Recording Electrocardiograms with Earables

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Introduction

The electrocardiogram (ECG) is a recording of the electrical activity of the heart, and is widely used for monitoring or diagnostic purposes. ECGs are recorded by measuring voltages between electrodes placed on the skin, with standardised electrode placements producing leads, each of which captures heart activity in a known direction. Lead I, for example, measures the horizontal cross-body cardiac vector, normally between electrodes on the left and right arms. Normal, healthy ECGs are cyclical in nature, with five major peaks and troughs labelled as P, Q, R, S and T waves.

Wearable ECG devices such as chest strap monitors and smartwatches allow the scaling of cardiac health observation out of clinical settings. However chest straps are uncomfortable, and can be inconvenient, while smartwatches require users to touch the watch with the opposite hand, blocking the use of both hands and preventing passive monitoring. Ear-worn wearables (earables) have the potential to solve these problems: earphones exist in comfortable form for daily use, and their symmetrical placement across the head is ideal for Lead I measurement.

The combination of attenuation of ECG signals by the body and frequency spectrum overlap with other biopotentials (such as EEG and EOG) mean that the ECG signal-to-noise ratio (SNR) at the ear is extremely low. A small number of works have been published focusing on this issue. Some only produced ensemble average single cardiac cycles, averaged using timestamps from separate sensors. The most successful denoising works in the field so far have used autoencoders trained with noisy ear-ECG as input and simultaneously recorded clean Lead I ECG as output. These have yielded acceptable performance in terms of SNR improvement. However, they have been shown to output time series signals with very large variations in heart rate from the ground truth, in some cases fail to recover morphologies, and at their base rely on non-explainable signal generation from a black box autoencoder.

Methods

To improve on these issues, we propose a multi-modal denoising system. Concurrently with ECG data, we recorded heart sounds from inside the ear canal which correspond to the R-peak in the ECG cycle. Initially these heart sounds were used to give timestamps demarcating individual cardiac cycles. The corresponding ECG cycles were then averaged together to form a single ensemble average cycle with reduced noise. This single cycle was used to fit the parameters of an ECG dynamical model to an individual user, which was then fed into the state prediction stage of an Extended Kalman Filter (EKF) alongside the noisy ear-ECG signal. The EKF also took heart sounds as inputs, giving it low-noise periodic measurements of the ECG phase, to produce a cleaned, accurate time series ear-ECG signal, from a fully explainable filtering process.

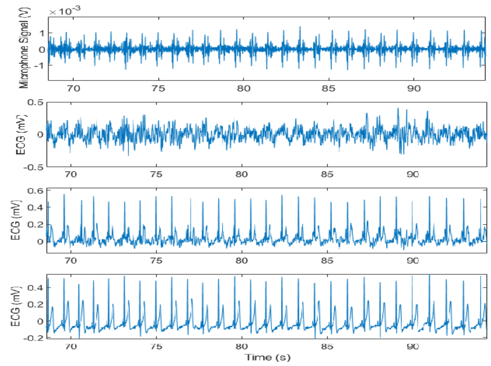

Figure 1: Example recorded signals for (top to bottom): in-ear heart sound audio, unprocessed ear-ECG, denoised ear-ECG, ground truth ECG

Results

Fig. 1 shows example signals for one participant. It is evident that the system has extracted the ECG signal and successfully suppressed the noise. The mean input SNR to the filter from recordings was -14.9 dB, and the mean output SNR was 6.4 dB. This gave a mean improvement of 21.3 dB, significantly higher than any other ear-ECG denoising works. The mean absolute HR error was 3 BPM, and the mean absolute QT interval error was 54 ms. A deeper methodological explanation and set of results can be seen in the published version [1].

References

[1] Adam Pullin et al., "Ear-ecg denoising using heart sounds and the extended kalman filter," in *2025 IEEE International Conference on Body Sensor Networks (BSN)*, 2025.