Evaluation of an Efficient Method for Handling Ectopic Beats in HRV

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Abstract: The problem of analyzing heart rate variability in the presence of ectopic beats is revisited. Based on the IPFM model and the closely related heart timing signal, a new computationally very efficient technique is introduced which corrects for the occasional ectopic beats. From actual heart rate data, the results show that the new technique is associated with a much lower computational complexity (almost 3000 times faster) than the original heart timing approach, while producing similar performance. This also implies that the power spectrum and related clinical indices obtained by the new technique are more accurately estimated than by other methods.

1. Introduction

The presence of ectopic beats perturbs the impulse pattern initiated by the sinoatrial node, and implies that RR intervals adjacent to an ectopic beat cannot be used for heart rate variability (HRV) analysis. Since ectopic beats may occur in both normal subjects and patients with heart disease, their presence represents an important error source which must be dealt with before spectral analysis can be performed. If not dealt with, the analysis of an RR interval series containing ectopic beats results in a power spectrum with spurious frequency components.

The heart timing (HT) signal was recently suggested for characterization of heart rate variability [1]. This signal is based on the well-known integral pulse frequency modulation (IPFM) model for the generation of normal sinus beats [2], characterizing HRV in terms of a modulation function $m(t)$. The definition of the HT signal has later been extended to also account for the presence of occasional ectopic beats [3]. In terms of spectral distortion, the results showed that the HT-based correction produced one order of magnitude lower error than did interpolation-based correction techniques. While producing excellent results, the HT-based correction is associated with heavy computations which, for example, in the analysis of Holter recordings, may become prohibitive. The present paper introduces a correction method which drastically reduces the computational demands of the method presented in [3], while introducing no significant deterioration in performance.

2. Methods

The heart timing signal $d_{HT}(t)$ is at each heartbeat occurrence time t_k defined as, $d_{HT}(t_k) = kT_0 - t_k$, where T_0 denotes the mean RR-interval length [1]. The HT signal is closely related to the IPFM model and its modulating signal $m(t)$. Using the HT signal, the modulating signal $m(t)$ can be estimated in order to produce the HRV power spectrum. If the Fourier transform of $m(t)$ and $d_{HT}(t)$ are denoted with $D_m(\Omega)$ and $D_{HT}(\Omega)$, respectively, it can be shown that [1]

$$D_m(\Omega) = j\Omega D_{HT}(\Omega), \tag{1}$$

where $\Omega = 2\pi F$. Hence, the desired spectral estimate $D_m(\Omega)$ can easily be computed once the Fourier transform of the heart timing signal, $D_{HT}(\Omega)$, is known.

In the description below, we assume that sinus beats occur at the times $t_0, t_1, \ldots, t_K$, and that one ectopic beat occurs at time t_e. The time t_e is not included in the series $t_0, t_1, \ldots, t_K$, and the sinus beat immediately preceding the ectopic beat occurs at t_{k_e} and the sinus beat immediately following at t_{k_e+1}.

Heart Timing Representation: In order to compensate for the presence of an ectopic beat, the above definition of $d_{HT}(t_k)$ is modified by the introduction of a parameter s according to [3].

$$d_{HT}(t_k) = \begin{cases} kT_0 - t_k & k = 0, \ldots, k_e, \\ (k+s)T_0 - t_k & k = k_e + 1, \ldots, K. \end{cases} \tag{2}$$

The parameter s can be viewed as a jump in the resetting of the integral in the IPFM model, and may be obtained by LS estimation described in [3]. An estimate of T_0 is obtained by $t_K/(K + \hat{s})$.

Computationally Efficient Representation: A different approach to deal with ectopic beats is to observe that an ectopic beat shifts the occurrence times of the following normal heart beats. By estimating the time shift δ, the presence of an ectopic beat can be accounted for by

$$d_{HT_\delta}(t_k) = \begin{cases} kT_0 - t_k & k = 0, \ldots, k_e, \\ kT_0 - t_k + \delta & k = k_e + 1, \ldots, K, \end{cases} \tag{3}$$

and δ estimated according to [4]

$$\hat{\delta} = t_{k_e+1} - 2t_{k_e} + t_{k_e-1}. \tag{4}$$

An estimate of T_0 is obtained by $(t_K - \hat{\delta})/K$.

3. Database

The database consists of 132 ECG episodes selected from the European ST-T database, previously studied in [3]. The ectopic beat composition of the 132 episodes is as follows: 91 episodes contain one ectopic beat, 28 contain two, 5 contain three, 4 contain four, 2 contain eight, and 2 contain ten ectopic beats. Each ECG episode is divided into three overlapping, four-minute segments: A, B, and C. Segments A and C are ectopic-free, whereas segment B contains the ectopic beat(s). Segment A contains the four minutes preceding the ectopic beat(s), segment B is centered around the ectopic beat(s), and segment C contains the four minutes following the ectopic beat(s).

The database is studied using the evaluation approach introduced in [3], where it was suggested that the spectral characteristics of the ectopic-free segments A and C can be compared to the corrected segment B assuming that the heart rate is stationary once ectopy has been removed. Three parameters, ΔAC, ΔAB, and ΔBC, are defined, where ΔAC denotes the difference in spectral power between segments A and C, and so on. Moreover, the power is divided into two subbands: a low frequency (LF) band (0.04–0.15 Hz) and a high frequency (HF) band (0.15–0.40 Hz). Assuming stationarity during the segments A, B, and C, ΔAC is expected to be close to zero in both frequency bands, and following correction of segment B, ΔAB and ΔBC should be close to that of ΔAC.

4. Results

The performance of the δ estimator in (4), based on $d_{HT_\delta}(t_k)$, is compared to that of the minimum LS estimator of s based on $d_{HT}(t_k)$, in terms of HRV power spectral differences. The HRV power spectra of the ectopic-free segments A and C is computed using the definition of the HT signal, whereas the power spectrum of segment B requires that either the δ estimator or the s estimator is used.

Table 1 presents the results when all 132 ECG episodes are analyzed. The performance of the two different estimators is almost identical for both the LF and HF bands of ΔAB and ΔBC, and is comparable to the variation of ΔAC.

In order to compare complexity of the two estimators, the number of floating point operations (flops) was studied, see Table 2. The results show that the s estimator requires almost 3000 times more flops than the δ estimator. It is also noted that the number of flops used by the δ estimator is deterministic since, in contrast to the s estimator, it is independent of where the ectopic beat occurs.

5. Conclusions

The present paper sheds new light on the problem of ectopic beat correction in HRV analysis with the contribution of a new HT-based method. The performance was compared to the original method, which is based on the heart timing signal [3], and was found to be the same when performance is measured in power spectral terms. However, the new method requires dramatically less computations and is therefore much better suited for implementation in systems for long-term ECG analysis.

Table 1. HRV power spectral differences related to the s and δ estimators. Values are given in mean ± std in the unit ms^{-2}.

	ΔAC	
Estimator	*LF*	*HF*
s / δ	49 ± 808	−22 ± 190

	ΔAB	
Estimator	*LF*	*HF*
s	−32 ± 644	−26 ± 153
δ	−32 ± 651	−30 ± 136

	ΔBC	
Estimator	*LF*	*HF*
s	80 ± 498	4 ± 158
δ	81 ± 501	8 ± 145

Table 2. Flop statistics for the s and δ estimators, when using the HT signal for the 132 ECG episodes.

Estimator	*Mean*	*Std*
s	22514	26359
δ	8	7

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