Optimization of ECG Signal Delineation Algorithms with Discrete Wavelet Transform

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Electrocardiogram (ECG) analysis is essential for diagnosing heart conditions, a major cause of death worldwide. Accurate identification of each heartbeat's start and end via ECG's PQRST points is crucial for assessing cardiac health[1]. These points, including the P-wave's onset and the T-wave's offset, reveal vital details about heart function, such as depolarization and repolarization of the atria and ventricles. Precise measurement of these segments and intervals is key for detecting heart abnormalities.

Open-source tools such as Neurokit [2] assist in refining automated ECG analysis methods. Previous advancements in ECG signal processing have focused on R-peak detection and denoising using enhanced wavelet transform techniques [3]. However, improving the accuracy of automatically segmenting ECGs, especially in long recordings, is crucial. Neurokit employs several techniques based on continuous and discrete wavelet transforms [4], but the need for predefined thresholds and parameters affects the identification of P-waves, QRS-complexes, and T-waves.

The discrete wavelet transform (DWT) algorithm's parameters, including wavelet function, decomposition level, and thresholding method for noise reduction, can be tuned for optimal results. Signal preprocessing parameters, such as filter types and cutoff frequencies, may also influence the performance of DWT-based algorithms.

This work aims to enhance the accuracy of ECG segmentation algorithms. The QT Database, comprising over 100 15-minute two-lead ECG recordings from various sources, is utilized for evaluation. These recordings include annotations for P, QRS, T, and U wave onset, peak, and end markers. Each recording contains 30-50 selected beats, providing a comprehensive dataset for algorithm validation. Figure 1 illustrates the annotation, with P onsets and T offsets delineating the boundaries of each beat.

A typical DWT-based algorithm involves four steps: (i) Manual detection of Q and S peaks within each segment of the cardiac cycle, using the locations of the R peaks as a reference; (ii) Resampling of the signal at the desired analysis sampling rate for multiscale DWT computation This decomposition separates the signal into various frequency components, enabling in-depth analysis; (iii) Resampling of R, Q, and T peaks to match the analysis sampling rate, ensuring alignment with the DWT-transformed signal for accurate delineation; (iv) Delineation of PT peaks, QRS boundaries and P- and T-wave onsets/ends using the DWT-transformed signal and resampled peak locations. Each step involves several input parameters related to the wavelet transform, typical expected values, and filter cutoff, which are optimized to improve the accuracy of segmenting PQ and QT intervals.

The discrete wavelet transform (DWT) it decomposes a signal into approximation and detail components at different scales and positions. From a mathematical perspective, the DWT for a signal $x[n]$ is defined as:

$$W_{j,k} = \sum_{n} x[n] \cdot \psi_{j,k}[n] \tag{1}$$

where $W_{j,k}$ represents the wavelet coefficient at scale j and position k, and $\psi_{j,k}[n]$ is the wavelet function.

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In the DWT process, the signal is filtered using two types of filters: the H and G filters. The H filter is used to obtain the approximation (low-frequency) component, while the G filter is used to extract the detail (high-frequency) component. The filters are defined as follows:

$$H(z) = \sum_n h[n]z^{-n}, \quad G(z) = \sum_n g[n]z^{-n}, \tag{2}$$

where, z is a complex variable that represents the frequency domain, $h[n]$ and $g[n]$ are the impulse responses of the H and G filters, respectively.

We optimize the algorithm parameters using Mean Squared Error (MSE) to minimize the difference between predictions and actual ECG annotations. MSE measures the disparity between estimations and ground truth annotations like PQ and QT segments. A Bayesian optimization framework, Optuna, systematically explores the parameter space to find the optimal parameter combination minimizing the MSE.

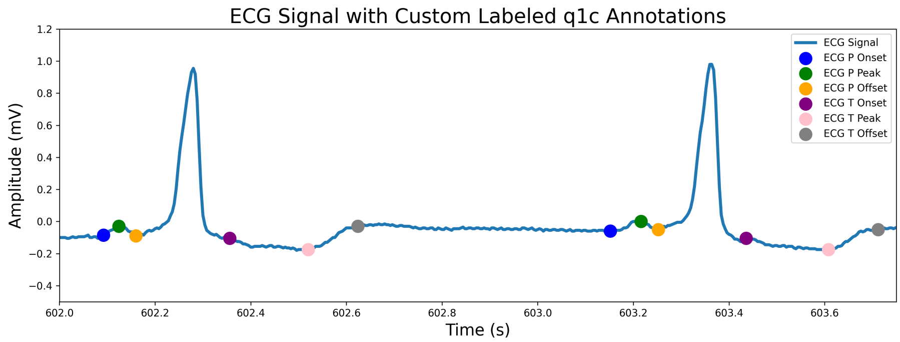

Figure 1: Selected ECG signal indicating two heartbeats along with their annotations from a recording in the QT database.

Typical numerical values for the PQ and QT segments in healthy individuals fall within the ranges of 120-200 ms and 350-440 ms, respectively. The root mean square error (RMSE) between measured and expected values for these segments typically ranges from 5 to 15 ms. In conclusion, ECG signal delineation stands as a fundamental aspect in enhancing the precision of cardiac disease diagnosis.

References

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