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Review

Signal processing techniques applied to human sleep EEG signals—A review

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ABSTRACT

A bewildering variety of methods for analysing sleep EEG signals can be found in the literature. This article provides an overview of these methods and offers guidelines for choosing appropriate signal processing techniques. The review considers the three key stages required for the analysis of sleep EEGs namely, pre-processing, feature extraction, and feature classification. The pre-processing section describes the most frequently used signal processing techniques that deal with preparation of the sleep EEG signal prior to further analysis. The feature extraction and classification sections are also dedicated to highlight the most commonly used signal analysis methods used for characterising and classifying the sleep EEGs. Performance criteria of the addressed techniques are given where appropriate. The online supplementary materials accompanying this article comprise an extended taxonomy table for each section, which contains the relevant signal processing techniques, their brief descriptions (including their pros and cons where possible) and their specific applications in the field of sleep EEG analysis. In order to further increase the readability of the article, signal processing techniques are also categorised in tabular format based on their application in intensively researched sleep areas such as sleep staging, transient pattern detection and sleep disordered breathing diagnosis.

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1. Introduction

Sleep is a crucial part of everyday life. It directly affects our cognitive performance, learning capabilities, and general physical and emotional well-being. Sleep is the primary activity of the brain in infancy and is thought to be a factor in neural plasticity [1,2]. Sleep problems in early life may result in lasting neurocognitive deficits. Krueger et al. [3] point out that "during sleep one gives up the opportunities to reproduce, eat, drink or socialise and one is subject to predation. Sleep could only have evolved despite these high evolutionary costs if it serves a crucial, primordial function". Understanding and measuring brain activity in sleep is an exciting frontier of neuroscience, and polysomnography (PSG) provides a data-rich source for understanding sleep in both health and disease. PSG combines multiple signals in sleep typically including neurophysiological signals:

- EEG (usually 4–8 channels), EOG and EMG (submentalis and/or tibialis muscle)combined with cardiorespiratory signals such as:
- ECG
- Oxyhaemoglobin saturation
- Oral-nasal air flow
- Abdominal and thoracic excursions

Visual inspection of these neurophysiological signals forms the basis for standard sleep staging [4]. Signal processing allows the extraction of detailed information from such signals. Applications of these methods in relation to sleep EEG range from simple time and frequency domain analysis to implementation of sophisticated nonlinear pattern recognition and classification algorithms. Kubicki et al. [5] emphasise that going beyond the well-known and commonly used Rechtschaffen and Kales scoring criteria [4] will not be possible without the use of signal processing techniques and computer aided analyses to reveal further information on the microstructure of sleep. The body of literature developed for the analysis of sleep EEG is vast and therefore this review paper provides a synthesis of a selection of this literature to generate an overview of signal processing techniques applied to human sleep EEG analysis and their relative merits.

The characteristic of the PSG signals to be analysed is rather challenging. The underlying signals are inherently non-stationary and the relationships between the different measurement channels maybe time-varying. Many of the physical processes giving rise to the observed signals are nonlinear in nature with the result that the measured signals exhibit non-Gaussian statistics. To further confound the problem many signal components of interest may be observed in the presence of contaminating noise at a comparatively poor signal noise ratio. The standard principled approach to the development of signal processing algorithms is generally based on modelling the underlying processes and using that model to then develop optimal algorithms. As is common in many biomedical applications, this approach flounders due to a lack of realistic signal models and so a more heuristic approach is flourished leading to the plethora of techniques observed in the field.

Signal processing techniques will be considered in three sections: pre-processing, feature extraction and feature classification, which constitute the basic underlying tasks in the automated analysis of sleep signals. Each section describes its most frequently reported signal analysis methods. An extended Taxonomy Table which summarises the sleep EEG related applications of the surveyed techniques, containing a significantly greater selection of references has also been collated for each section and may be found in the accompanying supplemental materials. A final supplementary Taxonomy Table re-categorises the addressed signal processing techniques based on their applications in well-established areas of sleep research such as obstructive sleep apnoea (OSA) diagnosis and automatic sleep staging. Studies included in this survey are limited to surface EEG signals in sleeping humans (including the paediatric population). In short, this review aims to synthesise the complex field of sleep EEG analysis to inform both the signal processing and the sleep research communities.

2. Pre-processing

There are several objectives when pre-proposing of PSG signals including: normalisation, calibration, detrending and equalisation, but these are aspects which are common to many signal processing applications and require only the most basic of processing strategies. The following focuses on two rather more specific aspects of