



Case report

Case comparison of sleep features from ear-EEG and scalp-EEG

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ABSTRACT

Background: We investigate the potential usability of a novel in-the-ear electroencephalography recording device for sleep staging.

Methods: In one healthy subject we compare simultaneous earelectroencephalography to standard scalp EEG visually and using power spectrograms. Hypnograms independently derived from the records are compared.

Results: We find that alpha activity, K complexes, sleep spindles and slow wave sleep can be visually distinguished using earelectroencephalography. Spectral peaks are shared between the two records. Hypnograms are 90.9% similar.

Conclusion: The results indicate that ear-electroencephalography can be used for sleep staging.

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1. Introduction

We present a case trial of sleep stage detection using a novel electroencephalographic (EEG) recording platform placed in the ear (ear-EEG). In current practice, polysomnography (PSG) during hospitalization is the gold standard for diagnosing sleep disorders. However, PSG is also a relatively resource intensive investigation, which limits its use. Home PSG as a less expensive alternative has been investigated finding unsatisfactory recordings in 13 of 48 patients, the main cause of unsatisfactory recordings being loss of EEG data [1]. We envision that ear-EEG fills this gap.

The ear-EEG devices are customized to each user similar to hearing-aid earplugs. This secures tight contact between the recording electrodes and the skin. Ear-EEG as a method has been tested in awake, healthy subjects using a variety of known EEG paradigms [2]. Compared to scalp EEG it maintains a similar signal-to-noise ratio, being less contaminated by electro-muscular artifacts albeit at a cost to signal amplitudes [3]. Correlation analysis between ear-EEG and scalp-EEG shows the highest degree of similarity for scalp electrodes near the temporal region decreasing towards the midline [4]. Thus one can make reasonable assumptions that sleep related phenomena predominantly found near the midline, such as vertex sharp waves, would be less likely to be

resolved with ear-EEG.

We present novel data showing identification of sleep specific graphoelements using ear-EEG and demonstrating that ear-EEG performs comparably to standard extracranial recordings for sleep staging purposes.

We envision a number of future applications for small non-intrusive biomedical devices such as ear-EEG for long term monitoring of brain electrophysiology.

2. Methods

The ear-EEG device consists of four recording electrodes embedded in a solid cast made from individually fitted ear impression moulds. We used two ear-EEG devices simultaneously. The recording electrodes are labelled E, I, B and A (Fig. 1).

We recorded simultaneous scalp EEG for comparison. Scalp electrode configuration followed the international 10–20 system with 25 electrodes including inferior temporal chain and EOG. For sleep staging, we used electrode positions F3, C3, O1, F4, C4, O2 contralaterally referenced to M1 and M2 on the mastoid processes as recommended by The American Academy of Sleep Medicine [5]. The study has been approved by the National Board of Health and the Local Ethics Committee.

We explored the ear-EEG channels by varying the choice of active electrode and reference electrode.

The validation setup is 3 fold:

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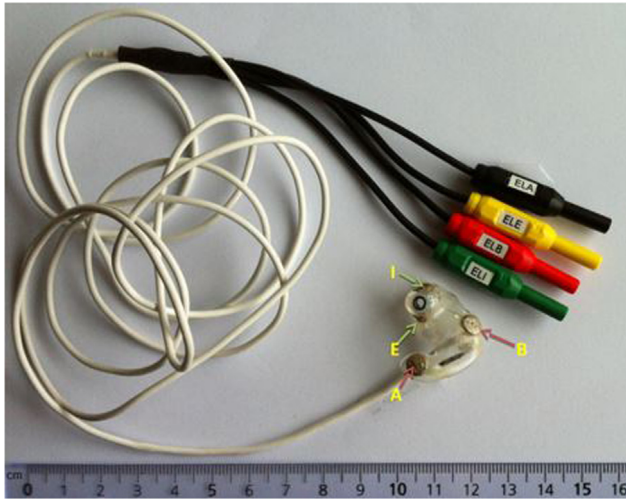


Fig. 1. Ear-EEG prototype. The four recording electrodes, I, E, B and A with connector cables labelled with 3-letter combinations. EL prefix stands for Ear-Left and ER for Ear-Right. The third letter refers to one of the four recording electrodes. Electrode I and E (green arrows) rest in the outer external acoustic meatus. B and A (red arrows) in the concha.

- 1) “Ear-scalp” referencing ERI (ear-right-I) to M1 to approximate C4-M1 for comparative reasons.
- 2) In “inter-ear” referencing each ear electrode is referenced to the contralateral homologue electrode, thus ELE (ear-left-E) is referenced to ERE (ear-right-E) and so on.
- 3) “Intra-ear” referencing uses electrode A referenced to electrode I. Bipolar intra-ear referencing can be expected to yield low voltages given the proximity of the electrodes used.

The subject was a 30 y.o. male with no known medical problems who participated after giving informed consent. Ear-EEG and simultaneous scalp EEG were recorded for 21 h including one night’s sleep. The amplifier used was a Nicolet wireless 64-channel system sampling at 256 Hz. Both scalp and ear-EEG electrodes was connected to the same amplifier. For visual inspection of raw data we used proprietary software (Nervus reader v.5.93.424, from Cephalon, Denmark). For frequency analysis of the EEG we calculated power spectrograms in Matlab using the pwelch function. Ear-EEG signals have smaller amplitudes compared to standard EEG. To compensate we displayed scalp signals at 100 $\mu\text{V}/\text{cm}$ and

ear-EEG signals at 30 $\mu\text{V}/\text{cm}$. This preferentially amplified low frequency noise in ear-EEG channels making parts of the EEG difficult to read due to high-amplitude waveforms. To offset this effect we displayed duplicates of ear-EEG channels with different low cut filters, one at 2.0 Hz and the other at 0.5 Hz. Using the latter is necessary for identification of the slow waves of N3 sleep, but using a low cut at 2.0 Hz improved the readability of parts of the EEG where faster frequencies predominated. We found this approach to be more efficient than dynamically altering the sensitivity throughout the sleep staging process.

Two experienced sleep scorers (one board certified) evaluated seven hours of recording. The recording contained 6 h and 45 min of sleep preceded by 15 min of wakefulness. Both scorers analysed first the standard EEG channels then repeated the process looking exclusively at the intra-ear and inter-ear channels and EOG. Each 30 s period was scored as either wake, N1, N2, N3 or REM. If the scores in an epoch differed it was jointly rescored and consensus reached (less than 10% of periods). Scalp referenced EEG (ERI-M1) was not evaluated to avoid mixing the two types of EEG signal. Submentalis EMG was lost due to electrode failure.

Scorers followed AASM criteria for sleep scoring [5]. This requires an amplitude above 75 μV in stage N3. Since signals had to be magnified by a factor of 5 in order to appear similar this cut-off was reduced to 15 μV in the ear-EEG. The resulting hypnograms for standard and ear EEG were compared.

3. Results

Visual comparison of short EEG epochs revealed striking similarities (Fig. 2). The ear-EEG amplitudes are reduced compared to the scalp channels, but the individual waveforms can be identified and appear similar between scalp and ear EEG channels. To ease the visual comparison of signals we displayed ear-EEG with increased sensitivity. Sensitivity adjustments in the intra-ear channel make the use of low-cut filters at 2 Hz necessary in order to keep some parts of the record visually interpretable. Panel B shows a K-complex. In panel C a sleep spindle is observed. Whereas the K-complex is less distinct in the ear-EEG channels than in standard EEG, the rapid oscillating morphology of the sleep spindle is fairly distinct in the intra-ear channel.

Spectral density estimates of the signals (Fig. 3) in two different states: wakefulness with closed eyes (75 s) and slow wave sleep

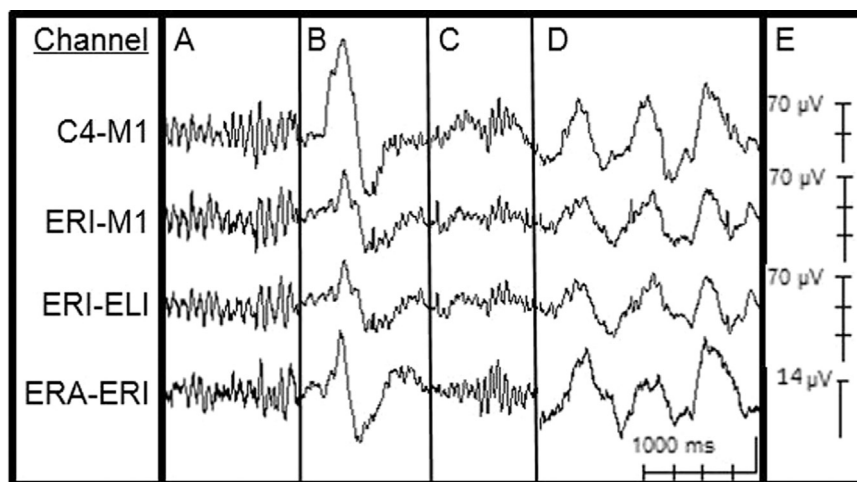


Fig. 2. Combined EEG montage showing scalp-channel C4-M1 (top) with three different ear-EEG channels (below). ERI-ELI is the inter-ear referenced Ear-EEG and ERA-ERI is the intra-ear referenced Ear-EEG channel. A) Resting alpha with closed eyes. B) K-complex. C) Sleep spindle during N2 D) N3, slow wave sleep. Discontinuities in the record are marked with vertical lines. Note use of different sensitivity settings throughout as indicated in panel E. Low cut filtering in the Intra-Ear channel, 2 Hz in A, 1 Hz in B and C, 0.5 Hz in D.

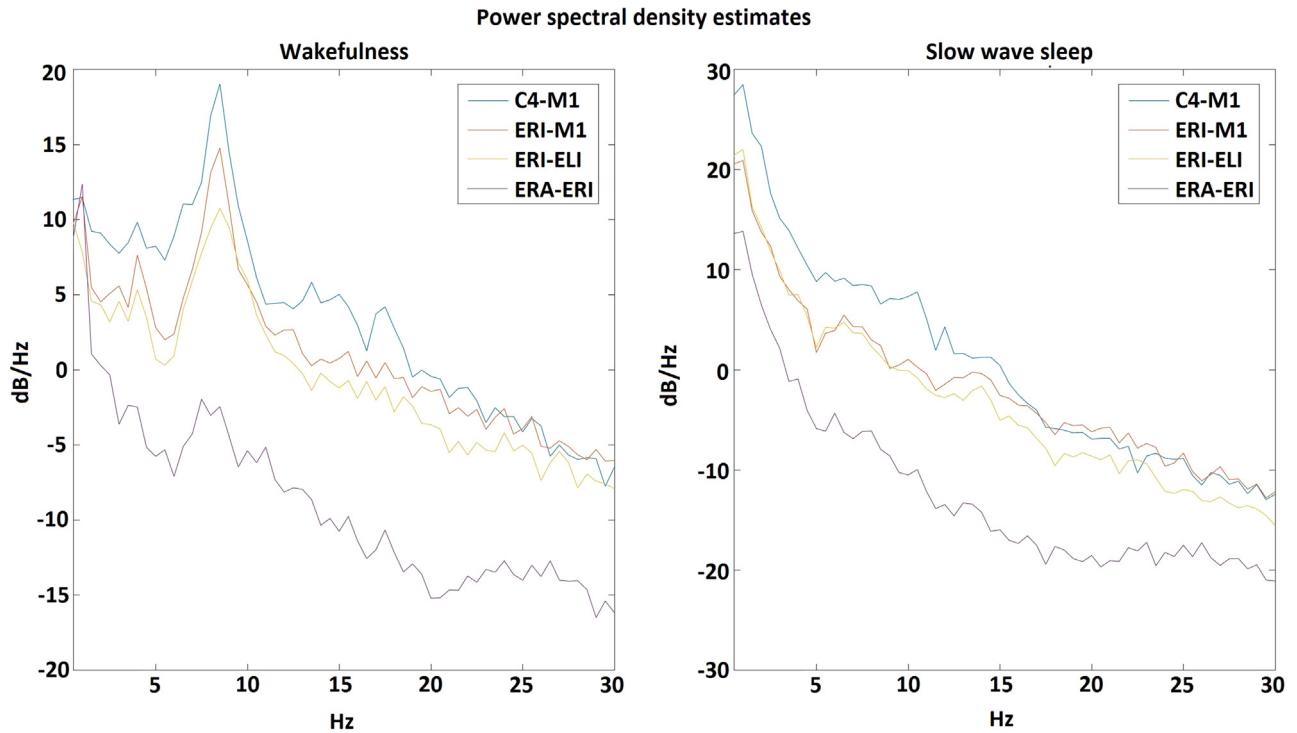


Fig. 3. Power spectra derived from Welch's method for four channels during 75 s of continuous wakefulness with closed eyes (left) and during 75 s of slow-wave sleep (right) plotted as a function of frequency. As anticipated amplitudes in the ear-EEG channels are reduced compared to the scalp channel. The reduction is small in the inter-ear channel, ERI-ELI, but almost an order of magnitude lower in intra-ear, ERA-ERI, than in the scalp channel, C4-M1. An alpha peak can be observed in all channels in the waking state. A low delta peak is seen during deep sleep. In the wakeful state ERA-ERI picks up more low-frequency noise than the other channels.

(75 s). The graphs follow a similar trajectory being vertically displaced versions of each other reflecting the decreasing signal amplitudes with increasing proximity of the active electrode to the reference. In both states, the peak frequencies approximately align across the four channels.

The two different hypnograms are plotted for comparison (Fig. 4). There is exact agreement between timing of sleep onset. The scores of N1, N2 and N3 are similar and for wakefulness and REM the scores are almost identical between EEG types. Of the total 846 scored epochs there is agreement in 90.9% between ear-EEG and standard EEG. In the standard EEG 30.5% of sleep time is spent in N3 sleep compared to 24.7% when evaluated from ear-EEG. For N2 the percentages are 40% and 45.3%, respectively. This suggests that ear-EEG slightly underestimates N3 and overestimates N2. REM onset and time spent in REM sleep was found to be the same in both standard and ear-EEG, but REM sleep staging was only possible by including assessment of EOG channels. In most cases of discrepancy between staging based on ear EEG is to mistaking N3 for N2, whereas the timing of wakefulness and REM is very similar. Less than 2% of the recording is spent in N1 sleep which is too little to determine significant deviances of using

either method.

4. Discussion

There are clear similarities in the temporal and spectral characteristics but the amplitudes recording using ear-EEG are smaller compared to scalp EEG. Compensating by sensitivity adjustments preferentially amplifies low frequency noise, especially for intra-ear referenced ear-EEG channels. A practical solution is to use multiple intra-ear channels with individual post-processing settings optimized for specific EEG feature detection e.g. one for slow-wave sleep and another for sleep spindles.

Comparing ear-EEG channels with scalp EEG channels we observe that the peaks in different frequency bands approximately align across the channels. This suggests that ear-EEG channels can be used as a surrogate for C4-M1. Visually we can identify sleep specific graphoelements such as K-complexes and sleep spindles. Further validation of the method comes from spectral analysis where we find overlapping power distributions in scalp and ear EEG channels.

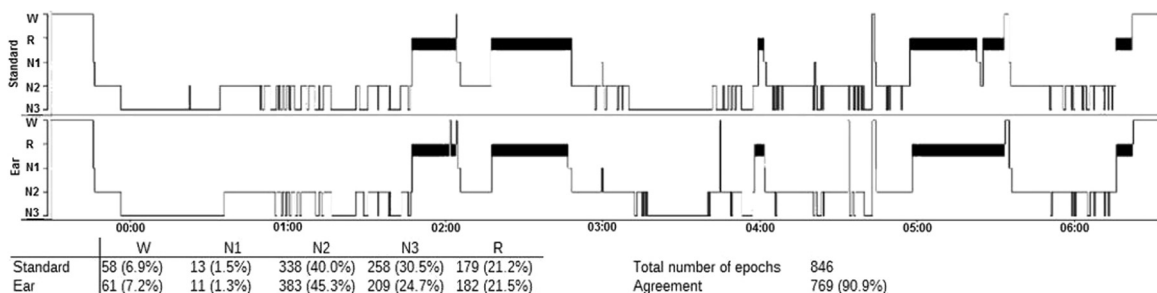


Fig. 4. Comparison of hypnograms from ear-EEG channels (top) and standard EEG channels (bottom). Overall the hypnograms are very similar. Onset of sleep is the same on both. Total time is 6.75 h. Percentages of time awake or in NREM or REM sleep is shown in parenthesis. (W=wake; N=Non-REM; R=REM sleep).

Sleep staging results were highly similar between scalp EEG and ear-EEG. REM sleep staging with ear-EEG necessitates at least use of EOG channels, which also accounts for the high agreement for REM between the two methods. Ear EEG slightly overestimates the amount of N2 and underestimates time spent in N3 sleep. One possible explanation for this could be the partial reliance of low cut filters at 2 Hz which eliminate very slow wave sleep characteristics. The 2 Hz low cut was used whenever amplified low frequency noise resulted from the sensitivity adjustment rendered the 0.5 Hz low cut channel too obscured for visual analysis. Time spent in N1 sleep was less than 2% of the entire record and is too little to determine if it can be reliably staged by ear-EEG or not. Given the overall similarity between hypnograms derived from standard and ear-EEG it seems plausible that ear-EEG sleep staging is possible, but further testing is required before any generalisations of the method can be stated given inter-individual and age-related differences. A better approach to the problem of noise frequency noise interfering with visual analysis is also desirable.

Single-channel A1-A2 EEG and automated sleep staging algorithms have recently demonstrated high agreement rate with PSG [6]. Abbreviated montages for sleep staging have also been successful [7] and it is thus conceivable that other single-channel locations could also perform well in algorithmic sleep staging. This indicates that frequency criterion in sleep staging can be assessed using ear-EEG. Additional sensors to monitor rapid eye movements (REM) and muscle tone will likely be necessary to fully differentiate between all sleep stages.

Future generations of the ear-EEG devices may offer added flexibility compared to the above-mentioned monitoring schemes. We envision integration with smartphones for computing purposes, data storage and geo-location. This facilitate real-time data analysis and makes it possible to deliver audio-visual feedback to the user [8] when such could be relevant. One such scenario could be to help people from falling asleep when driving or doing night calls. One strategy for maintaining vigilance during such

monotonous activities could be based on monitoring alpha spindles as an index of fatigue [9] and e.g. provide auditory feedback to the user to maintain arousal. The optimal choice of EEG features to analyze depends on the clinical problem, but could be supplemented with other biosensors, for instance pulse oximetry, electrocardiography leads and respiratory inductance plethysmography in case of sleep apnea. Combined with smartphone integration the ear-EEG apparatus provides a breadth of flexibility for various monitoring schemes, but further studies are required to determine its clinical feasibility.

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