughout the day in relation with sleep homeostatic pressure need to be performed to adequately verify this hypothesis.

Conclusion

This study represents the first to explore the association between sleep slow waves and white matter structure in adults with white matter damage. Our results showed strong associations between white matter and slow waves occurring during NREM sleep. More damaged brains were associated with markers of higher brain synchrony during sleep, and these associations could be caused by cerebral disconnection or by elevated homeostatic sleep pressure in TBI patients. White matter damage does not seem to impede the restorative function of sleep as we first thought. These results bring new insight to understanding the pathophysiology of sleep disturbances and fatigue observed after TBI as well as factors influencing brain synchrony during sleep. Moreover, this study challenges the current hypotheses regarding the role of white matter structure on the brain ability to synchronize its cortical regions during sleep and produce restorative sleep.

Acknowledgements

For their support in data acquisition, the authors wish to thank Catherine Duclos, Solenne Van der Maren, Caroline D'Aragon, Julien Lauzier, Carollyn Hurst, and André Cyr.

Funding

This study was funded by government granting agencies by grants to N.G. as a principal investigator: Canadian Institutes of Health Research (CIHR MOP 115172) and Fonds de Recherche Santé-Québec (FRQS #34851). E.S. and A.A.B. received scholarships from the CIHR and FRQS. N.G. received a salary award from the FRQS. J.C. received a salary award from the CIHR. M.D. holds a Université de Sherbrooke Research Chair in Neuroinformatics.

Competing interests

The authors report no competing interests.

Supplementary material

Supplementary material is available at *Brain* online.

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