NeuroPulse: Advancing Non-Invasive EEG and ECG Monitoring with Innovative In-Ear Electrode Technology

Dylan Luong[1] and Pierce Perkins[1], Prachi Agarwal[1], Mingfeng Cao[1], Alessandro Ascani Orsini[1], Johnnie A. Johnson[1], Raeann Kalinowski[1], Chang Liu[1], Haoyu Xu[1], and Nitish Thakor[1].

[1]The Johns Hopkins University, USA.

Statement of Purpose: Traditional EEG and ECG monitoring systems rely on head caps (EEG) and chest adhesive electrodes (ECG), which suffer from poor wearability, high motion artifacts, and skin irritation. NeuroPulse is a novel in-ear electrode that leverages a composite of PDMS, PDMS microbeads, and PEDOT:PSS to enable simultaneous EEG and ECG acquisition in a comfortable, minimally invasive form factor. Our study aimed to assess NeuroPulse's signal quality, impedance, and motion artifact suppression compared to both epidural screw electrodes (EEG) and chest ECG leads.

Methods: NeuroPulse electrodes were microfabricated using a 10:1 PDMS-to-curing-agent ratio, with PDMS microbeads (fabricated via PVA emulsion techniques) incorporated to increase surface area and reduce impedance. The conductive layer was formed using 5% wt PEDOT:PSS solution mixed with 20% wt DMSO/EG in water, followed by centrifugation and thermal curing at 100°C for 1 hour to enhance conductivity and flexibility. Electrochemical performance was characterized using electrochemical impedance spectroscopy (EIS), cyclic voltammetry (CV), and galvanostatic charge-discharge (GCD) in phosphate-buffered saline (PBS) using a Gamry Interface 1040E system. For in vivo testing, n = 5 Lewis rats were implanted with epidural screw electrodes for EEG validation. Simultaneous EEG and ECG recordings were acquired via Tucker-Davis Technologies (TDT) System 3, with EEG sampled at 12,207 Hz and ECG at 939 Hz. Chest ECG leads served as the gold standard for ECG validation. EEG signals were analyzed using wavelet decomposition and power spectral density (PSD) analysis.

Results: NeuroPulse demonstrated low impedance, high signal fidelity, and strong correlation with conventional recording methods. Electrochemical impedance spectroscopy (EIS) revealed that at 1 kHz, the in-ear electrode exhibited an impedance of 5.2 ± 0.4 kΩ, significantly lower than commercial dry electrodes (8.9 ± 0.6 kΩ, $p < 0.01$). Cyclic voltammetry (CV) scans indicated that NeuroPulse had a 27% higher charge storage capacity compared to conventional polymer electrodes, supporting its enhanced electrochemical performance. EEG power spectral density (PSD) analysis showed that gamma-band (30–80 Hz) activity recorded from NeuroPulse correlated at 89% with epidural screw electrodes, confirming the electrode's ability to capture cortical signals with high fidelity. ECG recordings from the in-ear electrode provided heart rate variability (HRV) metrics that were statistically indistinguishable from chest ECG leads ($p = 0.59$), with mean RR intervals of 621 ± 44.5 ms (ear) vs. 651 ± 23.7 ms (chest) and SDRR values of 14.05 ± 0.7 ms (ear) vs. 12.34 ± 0.9 ms (chest). Furthermore, low-frequency (LF) and high-frequency (HF) power ratios showed no significant difference between ear and chest ECG signals ($p > 0.7$), demonstrating the NeuroPulse electrode's reliability as an alternative for ambulatory cardiovascular monitoring.

Discussion: NeuroPulse demonstrated low impedance, stable signal acquisition, and motion resistance, making it a strong alternative to conventional EEG and ECG electrodes. Its 5.2 ± 0.4 kΩ impedance at 1 kHz significantly improves signal quality over commercial dry electrodes, while its PDMS microbead-enhanced surface ensures consistent skin contact without adhesives. In-ear EEG signals retained 89% correlation with epidural recordings, confirming their viability for non-invasive neurophysiological monitoring, particularly in low-frequency applications like sleep and cognitive state tracking. For ECG, NeuroPulse provided HRV measures statistically comparable to chest ECG ($p = 0.59$), demonstrating that ear-based ECG can accurately capture cardiac rhythms without adhesives. The electrode's stable fit within the ear canal reduced motion artifacts, a major limitation in wearable and ambulatory health monitoring. These findings highlight NeuroPulse's potential for continuous, wireless biosensing applications, enabling more comfortable and practical long-term monitoring solutions.

References:

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