Dynamic Brain States During Sleep: Initial Studies

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Abstract

Introduction: Nonlinear analysis of EEG signals using the RQA method quantifies deterministic (nonrandom) changes in brain states of arbitrary length. RQA has been used to study cognitive processing in normality and disease, but not to characterize sleep microstates. We sought evidence indicating RQA's usefulness for this purpose.

Methods: Polysomnograms scored based on the ASSM manual were analyzed using published computational procedures (implementing LabView code available). Employing the RQA variable %R, which measures amount of law-governed activity whether or not visually perceivable, we quantified EEGs from frontal, central, and occipital electrodes, resulting in approximately 25,000 sequential values in successive 1-s intervals (time series). Additionally, phasic events (EEG arousals, K complexes, spindles, delta bursts) were analyzed by calculating %R for 100-ms intervals using a step of 2 ms (500 values of %R per sec). Additional calculations were performed using the RQA variable %D (independent measure of determinism). Spectral power analysis was employed as a control procedure.

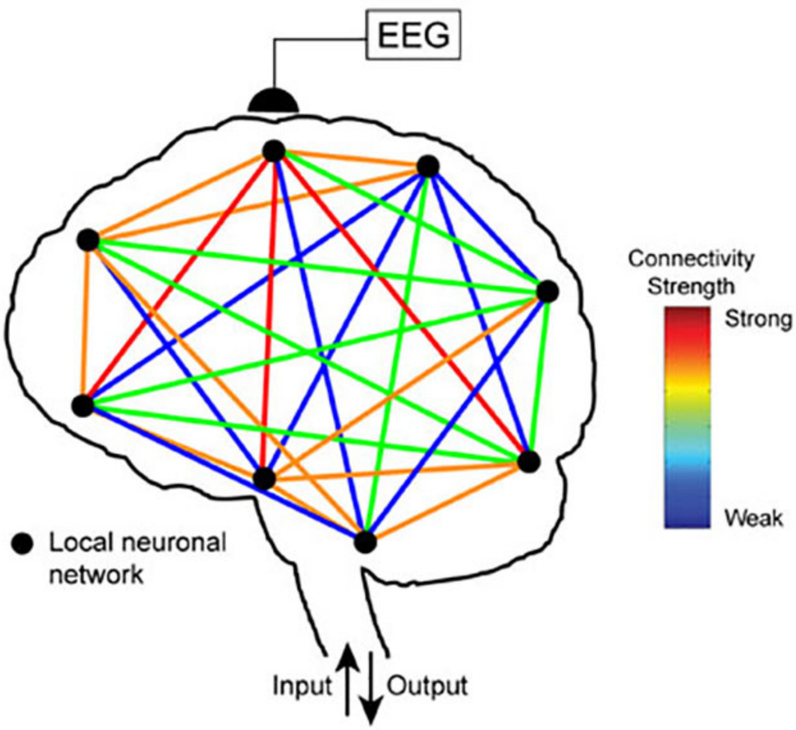
Results: In each case (6 patients × 6 electrodes), the %R time series consisted of 3 relative maxima with periods of 200–400 min; as expected, for each patient, the patterns for all derivations were essentially identical. The patterns were not detected using power analyses. Visible phasic events consistently resulted in localized increases in %R; similar changes occurred in the absence of visually-scored phasic EEG events. Averaged over 30-s epochs, increased %R correlated strongly with increased sleep-state depth as assessed by standard scoring (80–90% agreement); the extent of the agreement was increased when %D was included in the RQA sleep-stage classification.

Conclusion: Nonlinear EEG analysis reliably permitted quantification of brain states lasting 0.1–1 s and reproduced the scoring of gold-standard-scored PSGs, suggesting the possibility of an integrated approach to the study of brain dynamical changes that includes both background signals and superimposed phasic changes.

Introduction

Complex systems exhibit order (law-governed dynamical activity) not detectable by traditional methods. We used a novel method for studying complexity to characterize brain activity during sleep. Our goal was to quantify brain activity continuously during overnight sleep.

Complexity Conjecture



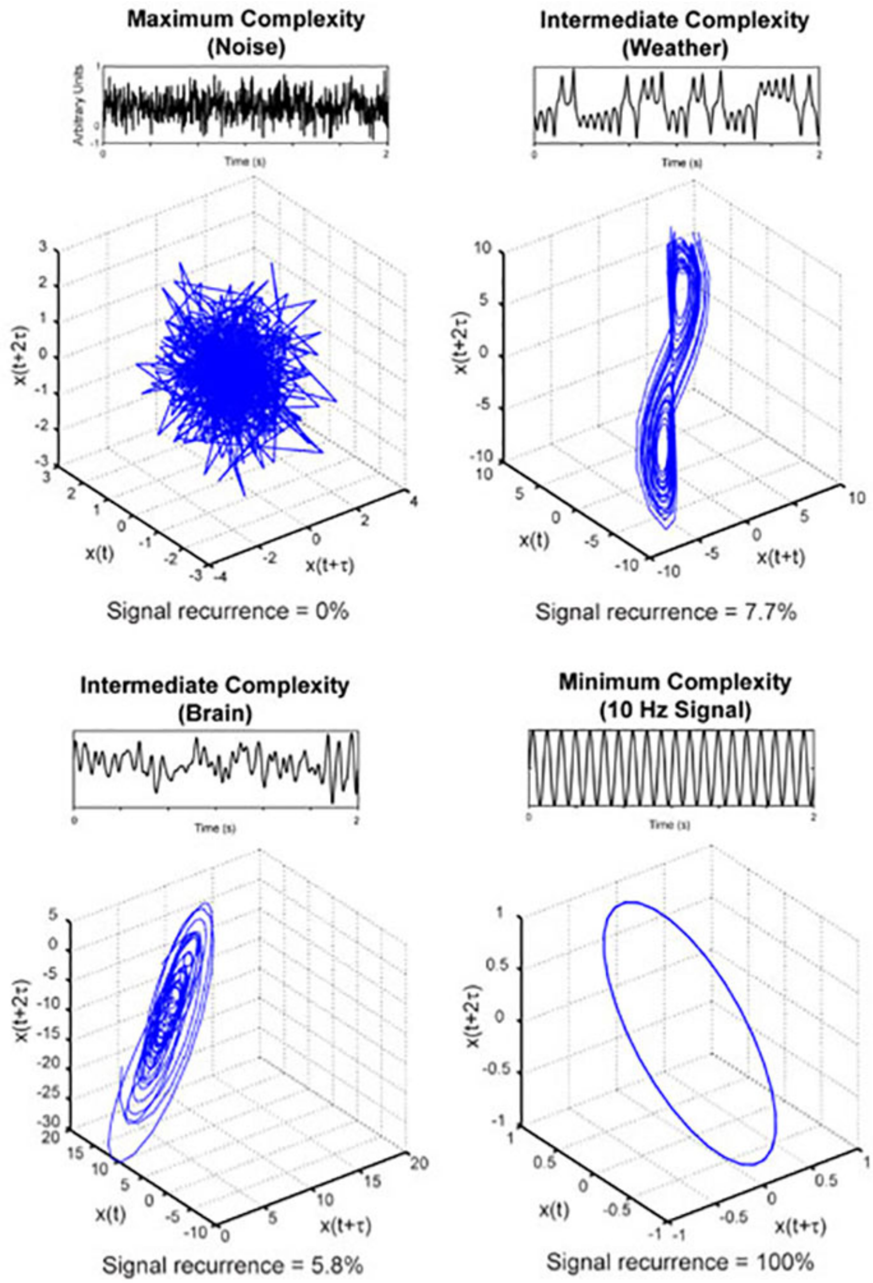
WE HYPOTHESIZED THAT:

- Brain function is mediated by electrical activity in localized neuronal networks and their internetwork electrical synchronization (instantaneous strength of connectivity represented by line color).
- Brain states can be defined by computing the complexity of the EEG over time intervals of interest. The time interval considered here was 30 sec.

OUR SPECIFIC AIMS WERE:

- Show that EEG complexity is correlated with sleep state (less complexity in deeper sleep).
- Examine the role of EEG derivation.

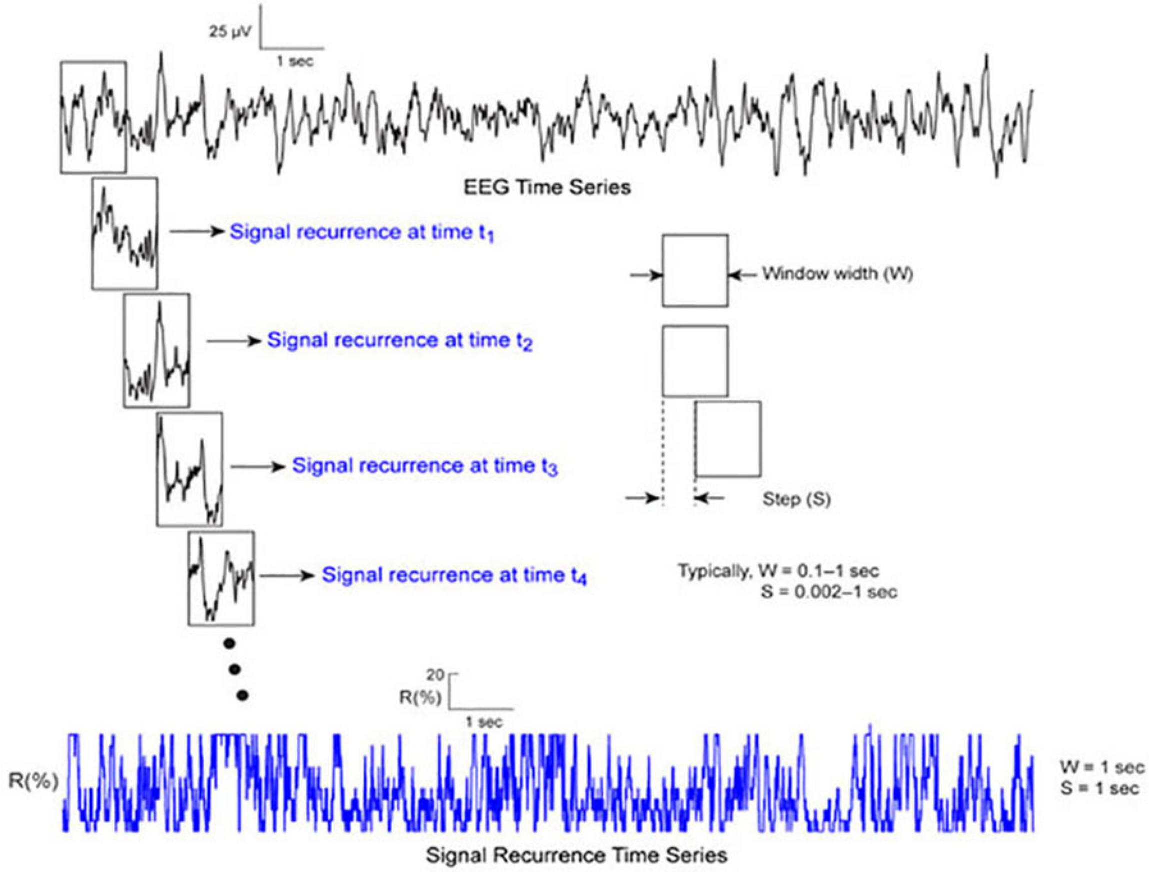
Computational Method: Recurrence Quantification Analysis (RQA)*



Signals from complex systems appear random in time but reveal structure when subjected to specialized mathematical transformation. Top row: time series plotted over time. Bottom row: corresponding plots from mathematical phase space.

*For details see Zbilut JP, Webber Jr. CL. Recurrence quantification analysis, in Wiley Encyclopedia of Biomedical Engineering, Akay M, ed. Hoboken: John Wiley & Sons, 2006: pp. 2979–2986.

Application of RQA to EEG*

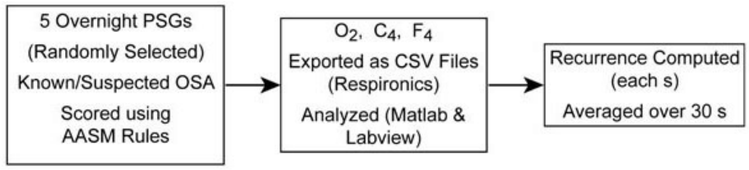


The amount of EEG recurrence (R) (assumed to be the brain's non-random dynamical activity) is captured in the signal recurrence time series which is averaged over intervals appropriate to the question of interest.

R is not an absolute number in the sense of temperature or weight, but rather is relative to the choices of a set of parameters in the process of previous studies of recurrence in human and animal studies.

*For details see Carrubba S, Frilot C, Chesson Jr. A, Marino A. Detection of nonlinear event-related potentials. J Neurosci Meth 2006; 157: 39–47.

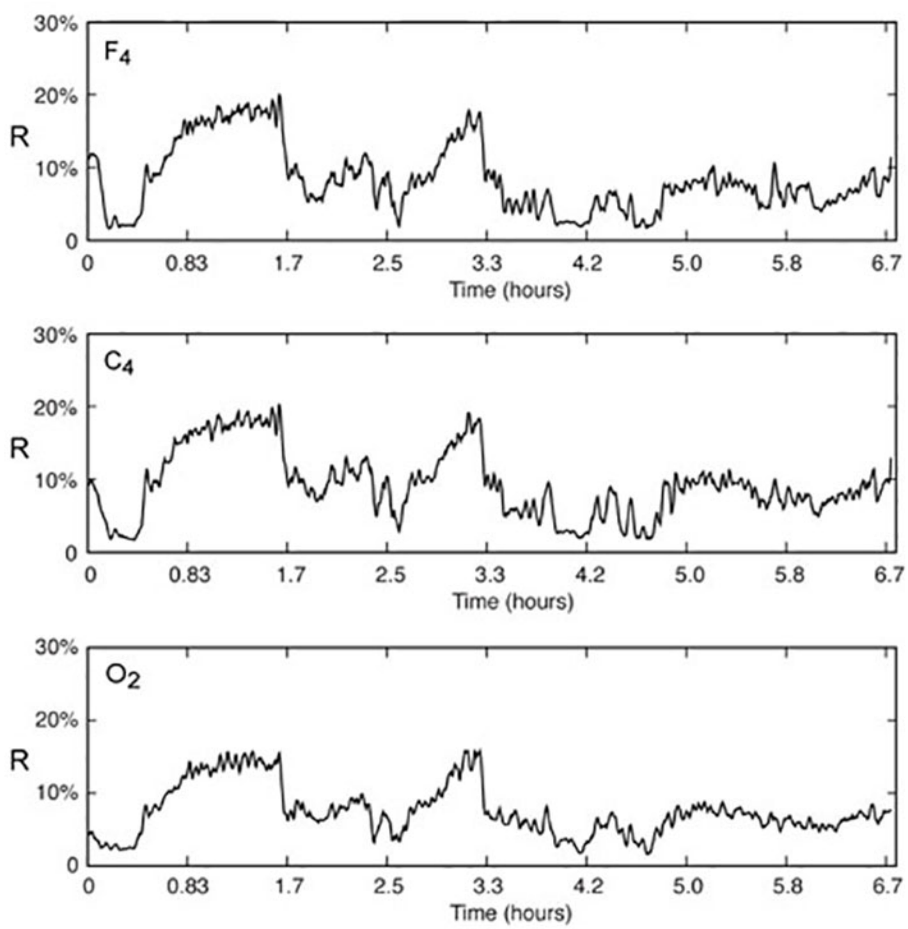
Procedure



Five randomly-selected PSGs were analyzed in this initial study. Only results pertinent to sleep architecture at time scales ≥30 sec are presented. The EEG was recorded at 500 Hz (Respironics) which would permit evaluation over time scales as short as 60 milliseconds.

Typical Results of PSG of a Patient with OSA (Patient No. 1)

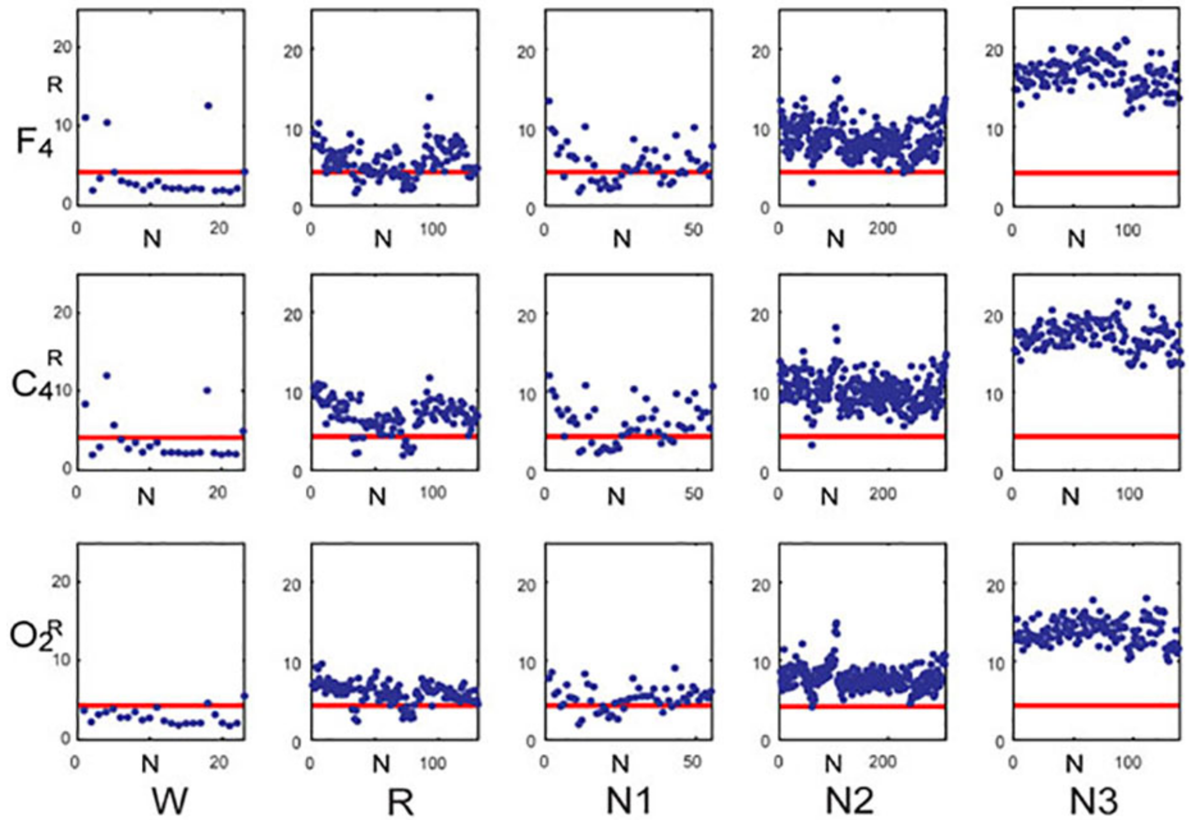
Recurrence computed over 1-sec intervals, averaged over 30 sec, and smoothed over 10 points (300 sec) while preserving local structure (Golay filtering).



Systematic changes occurred in brain electrical activity. The large-scale architecture was similar in the signal from each derivation.

Relation Between Recurrence and Sleep-State Score for Patient 1

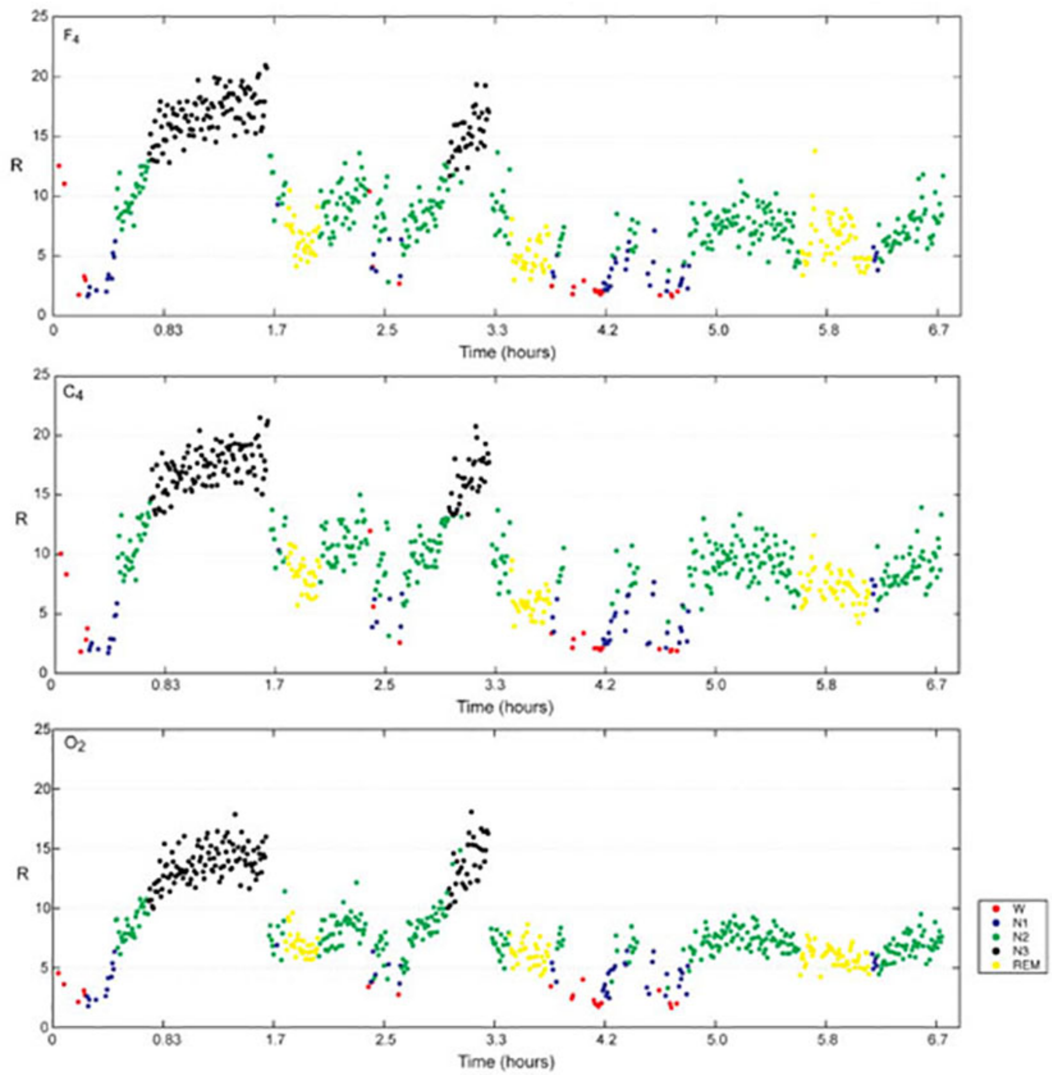
The average value of R was calculated for each 30-sec epoch from patient No. 1, and the values were grouped by sleep state as scored by a blinded scorer. (Each point is the R value for 1 epoch (N = 750 epochs)). The red bar at R = 4.3 ± 0.3 is the mean ± SD for N = 20 awake (eyes closed) clinically normal subjects. N, epoch number.



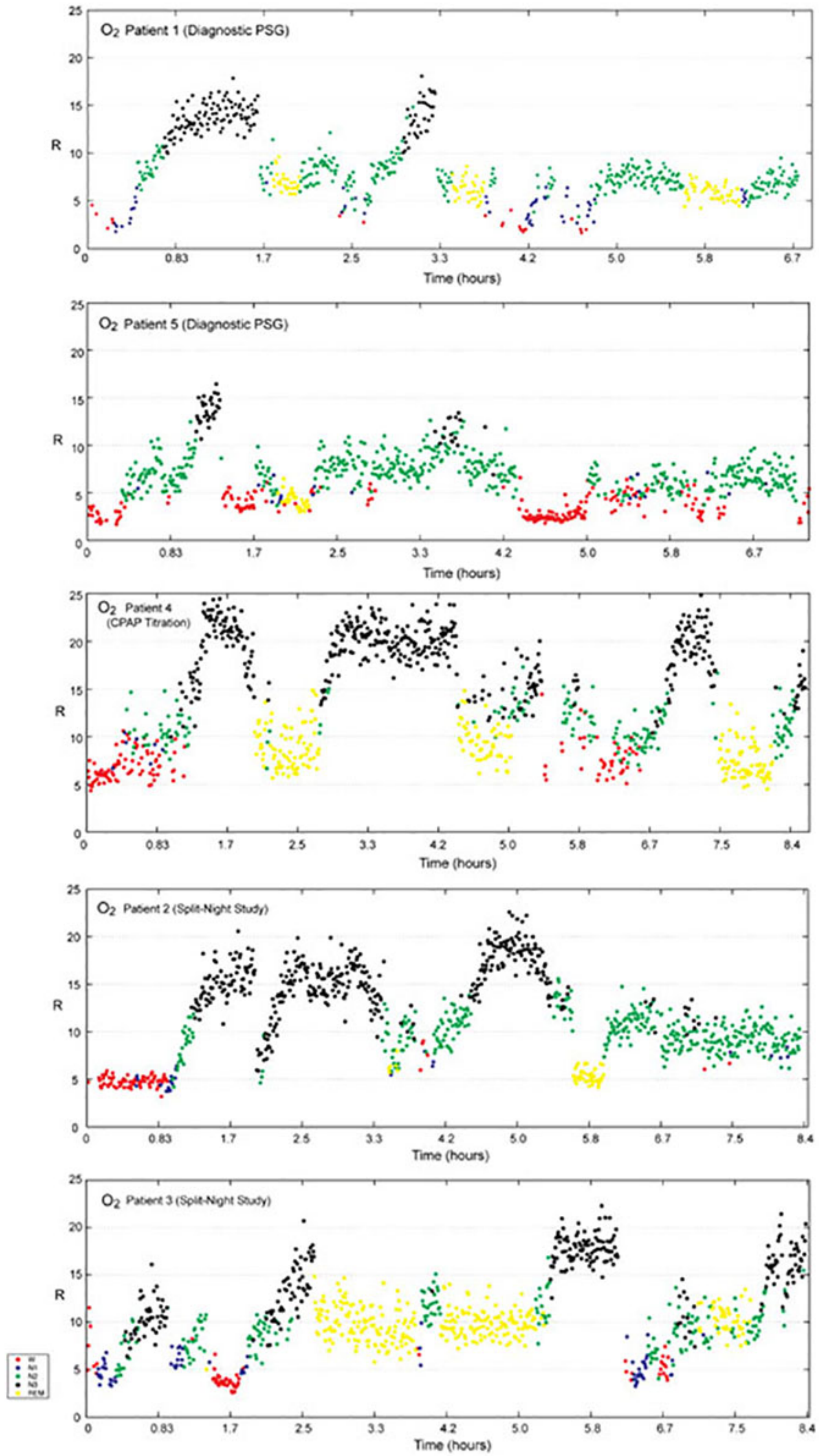
With the marked exception of REM sleep the recurrence (R) of the sleep epoch correlated well with the sleep-state classification.

Relation Between Recurrence, Sleep-State Score and Timing of Each Epoch for Patient No. 1

Recurrence was averaged over each sleep epoch and color-coded by stage.



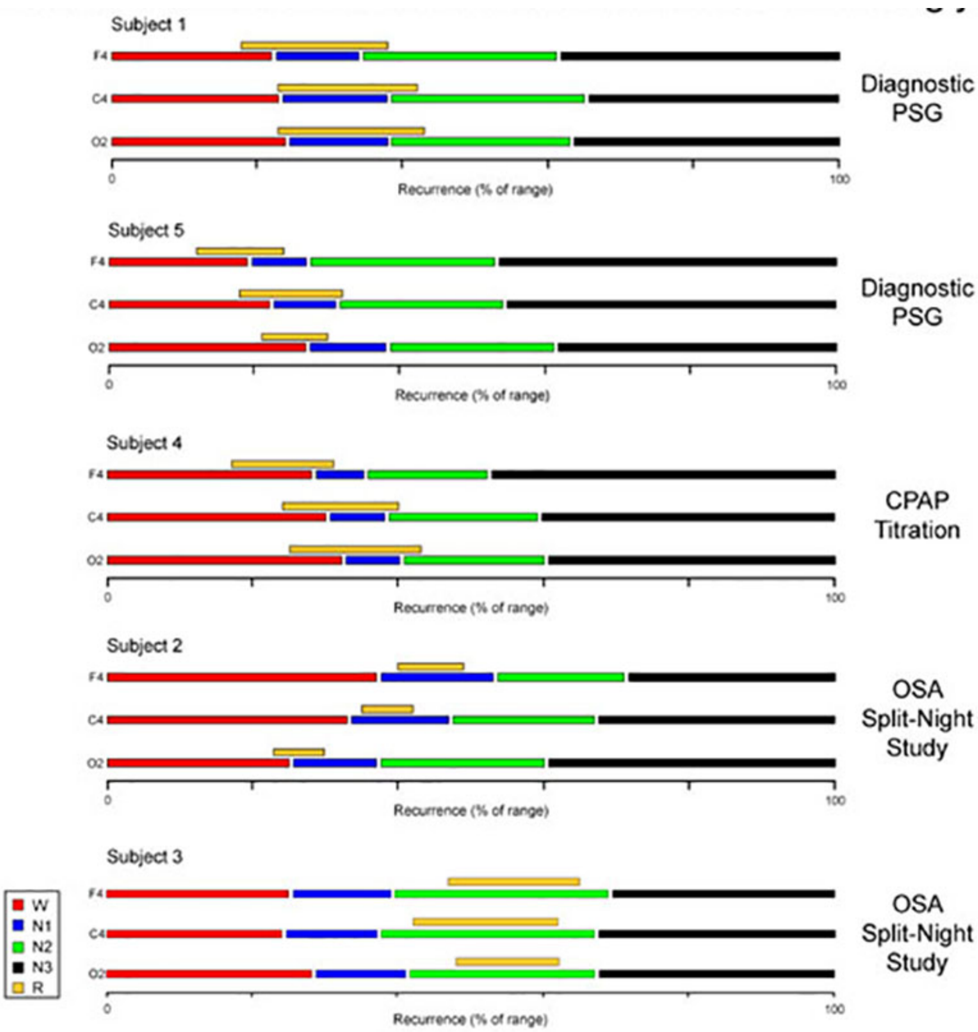
Relation Between Recurrence, Sleep-State Score and Timing of Each Epoch for Patients No. 1–5



In each subject non-REM brain complexity was periodic and correlated with sleep state. REM complexity, in contrast, overlapped all stages except N3.

Brain Deterministic Activity During REM Compared with Other Sleep States

For each derivation in each patient the highest recurrence value was set at 100 and all other values were scaled accordingly.



REM complexity in relation to complexity of the other sleep stages. REM sleep was less complex (higher R values) during the split-night studies.

Agreement Between AASM and Recurrence Scoring, Excluding REM

Results averaged across O_2, C_4, F_4. Number of scored epochs in parentheses.

Patient No.	A	N_1	N_2	N_3	Weighted Average
1	86% (22)	42% (52)	77% (321)	97% (142)	79%
2	89% (82)	63% (24)	74% (375)	88% (389)	82%
3	72% (62)	37% (70)	68% (201)	81% (262)	70%
4	76% (127)	52% (7)	59% (169)	84% (430)	77%
5	72% (205)	52% (23)	65% (465)	94% (45)	68%

Conclusion

- Brain law-governed activity varies continuously and systematically during sleep
- Abrupt changes rare or nonexistent
- Brain activity during REM overlaps all sleep states except N3

LIMITATIONS

- Small sample studied
- Normal controls not analyzed
- Small-scale architecture unknown
- Comparison of results needed with those from other methods