EEG SLEEP SPINDLE PROCESSING WITH INDEPENDENT COMPONENTS
ANALYSIS

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Abstract—Sleep spindles are bursts of rhythmic activity characterized by progressively increasing,
then gradually decreasing amplitude, present predominantly in stages 2, 3 and 4 of the sleep
electroencephalogram (EEG). Topographic analyses of sleep spindle incidence suggested the existence of
two distinct sleep spindle types, “slow” and “fast” spindles at approximately 12 and 14 Hz respectively.
There are indications that there exist at least two functionally separated spindle generators,
corresponding to each frequency spectrum class. The purpose of the present study was to process sleep
spindles with Independent Component Analysis (ICA) in order to investigate the possibility of
extracting, in the ICA-reconstructed EEG, spindle “components” corresponding to separate EEG
activity patterns, and to investigate the sources underlying these spindle components. Using 8-
channel EEG recordings of sleep spindles of a single subject, source analysis using Low-Resolution Brain
Electromagnetic Tomography (LORETA) was applied on the reconstructed EEGs. Results indicate
separability and stability of sources related to sleep spindle components reconstructed from separate
groups of Independent Components (ICs).

Introduction

Sleep spindles are among the most remarkable oscillations that appear on the electroencephalogram
(EEG) during non-rapid eye movement (non-REM) sleep. Sleep spindles are characterized by rhythmic
waxing and waning activities with frequencies between 11 and 16 Hz, grouped in sequences that last
approximatively 1 to 3 s and recur every 3 to 10 s [1,2]. Analyses of scalp-recorded sleep spindles have
demonstrated topographic distinction between slow and fast spindle waves, indicating the existence of
two distinct sleep spindle types: “slow” spindles at ~12 Hz, more prevalent in frontal EEG leads, and “fast” spindles
at ~14 Hz, more pronounced over parietal and central sites [3,4]. While there exist indications that at least two
functionally separated spindle generators are responsible for the difference in the frequency and
topography of the spindle types, the matter is still under investigation [5].

Independent component analysis (ICA) is a statistical technique that aims at finding linear projections of the data that maximize their mutual
independence [6,7]. Its main applications are in feature extraction and blind source separation (BSS). ICA has
been extensively used in electroencephalography and magnetoencephalography [8-11].

Low-resolution brain electromagnetic tomography (LORETA) is an EEG-to-intracranial current source
inversion technique widely used in EEG research [12,13]. It computes a unique three-dimensional (3D)
source distribution, by assuming that the smoothest of all possible inverse solutions is most plausible, which is
consistent with the assumption that neighbouring neurons are synchronously active.

The aim of the present study was the use of ICA for processing sleep spindles in order to investigate the
possibility of extracting, in the ICA-reconstructed EEG, spindle “components” corresponding to separate EEG
activity patterns, and to investigate the sources underlying these spindle components, using the
LORETA technique, so as to contribute on the on-going research concerning the existence of distinct sources for
the two spindle types.

Materials and methods

A single subject’s all-night polysomnographic recording was examined. EEG signals were acquired
with sampling frequency 256 Hz, at leads F4, C4, P4, O2, F3, C3, P3, O1. Sleep spindles were visually
detected and filtered using a 128th-order finite impulse response (FIR) bandpass filter, with cut-off frequencies
at 6 and 21 Hz.

ICA was applied at the original filtered EEG data, using the EEGLAB module [14], followed by visual
examination of both the EEG and the ICs (Fig.1). Short-Time Fourier Transform (STFT) was applied to the
EEG and the ICs, so that the temporal evolution of the
main frequency of the signals might be inspected, with a resolution of 1 Hz.

The most important step in the analysis consisted of dividing the original single spindle timeframe into parts that reflected different spindle-like activities, called spindle “components”, within that spindle. The division was based on the existence of a distinct waning-waxing cycle and/or on a transition from “low” to “high” frequencies (or vice versa). Frequencies ≥14 Hz were considered “high” and, together with the “limit high” frequency of 13 Hz, were considered as representing fast spindles. Frequencies ≤12 Hz were considered “low”, representing slow spindles. If such parts could be discerned, then an inspection of the ICs followed, in order to select those ICs who possessed spindle-like morphology and would best correspond to the previously selected parts of the EEG, both concerning their time duration and their frequency content. For facility of the exposition of the methodology, we suppose in the following that the EEG was divided into two parts, A and B. Therefore some ICs would be grouped together and be considered as “representatives” for part A and some other ICs for part B. Even if ICs’ activity possessed temporal coincidence and had similar frequency content with the respective EEG parts, they were rejected if their spindle-like waveform extended to more than one part and/or if their maximum power frequency varied between low and high in the same part. After ICs had been selected as representatives of the parts, EEG was reconstructed, for the whole time duration of the spindle, once based only on the ICs of group A, and once based on the ICs of group B. Spectral analysis was also applied to the reconstructed EEG, so that a comparison could be made between the spectrums of the reconstructions, their generating ICs and the original EEG, in order to confirm the selection of the EEG parts and the grouping of the ICs. The above procedure should enable the extraction, in the ICA-reconstructed EEG, of spindle components corresponding to separate EEG activity patterns.

Next we used LORETA [15] for investigating the sources underlying these spindle components. LORETA was used to compute the 3D distributions of current density, for each time sample, for both the original EEGs and the reconstructed ones. The data from each time sample were averaged for the whole duration of the respective part. Therefore, for each part, we possessed three 3D mean source activity maps, one for the sources of the original EEG in that part, and one map for the sources of each EEG reconstruction. The final step in the analysis was the comparison of the mean value images and the local maximum current activity voxels of the original and the reconstructed signals.

Figure 1: Original filtered sleep spindle EEG (left) and ICs (right).

Figure 2: ICA-reconstructed EEG corresponding to the slow spindle component (right) and the limit fast spindle component (left).
Results

In Figure 1 are shown an original sleep spindle EEG its ICs projections, in a representative case. By inspecting the waning-waxing cycle of both the EEG and the ICs, we divided the spindle time frame into parts A and B, with division time point at 1 sec from the start of the spindle. In part A there existed a spindle like activity with low frequencies (10-11 Hz) and in part B a longer lasting spindle-like pattern. In all leads, except the frontal ones, the spindle-like activity of part B was limit fast (13 Hz), while in the frontal leads, the “breakdown” of the spindle-like activity, which was apparent in all leads, was more pronounced with a frequency “dip” to 11 Hz. Therefore we might investigate the sources underlying the first (slow) spindle component and the second (limit fast) spindle component. The inspection of the ICs indicated that IC 2 might represent part A, since it was the only IC that in this part possessed well-defined spindle-like morphology at low frequencies (11-12 Hz). For part B ICs 4 and 7 were selected as representatives, since they were the only ICs that possessed spindle-like waveforms with maximum power frequencies not lower than 13 Hz. Further division of part B into two sub-parts, reflecting the waning-waxing present at approximately the middle of part B, was not undertaken, since no ICs were found to represent separately these sub-parts.

In Figure 2 are shown the reconstructed EEG corresponding to the slow spindle component (right) and the limit fast component (left). Both temporal and spectral coincidence existed between the ICA-reconstructed EEG and the respective spindle components that were apparent in the original EEG. It should be noted that activity of the reconstructed EEG was not restricted only to the part of the EEG where it was maximal but extended also to the other part, where, nevertheless, it did not possess spindle-like morphology.

In Figure 3 we present the average source activity for part A. Maximum source activity for the original EEG and the slow spindle component coincided. The global maximum was at frontal regions. The limit fast spindle component had maximum activity at posterior regions, but did not possess spindle-like morphology in that part. In Figure 4 we present the average source activity for part B. Maximum source activity for the original EEG and the limit fast spindle component coincided. The global maximum was at posterior regions. The slow spindle component had maximum activity at frontal regions, but did not possess spindle-like morphology in that part. Finally, by inspecting both Figures 3 and 4, we noted that the maximal sources of each spindle component remained stable between parts. These findings were also reproduced for other spindles processed in the present work.

Discussion

Based on the results from the spindles processed in the present study, positive indications were provided that sources related to sleep spindle components reconstructed from separate groups of ICs might be successfully extracted. As in the example presented in the Results Section, in each part of the spindle, the maximal sources of the spindle component representing the spindle activity in that part, mainly coincided with the maximal sources of the original EEG in the same part, indicating that the components’ source activity was the main locus of generators for the respective parts of the EEG.

Secondly, in most spindles analysed in the present study, the generators of slow spindle components were at frontal regions and of fast in posterior and central regions, in accordance with most existing literature [4,5].

The examination of the sources of each spindle component, showed a remarkable stability between parts of the EEG. E.g. the maximal source regions for the reconstructed EEG that reflected the spindle activity in one part kept their primacy in the other parts, albeit with lower amplitudes, as expected since they were not the EEG component that represented the dominant spindle-like activity in the other parts. This stability of the sources was in accordance with one of the main characteristics of ICA analysis, namely that ICs, or groups of ICs, reflect functionally and topographically separate sources, if independent components are successfully separated [9]. Therefore an indication was provided that slow and fast spindles originate in different parts of the brain and reflect distinct groups of generators, which remain active throughout the spindle duration, even if there is a frequency shift in the spindle.

The present study had limitations. Apart from the difficulties that are present when applying ICA to EEG data concerning the applicability of ICA assumptions in these category of biomedical data [8,9], the main limiting factor was the reduced number of electrodes available for performing the inversions to the intracranial sources. This prohibited the certainty in extracting specific regions for the sources, at the resolution of the LORETA technique, and made obligatory to use the source maps only as indicative of presence of sources in broadly defined brain areas, such as frontal, parietal, temporal, central and posterior.

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References

Figure 3: Projections of mean source activity for part A. Sources of the original EEG are given at left, of the ICA-reconstructed EEG representing the limit fast spindle component at center and of the ICA-reconstructed EEG representing the slow spindle component, which is the component active in this part, at right. Maximal activity is located at frontal regions for the original EEG and the slow component.

Figure 4: 2D projections of mean source activity for part B. Sources of the original EEG are given at left, of the ICA-reconstructed EEG representing the limit fast spindle component at center, which is the component active in this part, and of the ICA-reconstructed EEG representing the slow spindle component at right. Maximal activity is located at posterior regions for the original EEG and the limit fast component.


