

HANDLING OF ECTOPIC BEATS IN HEART RATE VARIABILITY ANALYSIS USING THE HEART TIMING SIGNAL

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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 technique is introduced which corrects for the occasional presence of such beats. The correction technique, which involves the occurrence times of a certain number of beats preceding the ectopic, is computationally very efficient. Based on actual heart rate data, the results suggest that the power spectrum, and related clinical indices, are more accurately estimated.

Introduction

The presence of ectopic beats perturbs the impulse pattern initiated by the sinus node and implies that the RR intervals adjacent to an ectopic beat cannot be used for heart rate variability (HRV) analysis. In such cases, the autonomic modulation of the sinoatrial (SA) node is temporarily lost, and an ectopic focus instead initiates the next beat prematurely. The location of the ectopic focus gives rise to different types of RR interval perturbation: a beat of ventricular origin inhibits the next sinus beat and therefore introduces a compensatory pause after the ectopic beat, whereas a beat of supraventricular origin discharges the SA node ahead of schedule causing the following sinus beat to also occur ahead of schedule. Other perturbations of physiological origin are those related to an interpolated ectopic beat, manifested by two short RR intervals adjacent to the ectopic beat, or to an escape beat, manifested by a prolonged RR interval.

Since ectopic beats may occur both in patients with heart disease and in normal subjects, their presence represents an important error source which must be dealt with prior to spectral analysis of heart rate variability. Straightforward spectral analysis of an HRV series with ectopic beats will produce a power spectrum that exhibits a fictitious “white noise” level.

A number of techniques have been developed for dealing with the presence of ectopic beats, all conforming to the restriction that only ECG segments with occasional ectopic beats should be processed [1, 2]. The presence of ectopic beats is dealt with by either modifying

an already existing processing block, or inserting an additional processing block in the analysis of HRV. The so-called heart timing representation is a recent development of the former approach which is particularly suitable for the analysis of HRV [3]. This type of signal representation is based on the well-known integral pulse frequency modulation (IPFM) model which is used for the generation of normal sinus beats. In a subsequent paper, the heart timing representation was modified to also handle the presence of ectopic beats [4]. In this paper, a new view of the heart timing signal is presented which allows ectopic beats to be handled by a computationally very efficient method.

IPFM model

The IPFM model is used for generating a series of occurrence times for normal sinus beats with known variability, and reflects basic electrophysiological properties of the atria [5]. The input signal to the IPFM model consists of the sum of a DC level related to the average heart rate and a modulating signal, $m(t)$, related to the variability due to parasympathetic and sympathetic activity. The input signal to the IPFM model is integrated until a threshold, \bar{T}_0 (representing the mean interval length between successive events), is reached. Then, an event is created at time t_k as output of the model, and the integrator is reset to zero. As a result, the output signal of the IPFM model becomes an event series, which represents the heart cycle occurrences in time. In mathematical terms, the following equation defines the series of event times,

$$\int_0^{t_k} (1 + m(\tau)) d\tau = k\bar{T}_0 \quad k = 0, \dots, N \quad (1)$$

where k is an integer that indexes the k^{th} beat following the initial beat, and the initial beat occurring at $t_0 = 0$. The function in (1) can be generalized to a continuous-time function by introducing the following definition

$$\int_0^t (1 + m(\tau)) d\tau = \kappa(t)\bar{T}_0 \quad (2)$$

The integral can now be calculated up to any time t and is proportional to an index function $\kappa(t)$ whose value at t_k

is identical to the integer beat index k , that is, $\kappa(t_k) = k$.

Heart timing representation

The heart timing signal $d_{HT}(t)$ is defined at the event time t_k as the difference between the event time t_k and the expected occurrence time at the mean heart rate, $k\bar{T}_0$, [3]. The heart timing signal is closely related to the IPFM model and its modulating signal $m(t)$. With the help of the heart timing signal, the modulating signal $m(t)$ and especially its Fourier transform can be determined in order to produce an estimate of the HRV power spectrum.

In order to see how $d_{HT}(t)$ and the modulating signal $m(t)$ are related, the model equation in (1), for a particular time t_k , is rewritten according to

$$\int_0^{t_k} m(\tau) d\tau = k\bar{T}_0 - t_k \equiv d_{HT}(t_k) \quad (3)$$

The mean RR interval length \bar{T}_0 must be estimated from the available data in order to compute $d_{HT}(t_k)$. This can be done by simply dividing the time of the last event with the number of events, that is, $\bar{T}_0 = t_K/K$.

Using the generalized IPFM model in (2), the heart timing signal can be expressed in continuous-time as,

$$d_{HT}(t) = \int_{-\infty}^t m(\tau) d\tau \quad (4)$$

Since $m(t)$ is assumed to be a causal function the integration interval can be extended to $-\infty$. If the Fourier transforms of $m(t)$ and $d_{HT}(t)$ are denoted with $D_m(\Omega)$ and $D_{HT}(\Omega)$ respectively, we have from (4) that

$$\begin{aligned} D_{HT}(\Omega) &= \int_{-\infty}^{\infty} d_{HT}(t) e^{-j\Omega t} dt \\ &= \frac{D_m(\Omega)}{j\Omega} \end{aligned} \quad (5)$$

where $\Omega = 2\pi F$ and $D_m(0) = 0$, since $m(t)$ was assumed to have a DC component equal to zero. Once the Fourier transform of the heart timing signal, $D_{HT}(\Omega)$, is known the desired spectral estimate $D_m(\Omega)$ can be computed. The spectral estimate is either obtained by a technique for unevenly sampled signals, or by interpolation and resampling followed by use of the DFT.

Dealing with Ectopic Beats

Ectopic beats introduce errors in the analysis of HRV. The errors are due to an impulse-like artifact in the RR intervals introduced by the RR intervals adjacent to an ectopic beat.

In this section, we briefly summarize a recently presented technique which compensates for the presence of ectopic beats when using $d_{HT}(t)$. This description is followed by a new view of such compensations for $d_{HT}(t)$. In the description of the techniques below, we assume that sinus beats occur at the times t_0, t_1, \dots, t_K ,

and that one ectopic beat occurs at time t_e in the signal. The time t_e is not included in the series t_0, t_1, \dots, t_K , and the sinus beat immediately preceding the ectopic beat occurs at t_{k_e} and the sinus beat immediately following occurs at t_{k_e+1} .

Heart Timing representation: In order to compensate for the presence of an ectopic beat the formulation of $d_{HT}(t_k)$ has to be modified. The modification is made in the time sequence following the ectopic beat (i.e. $t > t_e$), where the parameter s has to be inserted according to [4].

$$d_{HT}(t_k) = \begin{cases} k\bar{T}_0 - t_k & k = 0, \dots, k_e, \\ (k+s)\bar{T}_0 - t_k & k = k_e + 1, \dots, K. \end{cases} \quad (6)$$

The MSE estimate of s is given by

$$\hat{s} = \frac{1}{\hat{t}_{k_e+1}^f - \hat{t}_{k_e}^b} \int_{\hat{t}_{k_e}^b}^{\hat{t}_{k_e+1}^f} (\hat{\kappa}^f(t) - \hat{\kappa}^b(t)) dt \quad (7)$$

The new time $\hat{t}_{k_e+1}^f$ is the forward extension of the occurrence times t_0, \dots, t_{k_e} under the assumption that the sinus rhythm continues, and the new time $\hat{t}_{k_e}^b$ is the backward extension of the occurrence times t_{k_e+1}, \dots, t_K under the assumption that the sinus rhythm preceded t_{k_e+1} . These extensions assumes that $\hat{t}_{k_e+1}^f > \hat{t}_{k_e}^b$: if not the extensions are further continued until so. The two indexing functions $\hat{\kappa}^f(t)$ and $\hat{\kappa}^b(t)$ are the forward extension of $\kappa(t)$ until $\hat{t}_{k_e+1}^f$ and the backward extended $\kappa(t) - s$ until $\hat{t}_{k_e}^b$. Once \hat{s} is known, it is possible to update the estimate of the mean RR interval length \bar{T}_0 according to $\hat{\bar{T}}_0 = \frac{t_K}{K + \hat{s}}$.

A New View of the Heart Timing Signal: A different approach to dealing with ectopic beats is introduced by first concluding that an ectopic beat modifies the occurrence times of the following normal heart beats. By estimating this time shift, δ (connected to the s parameter according to $\delta = s\bar{T}_0$), the presence of ectopic beats can be accounted for by the following equation

$$d_{HT}(t_k) = \begin{cases} k\bar{T}_0 - t_k & k = 0, \dots, k_e, \\ k\bar{T}_0 - t_k + \delta & k = k_e + 1, \dots, K. \end{cases} \quad (8)$$

In order to estimate δ we make use of (1) such that

$$k_e\bar{T}_0 = \int_0^{t_{k_e}} (1 + m(\tau)) d\tau \quad (9)$$

and

$$(k_e + 1)\bar{T}_0 = \int_0^{t_{k_e+1} - \delta} (1 + m(\tau)) d\tau \quad (10)$$

Subtracting (9) from (10) we get the following equation:

$$\begin{aligned} \bar{T}_0 &= \int_{t_{k_e}}^{t_{k_e+1} - \delta} (1 + m(\tau)) d\tau \\ &= t_{k_e+1} - t_{k_e} - \delta + \int_{t_{k_e}}^{t_{k_e+1} - \delta} m(\tau) d\tau \end{aligned} \quad (11)$$

We now introduce a new parameter, \overline{m}_k , according to

$$\overline{m}_k = \begin{cases} \int_{t_k}^{t_{k+1}} m(\tau) d\tau & k \neq k_e, \\ \int_{t_{k_e}}^{t_{k_e+1}-\delta} m(\tau) d\tau & k = k_e. \end{cases} \quad (12)$$

where \overline{m}_k ($k \neq k_e$) is the integral of $m(t)$ between the two normal heart beats at t_k and t_{k+1} . This gives us

$$\delta = t_{k_e+1} - t_{k_e} - \overline{T}_0 + \overline{m}_{k_e} \quad (13)$$

For the special case of a constant heart rate (linear assumption on $\kappa(t)$ or, in other words, $m(t) = 0$ and $\overline{m}_{k_e} = 0$) we get an estimate of δ according to

$$\hat{\delta}_0 = t_{k_e+1} - t_{k_e} - \overline{T}_0 \quad (14)$$

which is referred to as the zero order estimate of δ .

We assume that the variations of $m(t)$ are typically small within the integral interval and thus the beat-to-beat variations in \overline{m}_k are also small. Thus a better estimate of \overline{m}_{k_e} would be the value corresponding to the previous beat according to

$$\begin{aligned} \hat{\overline{m}}_{k_e,1} &= \overline{m}_{k_e-1} \\ &= \int_{t_{k_e-1}}^{t_{k_e}} m(\tau) d\tau \\ &= d_{HT}(t_{k_e}) - d_{HT}(t_{k_e-1}) \\ &= t_{k_e-1} - t_{k_e} + \overline{T}_0 \end{aligned} \quad (15)$$

This estimate in combination with (13) gives us a first order estimate of δ according to

$$\hat{\delta}_1 = t_{k_e+1} - 2t_{k_e} + t_{k_e-1} \quad (16)$$

Note the similarity between (14) and (16), since (16) can be written as:

$$\hat{\delta}_1 = t_{k_e+1} - t_{k_e} - (t_{k_e} - t_{k_e-1}) = \hat{\delta}_0 - \hat{d}_{k_e-1,0} \quad (17)$$

where $\hat{d}_{k_e-1,0}$ is the zero order estimate of d_{k_e-1} , with d_k defined as:

$$d_k = t_{k+1} - t_k - \overline{T}_0 + \overline{m}_k = 0 \quad k \neq k_e \quad (18)$$

Note the close relationship between (13) and (18), since (18) becomes (13) when $k = k_e$.

Generalization: A generalization of a higher order estimate of \overline{m}_{k_e} would be to include variations in \overline{m}_k . If we continue to update the estimate of \overline{m}_k according to

$$\hat{\overline{m}}_{k,p} = \hat{\overline{m}}_{k,p-1} + \Delta \overline{m}_{k-1,p} \quad (19)$$

where $\Delta \overline{m}_{k-1,p}$ is the p^{th} order difference of \overline{m}_{k-1} according to:

$$\Delta \overline{m}_{k-1,p} = \Delta \overline{m}_{k-1,p-1} - \Delta \overline{m}_{k-2,p-1} \quad (20)$$

Then it can be proven that the N^{th} order estimate of δ is given by the following recursion equation:

$$\hat{\delta}_N = \hat{\delta}_{N-1} - \hat{d}_{k_e-1,N-1} \quad N = 1, 2, \dots \quad (21)$$

where

$$\hat{\delta}_0 = t_{k_e+1} - t_{k_e} - \overline{T}_0 \quad (22)$$

Instead of using the recursion in (21), we can express $\hat{\delta}_N$ directly in terms of the occurrence times:

$$\hat{\delta}_N = \sum_{l=0}^{N+1} (-1)^l \binom{N+1}{l} t_{k_e+1-l} \quad N = 1, 2, \dots \quad (23)$$

and $N = 0$ is given by (22), but can not be used since it makes use of \overline{T}_0 which is yet unknown. Once an estimate of δ according to (23) is obtained, it is straightforward to update the estimate of \overline{T}_0 according to $\hat{\overline{T}}_0 = \frac{t_{k_e} - \hat{\delta}_N}{K}$. Now $d_{HT}(t_k)$ in (8) can be calculated since all the involved parameters are available.

Results

In order to evaluate the performance of the estimate in (23) used in the method based on (8), the method was tested on actual heart rate data. A comparison was made with $d_{HT}(t_k)$ computed from (3), ignoring the presence of the ectopic beat and also with $d_{HT}(t_k)$ computed from (6) with the estimate in (7). The ECG data used was the European ST-T database segments already selected in [4] which consists of 132 ECG episodes. In this paper the results are illustrated on two of these episodes. Both these episodes consists of an 8 min ECG segment with one ectopic beat centered in the segment. The 8 min segment is divided into three overlapping segments of 4 minutes length starting at 0, 2 and 4 minutes, respectively. Segment A is the ectopic free ECG segment preceding the ectopic beat, segment B is the segment containing the ectopic beat and segment C is the ectopic free ECG segment following the ectopic beat.

The spectral estimate of the HRV in segments A, B and C are all obtained by first deriving $d_{HT}(t_k)$ and then applying (5). In segments A and C, $d_{HT}(t_k)$ is obtained by (3), since these segments are ectopic free. In order to compare the methods, four different versions of $d_{HT}(t_k)$ are calculated in segment B: one according to (3) when no compensation for the ectopic beat is made, one according to (6) and two versions according to (8), with $\hat{\delta}_1$ and $\hat{\delta}_2$.

In Fig. 1 two spectral estimates of the HRV in the first episode are shown for the different segments A, B and C. In Fig. 1(a), (3) is used on segment B, i.e. no compensation for the ectopic beat is made, and in Fig. 1(b), (8) is used on segment B with $\hat{\delta}_1$. The spectra are given in normalized units, i.e. normalized by the total energy in the LF and HF band. From Fig. 1 it is clear that, if no compensation is made for the ectopic beat, the energy in the LF band is, as expected, lower in B compared to A and C, whereas the energy in the HF band is higher in B compared to A and C, which is not the case when compensation is made.

Fig. 2 shows the normalized energy in the HF band from the first episode (from Fig. 1) for the different segments A, B and C. Note that the true value in segment

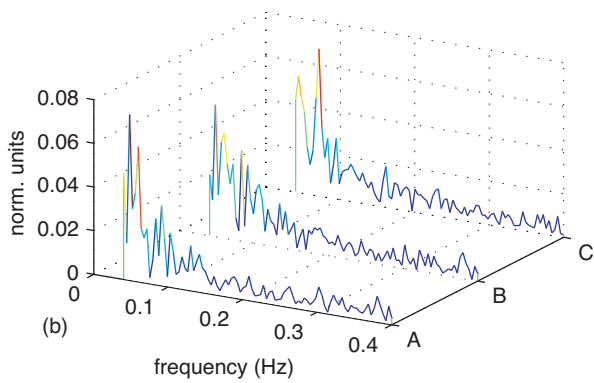
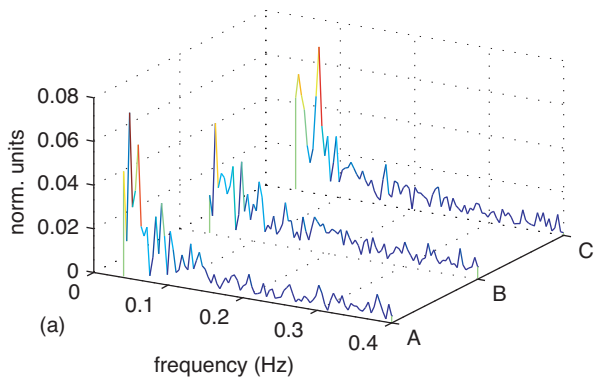


Figure 1. (a): HRV estimates for the different segments A, B and C when no compensation for the ectopic beat is made in segment B. (b): Same as in (a) but compensation is made in segment B.

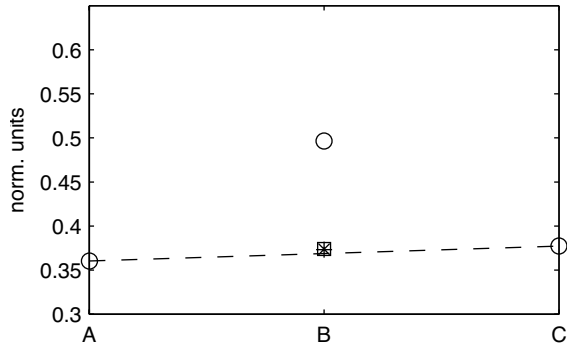


Figure 2. Normalized power in the HF band for the different segments A, B and C. The circles show the results when (3) is used to obtain the HRV spectra, the square when (6) is used, and the \times and $+$ marks when (8) is used with $\hat{\delta}_1$ and $\hat{\delta}_2$, respectively. Note that the \times and $+$ overlap each other.

B is not known due to the ectopic beat but if stationarity is assumed the “most likely” value in segment B would be the mean value between the values in segments A and C. This is illustrated with the dashed line in Fig. 2, hence the closer the value is to the dashed line the more likely it is to be true. Fig. 3 illustrates the performance on data obtained from another patient. From these figures it is

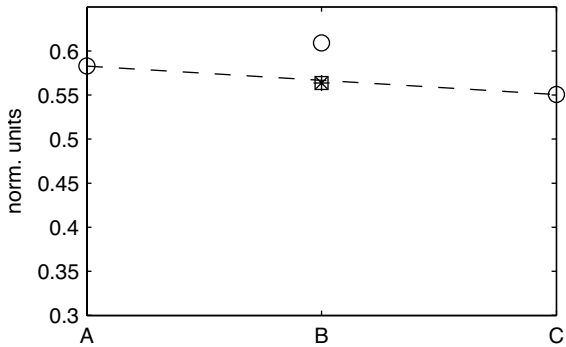


Figure 3. Same as in Fig. 2 but on different ECG episode.

clear that the power spectra are more accurately estimated when either (6) or (8) is used. In fact, the results from using (6) and (8) are almost identical.

Discussion

The performance of the method based on (8) is comparable to that of (6). However, there is a substantial difference in complexity between (6) and (8). In the estimation of the s parameter in (7) it requires two predictions (i.e. two estimates), interpolation, integration and division compared to the estimate of δ in (23) which only is a linear combination of known event times (i.e. no estimates), e.g. $\hat{\delta}_1$ only requires two additions in DSP implementation.

Acknowledgments

We would like to thank *Dr. Javier Mateo* for providing us with the real data making the result section possible. This study was supported by a grant from Gambro AB.

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