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Empirical Mode Decomposition (EMD) analysis of HRV data from locally anesthetized patients

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***Abstract*—Spectral analysis of Heart Rate Variability (HRV) is used for the assessment of cardiovascular autonomic control. In this study data driven adaptive technique Empirical Mode Decomposition (EMD) and the associated Hilbert spectrum has been used to evaluate the effect of local anesthesia on HRV parameters in a group of fourteen patients undergoing brachial plexus block (local anesthesia) using transarterial technique. The confidence limit for the stopping criteria was establish and the S value that gave the smallest squared deviation from the mean was considered optimal. The normalized amplitude Hilbert spectrum was used to calculate the error index associated with the instantaneous frequency. The amplitude and the frequency values were corrected in the region where the error was higher than twice the standard deviation. The Intrinsic Mode Function (IMF) components were assigned to the Low Frequency (LF) and the High Frequency (HF) part of the signal by making use of the center frequency and the standard deviation spectral extension estimated from the marginal spectrum of the IMF components. The analysis procedure was validated with the help of a simulated signal which consisted of two components in the LF and the HF region of the HRV signal with varying amplitude and frequency. The optimal range of the stopping criterion was found to be between 4 and 9 for the HRV data. The statistical analysis showed that the $^{LF}/_{HF}$ amplitude ratio decreased within an hour of the application of the brachial plexus block compared to the values at the start of the procedure. These changes were observed in thirteen of the fourteen patients included in this study.**

I. Introduction

THE study of interbeat variations of the Electrocardiograph (ECG) is known as Heart Rate Variability (HRV). In the frequency domain, three frequency bands can be distinguished in the spectrum of short term (2 to 5 minutes) HRV signals [12]. These components are termed as High-Frequency (HF) band (0.15 Hz to 0.4 Hz), Low-Frequency (LF) band (0.04 Hz to 0.15 Hz) and Very Low-Frequency band (VLF) which is the band of less than 0.04 Hz frequencies. The HRV indices such as the ratio of $^{LF}/_{HF}$ power or the fractional LF power have been used to describe sympathovagal balance [5]. The dependence on linearity and stationarity make the parametric and non-parametric spectral methods unsuitable for the analysis of the data like HRV which depends on time-varying phenomena such as respiration.

In this study the Empirical Mode Decomposition (EMD) and the associated Hilbert spectrum technique [7] has been used to evaluate the effect of local anesthesia on HRV parameters in a group of patients undergoing local anesthesia (brachial plexus block) using the transarterial technique. The ability of driving a basis set directly from the data instead of using fixed predefined basis as used by other techniques allows EMD to provide more compact and meaningful representation of the signals especially in the case of non-stationary and non-linear signals [7]. This signal analysis technique has been used previously for analyzing HRV signals [3], [11] and other biological signals [1], [2].

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II. Methods

A. Subject and Protocol

Before commencing clinical trials on ASA 1 and 2 patients undergoing local anesthesia, research ethics committee approval was obtained. Fourteen patients (7 males and 7 females) aged 50.6 ± 20.7 years (mean weight 67 ± 15.3 Kg, mean height 1.6 ± 0.2 m) undergoing elective general surgery under local anesthesia were recruited to the study. In all cases the transarterial approach was used for the brachial plexus block. A combination of 30 ml of 1% Lignocaine and 29 ml of 0.5% Bupivacaine with 1:200000 part Adrenaline was used as anesthetic agent. An AS/3 Anesthesia Monitor (Datex-Engstrom, Helsinki, Finland) was used to collect lead II ECG signals from the patients. The monitoring started about 30 minutes before the start of the block and continued for approximately another 30 minutes after the surgery in the recovery ward. The ECG signal was digitized at 1 kHz sampling frequency using a PCMCIA 6024E 12-bit data acquisition card (National Instruments Corporation, Austin, Texas).

B. Data preprocessing

The algorithm for the detection of the R-waves in the recorded ECG signals was developed using the wavelet transform with first derivative of Gaussian smoothing function as the mother wavelet. The detection was carried out using wavelet scales 2^m, m=4, 8, 12, 16, 20. After the R-wave detection the *heart timing* signal [10] was used for the HRV signal representation and also for the correction of missing and/or ectopic beats. The signals were resampled using cubic spline at a sampling rate of 4 Hz as recommended for HRV studies [12].

C. Empirical Mode Decomposition (EMD)

In the EMD technique the signal is first decomposed into a set of simple functions called Intrinsic Mode Function (IMF). Definition and further details about IMF properties and extraction can be found in the literature [7], [8]. A systematic way for extracting IMF from a complicated data set is known as sifting. The properties of the IMF depend to a large extent on the stopping criterion that is used in the sifting process. In this study the criterion suggested by Huang *et. al* [9] was used and the sifting process was stopped when the number of zero crossings and extrema remains the same for S successive sifting steps. The confidence limit for the parameter S was established $S =$ 2-10, 15 and 20 as proposed by Huang *et. al* [8]. Using the Hilbert spectrum obtained from the individual decompositions, the mean and the standard deviation values were estimated. The S value that gave the smallest squared deviation from the mean was considered optimal and used as the stopping criteria for the sifting process.

D. Normalized Amplitude Hilbert spectrum and instantaneous frequency error index

In order to validate that the estimation yields a physically meaningful instantaneous frequency for the IMF components, the Normalized Amplitude Hilbert spectrum (NAHS) introduced by Huang and Long [6] was used and the error bound was defined as shown in Eq. 1.

$$E(t) = [abs(\text{Hilbert Transform}(y(t))) - 1]^2 \tag{1}$$

The instantaneous frequency was considered to be incorrect at positions where the error index was higher than twice the standard deviation of the error. These values were corrected by using a model based interpolating scheme purposed by Paul *et. al* [4]. After the correction, the marginal spectrum (Eq. 2) of the IMF components was used to estimate the center frequency and the standard deviation spectral extension using Eq. 3 and Eq. 4.

E. IMF component assignment to LF and HF band

The IMF components were assigned to the LF or the HF band of the signal if the center frequency lay within the band limits and the center frequency $\pm$ standard deviation spectral extension value was not more than twenty percent outside the boundary of that band.

$$h(\omega) = \int_0^T H((\omega,\, t)\mathrm{d}t \tag{2}$$

$$\bar{f}_p = \frac{\int_{-\infty}^{\infty} f\, h(\omega)\, df}{\int_{-\infty}^{\infty} h(\omega)\, df} \tag{3}$$

$$\Delta f_p = \left(\frac{\int_{-\infty}^{\infty} (f - \bar{f}_p)^2\, h(\omega)\, df}{\int_{-\infty}^{\infty} h(\omega)\, df} \right)^{1/2} \tag{4}$$

F. Simulated signal study

In order to validate the analysis setup described in this work a simulated signal representing the non-stationary conditions, with changing amplitude and frequency, usually encountered in the HRV analysis was used. The signal was generated using an Integral Pulse Frequency Modulation (IPFM) model for a duration of five minutes. The threshold and the DC component of the IPFM model were kept constant at one. Equispace representation of the signal from the IPFM model was obtained at 4 Hz through cubic spline interpolation.

The signal consisted of two frequency components one in the LF region and one in the HF region of the HRV signal. The amplitude of both the components at the start of the IPFM simulation was set to unity and the frequencies of the LF and the HF component were set to 0.1 Hz and 0.25 Hz respectively. The amplitude of the LF component was dropped to half and that of the HF component was increased to two midway through the IPFM simulation. The frequencies of both the components were increased to 0.12 Hz for the LF component and to 0.3 Hz for the HF component at the same time.

G. Statistical test

An unpaired t-test and a Mann–Whitney rank sum test were used to compare the parameters values estimated from the data obtained from the locally anesthetized patients. The parameters from each patient were tested individually to check for differences before and after the block. The statistical analysis was carried out using *SigmaStat 2.03* (Systat Software Inc., USA). The significance level was set at $P < 0.05$ in all the tests.

III. Results

A. Simulated signals results

The S value of eight gave the minimum squared deviation from the mean and was considered optimal. The results obtained for the simulated signal are shown in Fig. 1. The changes in the amplitude and the frequency can be clearly seen in the first two IMF components shown in Fig. 1. The ratio values calculated using these two IMF components are close to the theoretical value of one in the first half of the data, while it changes to one fourth in the second half reflecting the changes in the amplitude of the two signal components. In this case the dotted line in the ratio plot, second last plot in the right column of Fig.1, shows the values calculated before the correction of instantaneous frequency and amplitude as described in section II-D. The uncorrected ratio values show a large fluctuation in the middle of the data where the parameters of the signal components were changed and the error index was considered high. After the correction the fluctuations have been reduced quite considerably. Due to the smoothness caused by the correction procedure the transition in the corrected ratio values is slower than it was in the uncorrected ratio values and care should be taken while defining the threshold for the error index as too low threshold would result in the loss of meaningful information present in the signal.

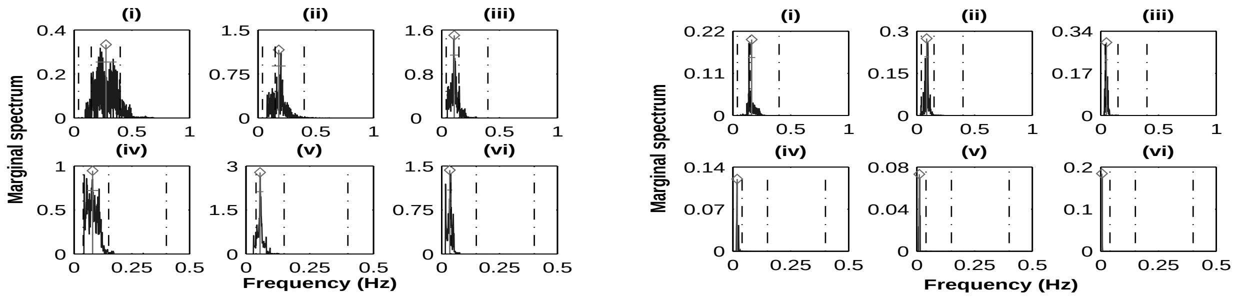

Fig. 2: Part (a) and (b) of this figure shows marginal spectrum of first six IMF components (labeled (i) to (vi) in each subfigure) for two different five minute data segments from locally anesthetized patients. In each plot the solid black line represents the marginal spectrum and the dash dotted black lines represent the traditional LF and HF rigid a priori frequency bands. The diamond mark represents the center frequency and the solid horizontal (gray) line indicates the center frequency $\pm$ standard deviation spectral extension.

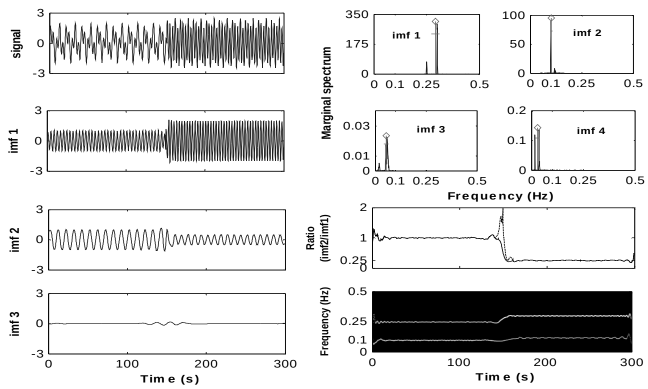

Fig. 1: Results from the simulated signal. The left column represents the signal and the first three IMF components. The marginal spectrum of the first four IMF components are shown in the right top corner. In each plot the diamond marker indicates the center frequency while the horizontal line indicates center frequency $\pm$ standard deviation spectral extension. The graphs at the bottom right corner indicates the ratio between the first two IMF components and the Hilbert spectrum obtained with these two components

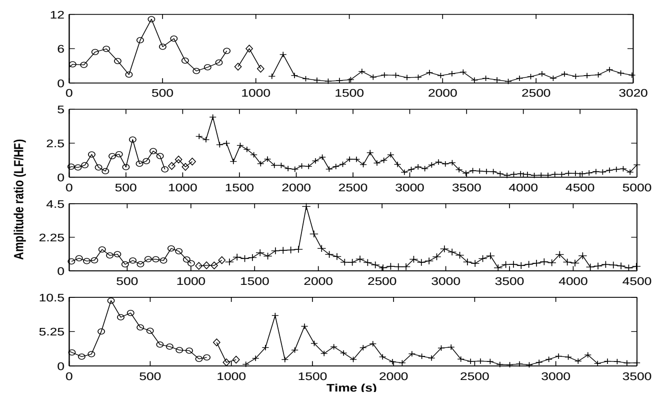

Fig. 3: $^{LF}/_{HF}$ amplitude ratio obtained from four locally anesthetized patient data. In each case the values with circle marks represent the ratio values before the block, diamond marked values represents ratio during the block while values with plus mark represent the ratio after the application of the block

B. HRV data from locally anesthetized patients

The minimum value of squared deviation has occurred between S values of 4 to 9. Each data set was decomposed using the optimal S value. After obtaining the IMF components the amplitude and frequency values where corrected as mentioned in section II-D. After the correction the IMF components were assigned as the LF or the HF part of the signal by making use of the marginal spectrum and calculating the center frequency and the standard deviation spectral extension through Eq. 3 and Eq. 4 respectively (see section II-E). The marginal spectrum of the first six IMF components from two different five minutes data sets are presented in Fig. 2(a) and Fig. 2(b). The spectrum in Fig. 2(a) indicates that the first two IMF components belong to the HF band and the next three belongs to the LF band. The situation is different in case of Fig. 2(b) where the first component belongs to the HF band and the second and third component make up the signal in the LF region.

After the assignment of the IMF components into the HF and the LF bands their amplitude ratio was calculated. Apart from the ratio the total amplitude and the amplitude of the LF and HF components were also estimated in the normalized units. These values were averaged over a period of one minute. The ratio changes in data from four locally anesthetized patients are presented in Fig. 3. By looking at the ratio values presented in Fig 3 it can be seen that after the application of the brachial plexus block the ratio shows a peak and then decreases to a minimum value. The increase in the $^{LF}/_{HF}$ ratio values could be due to the presence of small amount of adrenaline in the anesthetic drug mixture. The decrease in the $^{LF}/_{HF}$ ratio values and the less variability shown by the values were accepted due to the anesthetic drug. The timing of the drop in the ratio value differs from patient to patient, but in each case the drop occurs within an hour of the start of the block.

C. Statistical analysis

Statistical tests were also carried out on the parameters estimated using the EMD analysis technique. Depending on

Table I: Summary of the statistical test results obtained from the EMD analysis of the data from locally anesthetized patients. $^{LF_{amp}}/_{HF_{amp}}$ ratio cell indicates the total number of cases showing significant changes after the block. For all other parameters the first value indicates the number of cases where the parameter values have shown significant changes while the second value indicates the cases where the parameter values have shown significant changes simultaneously with the $^{LF_{amp}}/_{HF_{amp}}$ ratio changes

$^{LF_{amp}}/_{HF_{amp}}$	Amp_{total}	HF_{amp}
13	8, 8	9, 9
LF_{amp}	HF_{N_amp}	LF_{N_amp}
12, 12	13, 13	13, 13

the normality test results, data was analyzed either by using Unpaired t-test or Mann–Whitney rank sum test. The parameters related to the amplitude of the of the signal (*i.e* $^{LF_{amp}}/_{HF_{amp}}$ ratio, total amplitude (Amp_{total}), amplitude related to the HF band of the signal (HF_{amp}), the LF band amplitude (LF_{amp}) and the HF and LF normalized amplitude amplitudes (HF_{N_amp},LF_{N_amp})) were compared in order to see if their values differ significantly after the introduction of the anesthetic drug into the patient system. The statistical results are summarized in table I. From the results presented in table I it can be seen that the EMD analysis has been able to detect significant changes in the ratio values after the application of the anesthetic drug in thirteen out of the fourteen patients included in this study.

IV. Conclusion

In this study the EMD decomposition technique along with the Hilbert transform was used to obtain the time-frequency distribution of the data obtained from the locally anesthetized patients. The decomposition into the IMF components was carried out by establishing the confidence limit for the stopping criteria S and then using the optimal value. The normalized amplitude Hilbert spectrum was used to estimate the error index associated with the instantaneous frequencies of the IMF components. The instantaneous amplitude and frequency values were corrected (see section II-D) in the region where the error index values were more than twice the standard deviation. After the correction, the IMF components were assigned to the LF and the HF part of the signal by using the center frequency and standard deviation spectral extension calculated from the marginal spectrum of the IMF components.

The analysis approach described in the study and the amplitude and/or frequency tracking capabilities of the EMD technique was validated with the help of a simulated signal. The error correction method has reduced the error in the frequency and amplitude values hence reducing the larger fluctuations in the ratio values (see Fig. 1). However, such correction technique should be applied with care as it might cause undesirable smoothing.

After the validation with the simulated signal the same approach was used to analyze the data obtained from fourteen patients undergoing local anesthesia, using a combination of 30 ml Lignocaine and 29 ml of 0.5% Bupivacaine as the anesthetic agent. The $^{LF}/_{HF}$ amplitude ratio calculated from these data sets showed a change after the application of the anesthetic drug (see Fig. 3). The ratio values showed a sharp peak almost right after the application of the block followed by a significant decreases when compared to the values approximately fifteen minutes before the block. Apart from the amplitude ratio between the LF and the HF components the total amplitude and the normalized amplitude of the two components were also calculated. The statistical test summary presented in table I showed that thirteen out of fourteen patients showed significant changes in ratio values after the application of the block. Normalized amplitude of the two components also showed changes in the same number of patients.

These results suggest that during brachial plexus block using a mixture of Lignocaine and Bupivacaine there is a noticeable and almost consistent change in the sympathovagal balance which can be detected through HRV analysis. Such encouraging results suggest further and more rigorous clinical studies.

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