Whole Night Sleep Monitoring With A Low-Cost In-Ear Wearable Device

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Background: Three bioelectrical signals generated by brain activities (EEG), eye movements (EOG), and muscle contractions (EMG) are used for sleep studies. Traditionally, expensive Polysomnography (PSG) is used to acquire these signals by attaching uncomfortable wired sensors to patients' face and head with the risk of losing sensor contact.
Hypothesis: The bioelectrical signals associated with EEG, EOG, and EMG can be recorded as a mixed biosignal inside the human ear using passive electrodes. Specifically, an earplug-based device can be safely plugged into the ear canal to collect the biosignal. A machine-learning separation algorithm can be then deployed to extract the three signals used for sleep staging.
Methods: We developed a wearable that can be placed safely inside human ears to capture EEG, EOG, and EMG. To adapt to complex ear structure and provide firm connection between electrodes and the skin, we selected an elastic material for its sensory base. To enhance the sensitivity to these low amplitude signals, the electrodes were designed from conductive cloth coated by thin pure silver leaf attached to the base and placed in both ears. Moreover, a signal separation model was developed, adopted from the non-negative matrix factorization (NMF) technique to overcome the limited number of recording channels compared to the number of signals. A learning process was used to develop a template matrix for each signal compared to ground truth which improved signal recognition between people.
Results:

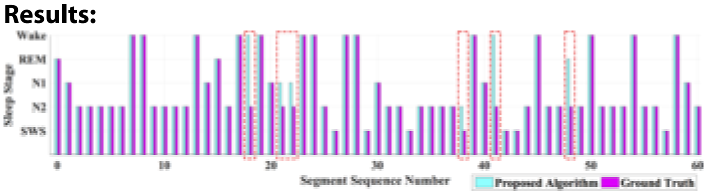

Figure 1. A 30-minute hypnogram produced by a sleep staging system using in-ear EEG, EOG, and EMG (blue) is compared with the ground truth (pink) PSG. Misclassification is marked by red dashed rectangles.
We prototyped our device and conducted 38-hour sleep experiments to evaluate its practicality and usability. Figure 1 demonstrates a promising result of a sleep staging model using EEG, EOG, and EMG provided by our in-ear wearable. Compared to PSG, our system achieved 94% accuracy in sleep stage classification on average when using the three separated signals as input.
Conclusion: Preliminary results demonstrate that an unobtrusive wearable, which captures EEG, EOG, and EMG from inside the ears, shows the feasibility of collecting bioelectrical signals for sleep staging. We believe that our in-ear device has a potential to become a fundamental sensing solution applied in numerous other healthcare and human-computer interaction (HCI) applications.

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