Extension of the Heart Timing Signal to the HRV Analysis in the Presence of Ectopic Beats

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Abstract

In this paper, the Integral Pulse Frequency Modulation (IPFM) model has been extended to continuous time to model the premature resetting of the sino-atrial (SA) node when ectopic beats appear. Heart Timing (HT) signal is a precise representation of the Heart Rate Variability (HRV) according to the IPFM model. A method based on the HT signal and the extended IPFM model is presented for reducing the spectral corruption generated by the ectopic beats. A white noise driven autoregressive (AR) model of a clinically normal HRV subject is taken to input the IPFM model and simulate the beat sequences to evaluate the new technique. The more usual methods of HRV Power Spectral Density (PSD) estimation are compared. Results show how the HT signal, with the proposed method for ectopic effect reduction, exhibits the lowest sensitivity to the ectopic beats presence, 20 times lower than the next best method.

1. Introduction

Heart Rate Variability (HRV) analysis is based on the study of the sinoatrial (SA) node activity as the source of repetitive impulses that generate normal sinoatrial heart beats. Sometimes, additional pacemakers may interpose additional electrical impulses that generate ectopic beats, which are usually manifested as a premature beat followed a longer than normal heart period interval (RR). The time-domain signals associated with HRV exhibit a sharp transient at the ectopic beat, making it unusable, particularly in the Power Spectral Density (PSD) estimate of HRV. An isolated ectopic beat can corrupt the PSD estimate because the frequency content of the impulse-like artifact is broad. Therefore, corrections of this kind of beat artifacts must be done prior to any PSD estimation of the HRV. Moreover, when the location of the ectopic focus is supraventricular, its electrical activity is able to reset the SA node activity resulting in two adjacent normal beats with noticeably smaller separation than twice of the ongoing RR intervals. The simplest alternatives of including an intermediate beat or shifting the remaining beats are not valid solutions, since they distort the PSD estimation of the HRV.

A method for the ectopic effect reduction is hereby presented. It is based on the Heart Timing (HT) signal [1, 2] and the continuous time generalization of the Integral Pulse Frequency Modulation (IPFM) model [2].

2. The IPFM model in the presence of ectopic beats

Many authors [3, 4, 5] have assumed that the IPFM model explains the mechanism of the autonomic system in controlling the heart rate. The IPFM model considers a modulating signal, $m(t)$, which generates the beat occurrence times when acting through the model.

The continuous time generalization of the IPFM model can be written as

$$x = \int_0^{t(x)} \frac{1 + m(\tau)}{T}\, d\tau \qquad (1)$$

where $t(x)$ is a continuous function that solves the model equation and whose values at $x = k = 1, 2, \ldots, N$, are the kth beat occurrence times, $t(k)$. $(1 + m(t))/T$ can be seen as the instantaneous heart rate. T is the mean RR interval in the analyzed period and $m(t)/T$ represents the dynamic part of heart rate, which is zero-mean. The dynamic part is usually small compared to the mean heart rate ($m(t) \ll 1$). The first beat is considered to occur at $t_0 = 0$, being $m(t)$ considerd causal.

The HT signal is also defined [2] as the integral of the $m(t)$ signal

$$ht(t) = \int_0^t m(\tau)\, d\tau \qquad (2)$$

and from (1) we obtain

$$ht(t) = x(t) \cdot T - t. \qquad (3)$$

An ectopic electrical impulse may cause the premature resetting of the integration process on the SA node, giving a phase shifted series of normal beats following the ectopic beat. Even the involved physiology is complicated, the effect over the beat sequence can be modelled as follows: We assume that the IPFM integration process may be reset by the electrical activity of the ectopic focus. If the ectopic beat is the k_eth one, it can be interpreted that the beats preceding the ectopic beat are given by $t_k = t(k)$ with k integer and $k < k_e$, and the beats subsequent to the

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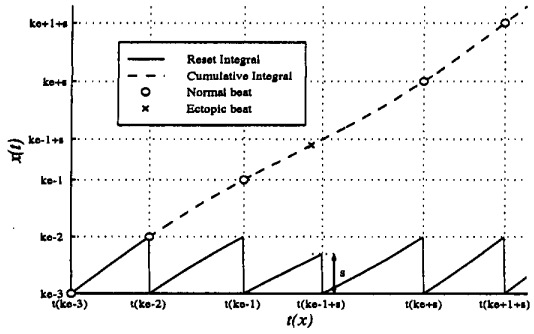

Figure 1. Beat occurrence time generation with ectopic beat presence from the integral of the IPFM model.

ectopic beat are given by $t_{k+1} = t(k+s)$ with k integer and $k \geq k_e$. The premature resetting of the integration occurs at $t(k_e - 1 + s)$ and s is an unknown real quantity corresponding to the value reached for the integral at the resetting time $t(k_e - 1 + s)$.

Figure 1 shows the signals involved in this extension. The dashed curve represents the $x(t)$ function given by (1). The continuous curve is the same function but reset when it reaches the corresponding threshold. The following beats after the ectopic correspond to x values coming from the corresponding integer, k, plus a constant magnitude s. Equation (3) continues being valid in ectopic presence and if the s and T values are known, the correct values of $ht(t)$ at each beat occurrence time can be calculated. Explicitly, in a series of N beats with an ectopic beat detected at the k_e position the correct values of the HT signal for the beats preceding and following the ectopic will be

$$\begin{cases} ht(t(k)) = kT - t(k), & \text{for } k < k_e \\ ht(t(k+s)) = (k+s)T - t(k+s), & \text{for } k \geq k_e \end{cases} \quad (4)$$

where the instants $t(k)$ with $k < k_e$, and $t(k+s)$ with $k \geq k_e$, are the known beat occurrence times before and after the ectopic beat, respectively. If there are several ectopic beats, the jump s for each ectopic beat and the correct T need to be known to calculate the HT values. The section below shows the method for determining these unknown quantities.

3. HT signal computation in the presence of ectopic beats

The objective is to calculate the s value for each ectopic beat and the correct T from the known beat occurrence times before and after the ectopic beat. Using these values, a signal based on differences as the Heart Period (HP) can be built, considering that all values obtained will be correct except for those involving the ectopic beats. The HP signal has a continuous definition as $hp(t(x)) = t(x) - t(x-1)$ [2].

A continuous estimate $\widehat{hp}(t)$ is obtained by means of spline interpolation, and the beat time, $t(k_e)$, of the hypothetical beat that would have occurred if no ectopic beat appeared can be inferred as

$$t(k_e) = t(k_e - 1) + \widehat{hp}(t(k_e)) \quad (5)$$

This recurrent equation can be solved iteratively converging quickly from a starting guess $t(k_e) = (t(k_e - 1) + t(k_e + s))/2$. The hypothetical beat time, $t(k_e - 1 + s)$, prior to the after ectopic sequence can be inferred as

$$t(k_e - 1 + s) = t(k_e + s) - \widehat{hp}(t(k_e + s)). \quad (6)$$

In this case, an iterative process is not needed.

Once the overlapped time between the extended beat sequences is obtained, the continuous function $x(t)$ can be calculated by interpolating the known pairs $(k, t(k))$ for $k = 1, ..., k_e$, and similarly, the continuous function $x(t) - s$ can be calculated by interpolating the pairs $(k, t(k+s))$ for $k = k_e - 1, ..., N$. Figure 2 shows both functions, the original normal beats and the calculated extended beats. The vertical distance between both curves is the wanted s value and it must be calculated for each ectopic beat.

The mean heart period T must still be evaluated. If there had not been ectopic beats, T would be $T = t(N)/N$, where N is the total number of beats. In the presence of ectopic beats, the same calculation can be made, taking into account that the effective number of beats will be $N + \sum_j s_j$ for all jumps s_j at each ectopic beat. Thus, T will be

$$T = \frac{t_N}{N + \sum_j s_j}. \quad (7)$$

Knowing s_j and T values, equation (4) can be used to estimate the HT signal at irregularly spaced beat times. By spline interpolation, the HT signal can be taken at evenly spaced instants. Finally, the PSD of the HRV is estimated from the Fast Fourier Transform of the HT signal multiplied by $j\omega$, as described in [1, 2].

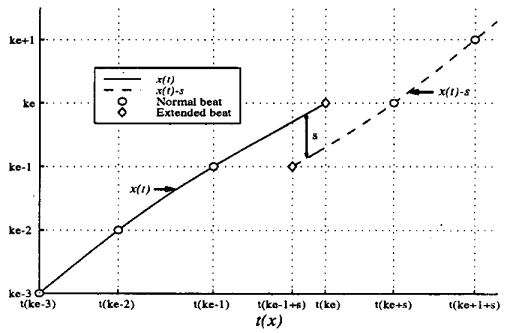

Figure 2. Forward and backward extended beat sequences. Circles represent the known beats and diamonds represent the extended beats.

4. Methods

In comparing the behavior of the spectra estimates in the presence of ectopic beats, the beat series is generated from an AR modelled $m(t)$ signal that approximately matches a typical PSD at supine rest [1, 2]. Fifty random trials of the $m(t)$ signal were generated following the modelled PSD. Then, the cumulative integral of the $1 + m(t)$ is calculated, obtaining the sequence of the beat times, t_k, as the instants when the integral crosses $kT + \sum_{j=1}^{M} s_j\, u(k - k_{e_j})$, where $u(k)$ is the unitary step function. For each assessment of $m(t)$, a variable number of ectopics, $M = [0, 1, 2, 3, 4, 6, 8, 12, 16, 20]$, as well as three different $s = [0.6, 0.8, 1]$ values (denoting different reset locations) are introduced to simulate the ectopic beats located at random positions k_{e_j}. Therefore, a total of 1500 different realizations of 1024 beats each one were made. In all cases, $T = 1$ s. was used. Finally, the PSD is estimated by the following methods:

- DFT of the interpolated HT signal (FHTIS). Following the above described method, the HT signal is estimated and evenly resampled by fourteenth order spline interpolation at regular time intervals. Then, the DFT is applied to obtain the PSD estimation, as referred to in [1, 2].
- DFT of the interpolated HP and HR signals (FHPIS, FHRIS). These signals are evaluated by spline interpolation of fourteenth order with the ectopic values previously removed. Then, the DFT is applied to obtain the PSD.
- Lomb method of the HP and HR signals (LHP, LHR). The Lomb-Scargle periodogram is used as representative of the direct spectral estimation methods and one that estimates the PSD of a unevenly sampled signal without interpolation [6]. The method is applied to the HP and HR signals with the values at each ectopic previously removed.
- Spectrum of Counts with filling (SPC-F). The Spectrum of Counts obtains the information directly from the beat occurrence times [3, 4]. Provided that there is no intermediate time-domain signal, the ectopic-created gaps between beats can be corrected by filling the gap or by shifting all the successive beats to cover up the gap. If the ectopic gaps are not covered, the spectrum obtained will be corrupted. In this case, the gaps are filled by a beat in the middle of each gap, and then, the Spectrum of Counts method is applied.
- Spectrum of Counts with shifting (SPC-S). In this case, the subsequent beats are shifted after each ectopic to maintain the correct RR intervals between beats, and then, the regular Spectrum of Counts method is applied.

5. Results

The PSD of each $m(t)$ realization, $PSD_i(f)$, is taken as the objective to be estimated and it is termed "Original spectrum". The global behavior of each method was shown

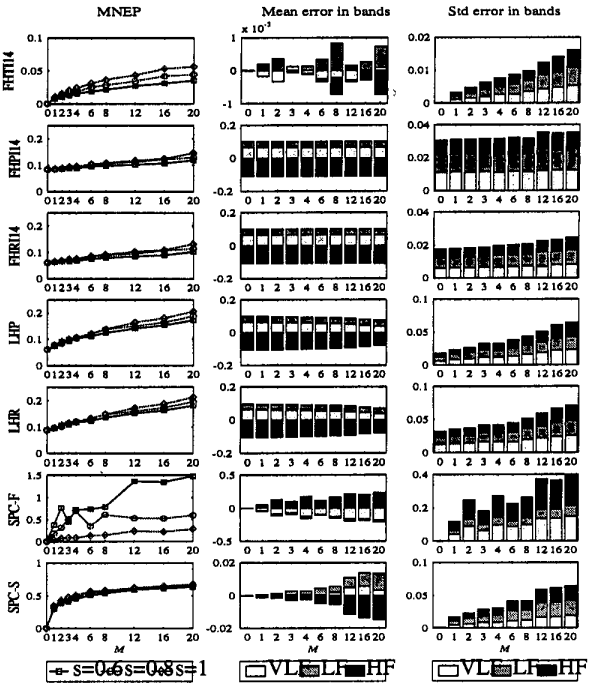

Figure 3. MNEP of each method as a function of M and s. Mean and standard deviation of the relative error in the VLF, LF, and HF bands.

by calculating the normalized error power, NEP, defined as

$$NEP = \frac{\int_{-\frac{1}{2T}}^{+\frac{1}{2T}} \left| \widehat{PSD}_i(f) - PSD_i(f) \right| df}{\int_{-\frac{1}{2T}}^{+\frac{1}{2T}} PSD_i(f)\, df} \qquad (8)$$

where $PSD_i(f)$ is the ith realization of the "Original spectrum" and $\widehat{PSD}_i(f)$ is the estimate with each method. The mean of the NEP, MNEP, is calculated for the 50 realizations. The calculated MNEP is an effective index of the quality of the estimation methods. However, in HRV the PSD is usually divided into different frequency bands: VLF (0.003 - 0.04 Hz), LF (0.04 - 0.15 Hz), and HF (0.15 - 0.4 Hz). The most usual clinical indexes are based on the power in each band. We calculate the mean and the standard deviation of the relative error from the "Original spectrum" in each band.

Figure 3 shows the obtained results. The first column shows the MNEP of the seven different methods as a function of the number of ectopic beats, M, and for each jump magnitude, s (50 realizations for each s). The second and third columns presents the mean and the standard deviation respectively of the relative error in each band, joining the realizations with different s values (150 realizations). A signed stacked bar was used to represent the different magnitudes; the total amplitude of the bar

representing the total mean error and each shaded area represents the contribution of each band.

From the analysis of the MNEP curves, it can be observed that the FHPIS, FHRIS, LHP, and LHR methods keep a remaining error due to the election of the HP or HR signals as representatives of the HRV. The differences between HR or HP are small being slightly favorable to FHRIS with respect to FHPIS, and LHP with respect to LHR. With the dependence on the number of ectopic beats, the four methods mentioned exhibit a quasi-linear dependence, with larger slopes when the (s values) are larger. The SPC-based methods show how their appropriate performance without ectopic beats is quickly lost in the presence of ectopic beats. The SPC-F is the only method that performs better with larger s values. This was expected, as filling with a new beat offers a better solution when $s = 1$. The FHTIS has the best performance without ectopic beats (MNEP = $0.37 \cdot 10^{-3}$) with respect to the closest method, SPC (MNEP = $1.45 \cdot 10^{-3}$). Also the sensitivity to the ectopic beats (slope of the MNEP) is better ($\alpha = 2.6 \cdot 10^{-3}$) with respect to the closest method, FHPIS ($\alpha = 2.8 \cdot 10^{-3}$). However, since the HT ectopic beat treatment comes from the interpolation of the HP signal, it can be stated that the ectopic influence is similar in both cases with HT given by the exact reproduction of the $m(t)$ signal being better as it does not exhibit an inherent residual error as the HP signal does.

The mean and standard deviation of the error in each band shows that the SPC-S estimates much better the clinical indexes (integrating the PSD in large bands) than when studied through MNEP. So, this method does not keep an accurate shape of the spectrum but keeps reasonably the power at each band. Most of the methods exhibit a low pass filtering effect except for the SPC-F method that has an increased power at the HF band. The FHTIS has no noticeable filtering effect. The curious decrease of the mean error with the ectopic number in the LHP and LHR methods is due to the presence of the ectopic beat that increases the high frequency power and compensates the low pass filtering effect introduced by the HP or HR signals themselves. However, in all methods the standard deviation is larger when the number of ectopic beats increases, as was expected. The obtained mean error in the PSD clinical indexes estimation with the HT signal becomes negligible (0.1% mean error in the 2% ectopic rate case) representing a factor 20 lower than for the next best usual method (SPC-S) and practically unbiased PSD estimates. Also the obtained standard deviation (1.7%) is 5 times lower.

6. Conclusion

This paper presents a study analyzing the problems of ectopic beats on the estimation of the PSD in HRV. The continuous time IPFM model has been extended to model the resetting of the SA node when there are ectopic beats and it is found that the HT signal goes on being an adequate representation of the HRV. The simulations were based on a normal subject AR model of the HRV and most of the common correction methods for the ectopic effect were compared. Results show how the presented method achieves the best behavior in the presence of ectopic beats. The satisfactory performance of the SPC method in ectopic-free situations is quickly lost with the presence of ectopic beats. The other methods start with a poorer performance, even when there are no ectopic beats. In summary, the presence of ectopic beats greatly reinforces the convenience of using the HT signal. The IPFM model can be adapted to the presence of ectopic beats and from this perspective, the PSD method that gives the best estimates, also with ectopic beats, is the Fourier transform of the HT signal.

Acknowledgments

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