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A novel compression framework using energy-sensitive QRS complex detection method for a mobile ECG

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Dear editor,
Novel wearable applications provide improved data compression for reduced power consumption [1, 2]; however, real-time monitoring of a single source electrocardiogram (ECG) signal leads to extended data usage of 2.77 GB per day. The Q wave, R wave, and S wave (QRS) complex seen on an ECG is the basis for the automatic determination of heart rate and an entry point for the classification schemes of the cardiac cycle [3]. Therefore, it is necessary that the compressed data should retain maximum QRS area information, which is the origin of the concept of areas of interests in compressed sensing [4]. Currently, most researches concentrate on developing methods for efficient extraction of QRS waves without redundant calculations from the complex and noisy ECG signals and compression frameworks. This study aims to propose a novel framework that includes an energy-sensitive QRS complex detection algorithm based on simplified empirical mode decomposition and Hilbert transform (EMD-HT) method and a multi-compression ratio CS strategy. The proposed framework encompasses three advantages: (a) In comparison with a previous study [4], the proposed method uses percentage root-mean-square difference (PRD) and improved reduction quality under the same compression ratio (CR); (b) it can accurately locate the interested area of the QRS cluster, which solves the interference problem of stationary noise and; (c) it is indicated that EMD-based compression results in a better CR and PRD than the other methods [2]. Considering the specific conditions for the wearable devices, we employ a simplified EMD algorithm whose operation for detecting interested area for ECG reconstruction is characterized by sufficient accuracy. Using the EMD-HT method, the proposed framework can overcome the limitations associated with stationary noise interference and thus, can achieve precise positioning.

Energy-sensitive QRS complex detection. The QRS detection algorithm is initiated by a discrete Haar wavelet transformation (HWT). Herein, a 2^2-th Haar wavelet transform was applied on 3600 point frames of the input signal at a sampling rate of 36 Hz. The output wavelet coefficient series was isolated from the baseline draft and high-frequency noise. Haar wavelet at the 2^2-th scale was chosen due to advantageous simple calculations that correspond to the equivalent frequency-response coefficients $(-0.5, -0.5, 0.5, 0.5)$ [5, 6]. Subsequently, the simplified EMD method was employed. Although common EMD computation is costly for

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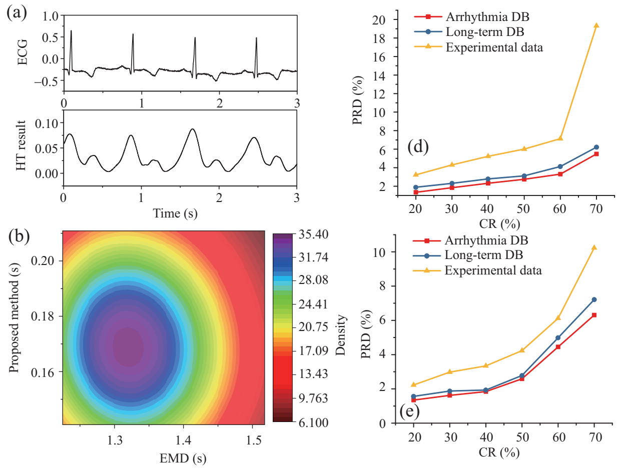

Experiment settings	PRDs (%) of overall (top) & AIs (bottom)	
	Proposed method	IESBM [5]
BSBL+DWT	3.1	3.16
	1.84	2.1
BSBL+DCT	2.72	2.74
	1.72	1.76
OMP+DWT	4.98	5.1
	3.47	3.79
BSBL+DCT	3.85	3.98
	2.76	2.98

(f)

Algorithm	Arrhythmia DB		Long-term DB		Experimental	
	DR	PR	DR	PR	DR	PR
Different threshold	98.2	99.2	95.1	98.3	89.6	92.3
Wavelet threshold	99.2	100	96.3	100	93.7	95.2
Proposed method	99.6	100	98.3	99.2	96.6	98.4
EMD [7]	99.6	100	99.3	100	98.2	99.2

(c)

Figure 1 (Color online) (a) Envelope demodulation result by HT and typical ECG signal; (b) comparison of operational time between a classic EMD and a simplified EMD; (c) the test results; effect of CR adjustment on (d) signal reconstruction accuracy (ECG signal) and (e) signal reconstruction accuracy (QRS cluster); (f) comparison of the proposed framework and IESBM in PRD.

regular applications, the cost can be largely reduced through two types of modification. First, linear interpolation may be substituted for cubic spline interpolation when calculating the upper and lower envelopes in a conventional EMD. Second, the decomposition process is terminated after generation of the necessary intrinsic mode functions (IMFs). The first several IMFs give the highest correlation with the original input empirically; decomposition can be stopped once the correlation coefficient between the original input and the present IMF becomes smaller than the former one. Considering that the output of HWT carries too much noise that can easily corrupt the relevant order, we chose the current IMF on the inflection point. The next step in the algorithm is the application of HT on the chosen IMF. An additive stationary noise often causes disturbances in the outputs of common denoizing methods and hence, needs to be carefully dealt with, especially with its frequency band covering the input ECG. Using Fourier transform, a stationary function can be decomposed as a set of sine waves as

$$\hat{H}(S(t)) = \sqrt{(\hat{S}(t))^2 + (S(t))^2}.$$

Nevertheless, the narrow-band property of IMF makes the above calculation viewed as an envelope demodulation on an envelope modulation input. In comparison with similar methods, the IMF produced by EMD is more accurate in energy distribution and has a narrower frequency band. Figure 1(a) explains that information in QRS complexes can be well preserved after HT even in the presence of noise interference as an effect of their higher frequency and energy. Application of HT in the algorithm serves two purposes, namely: (a) As part of Hilbert-Huang transform, the output signal reflects the distribution of high-energy components and (b) if the input noise is stationary, then its corresponding decomposed output generally represents a close-to-zero sequence (with energy weaker than that of ECG). In this regard, the HT output is no longer affected by the common periodic noises problem in traditional algorithms. Figure 1(a) confirms that output $\hat{H}(S(t))$ is free from stationary noise components and that the energy distribution is consistent with the input signal after phase correction.

Multi-compression ratio CS strategy. The following steps describe the compression of the interested area under low compression ratio to preserve higher amount of details. Initially, the ECG signal was compressed using a sparse binary matrix of compression ratio CR_1. Next, a QRS cluster was obtained using the QRS cluster detection algorithm, after which it experienced secondary compression at the ratio CR_2. The QRS cluster accounted for approximately 12.5% of the ECG signal's overall length. Moreover, the overall equivalent compression ratio was approximated as

$$\mathrm{CR} = \frac{N_{\mathrm{real}} - N_{\mathrm{measure}}}{N_{\mathrm{real}}}$$

$$= \frac{N - N\times(\mathrm{CR}_1\times(1-0.125)+\mathrm{CR}_2\times 0.125)}{N}.$$

The ECG signal and QRS cluster parts were reconstructed separately; the reconstructed QRS cluster was spliced into the ECG signal to obtain a final reconstructed signal.

Methods validation and experimental results. As described earlier, the proposed framework comprises detection of interested area and a multi-compression strategy. The algorithm for detection of interested area was tested in terms of accuracy and computational cost. Conventionally, in methods based on different threshold and wavelet threshold algorithms, the positivity rate (PR) decreases although the detection rate (DR) can be improved with the application of a smaller threshold. Moreover, these methods are inefficient for distinguishing disturbances caused by rhythmic noises. Figure 1(c) shows the four algorithms tested by identical inputs from (a) MIH-BIH arrhythmia ECG database, (b) MIH-BIH long-term ECG database, and (c) experimental data from our own ECG collection module. The results showed that the proposed method significantly improved DR and PR in comparison with popular algorithms. with a slightly worse performance than EMD due to some approximations. Figure 1(b) displays the simulation results comparing the computational costs between two EMD types (standard and the proposed simplified EMD) using kernel density analysis. While both methods showed enough accuracy for ECG reconstruction, the time and cost of the sim-EMD was 7.9 times less than those of the standard EMD. Therefore, the interested area detection method was useful for diagnostic wave detection and was suitable as well for long-term applications. Moreover, its performance was demonstrated in wearable devices with which the subjects were instructed to perform regular work. Furthermore, the multi-compression strategy was validated using the No. 100, 1024-points-length ECG signal in the MIT-BIH arrhythmia database. We used PRD to quantify the recovered quality

$$\mathrm{PRD} = 100 \times \sqrt{\frac{\sum\left(x(n)-x'(n)\right)^2}{\sum x(n)^2}},$$

where x' indicates recovery from using block sparse Bayesian learning algorithm in the wavelet domain and x is the origin ECG. Figure 1(d) displays the results showcasing the barely changing PRD of the ECG as CR decreases to 60%, which is denoted by CR_1. Figure 1(e) describes this inflection point to appear at approximately 40%–50%, and is denoted by CR_2. Apparently, the QRS complexes needed lower CR to gain better results in refactoring. Setting $\mathrm{CR}_1 = 60\%$ and $\mathrm{CR}_2 = 50\%$, we applied the proposed method on a few records from the MIT-BIH ECG arrhythmia database. The total duration of the tested signal was 30 min; QRS length was approximately 12.5% of the whole ECG signal; and the final equivalent CR of the proposed method was 51.25%, while those of the other algorithms were close to 50% (Figure 1(f)). Therefore, the proposed method achieved higher signal recovery quality in both interested area and full signal lengths.

Conclusion. Herein, we proposed a novel, validated, and effective compression framework for mobile ECG devices, which was able to avoid stationary noise interference and had higher compression quality than the conventional structures, due to implementation of a multi-compression strategy. The standard EMD was simplified for hardware use. All points in the above discussion were validated to be effective for long-term and real-time noisy CS-based ECG applications.

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