HRV analysis in local anesthesia using Continuous Wavelet Transform (CWT)

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***Abstract*—Spectral analysis of Heart Rate Variability (HRV) is used for the assessment of cardiovascular autonomic control. In this study Continuous Wavelet Transform (CWT) has been used to evaluate the effect of local anesthesia on HRV parameters in a group of fourteen patients undergoing axillary brachial plexus block. A new method which takes signal characteristics into account has been presented for the estimation of the variable boundaries associated with the low and the high frequency band of the HRV signal. The variable boundary method might be useful in cases when the power related to respiration component extends beyond the traditionally excepted range of the high frequency band (0.15-0.4 Hz). The statistical analysis (non-parametric Wilcoxon signed rank test) showed that the $^{LF}/_{HF}$ ratio decreased within an hour of the application of the brachial plexus block compared to the values fifteen minutes prior to the application of the block. 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 [1]. These components are termed as High-Frequency (HF) band (0.15 Hz to 0.4 Hz), Low-Frequency (LF) (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 [2]. The dependence on linearity and stationarity make the parametric and non-parametric spectral methods unsuitable for the analysis of transient changes that might be occurring in the HRV data due to local anesthesia.

In order to deal with the issues of nonstationarity and non-linearity, in this study Continuous Wavelet Transform (CWT) has been used to obtained the scalogram of the signals acquired from a group of patients undergoing local anesthesia (axillary brachial plexus block). This analysis was carried out in order to investigate the effect of local anesthesia on the cardiovascular autonomic control.

This work was supported by Chelmsford Medical Education and Research Trust (CMERT).

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II. Methods

A. Subject and Protocol

After obtaining approval from the Local Research Ethics Committee and informed written consent, fourteen ASA I and II patients (7 males and 7 females) mean age 50.6 ± 20.7 years and mean weight 67 ± 15.3 Kg undergoing elective general surgery under local anesthesia were recruited to the study. Patients with known cardiovascular and respiratory problems and those suffering from diabetes were excluded from the study. In all cases the axillary 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 ECG signal was digitized at 1 kHz sampling frequency using a PCMCIA 6024E 12-bit data acquisition card (National Instruments Corporation, Austin, Texas). 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.

B. Data preprocessing

The ECG R-wave peak detection was carried out 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=2, 3, 4, 5 and 6. The algorithm achieved an accuracy of 99.96% and sensitivity of 99.7% in the recorded ECG signals. After the R-wave detection the *heart timing* signal [3] was used for the HRV signal representation and also for the correction of missing and/or ectopic beats. The signals were interpolated using cubic spline at a sampling rate of 4 Hz as recommended for HRV studies [1]. The VLF component of the signal was removed by detrending the signal using wavelet packet analysis [4]. The respiration signal was also estimated using the ECG Derived Respiration (EDR) technique [5]. After these preprocessing steps the data was ready to be analyzed with the CWT technique.

C. Time-frequency analysis

In this study, scalogram (the squared modulus of the CWT), using Morlet wavelet (1) as the mother wavelet was used to obtained the Time Frequency Distribution (TFD) of the HRV data obtained from the locally anesthetized patients.

$$\psi(x) = \pi^{-1/4} e^{i\omega_0 x} e^{-x^2/2} \quad (1)$$

Where $\omega_0 = 6$ was used to satisfy the admissibility condition [6]. All the signals were analyzed in the analytical form.

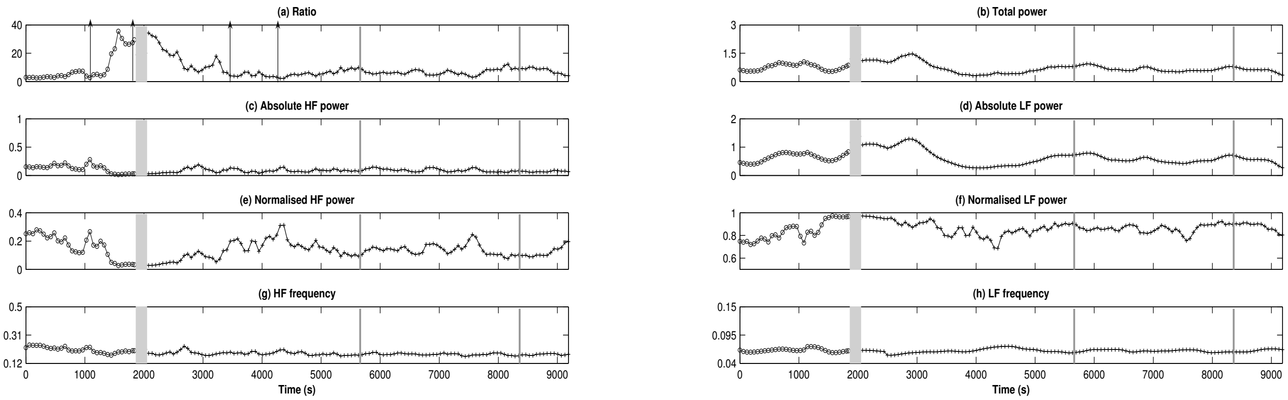


Fig. 1: Results obtained from the CWT analysis of a patient undergoing surgery under local anesthesia. In each plot the gray vertical block represents the time of anesthesia application and the black vertical lines represent start and end of the surgery. The vertical arrow pairs in part (a) show the data segment before and after the application of block which was used in the statistical analysis. In each plot the values before and after the block are represented with circle and plus (+) markers respectively. The units on the y-axis for the subplots (b, c and d) showing absolute power values are s^2/Hz and for the subplots (g and h) showing frequency values is Hz

The estimated respiration signal was used in the HRV analysis for defining the HF band boundaries. The boundaries were defined using the cross-spectrum, which was also obtained with the CWT, between the HRV signal and the estimated respiration signal. From the cross-spectrum the Instantaneous Center Frequency (ICF) and the Standard Deviation Spectral Extension (SDSE) were estimated using (2) and (3) respectively. Using the estimate of the ICF and the SDSE, the range of the HF band was defined as ICF$\pm$SDSE.

$$ICF = \frac{\int_{lb}^{hb} f\, CWT(f,t)\, df}{\int_{lb}^{hb} CWT(f,t)\, df} \quad (2)$$

$$SDSE = \left(\frac{\int_{lb}^{hb} (f - ICF)^2\, CWT(f,t)\, df}{\int_{lb}^{hb} CWT(f,t)\, df} \right)^{1/2} \quad (3)$$

Where the integral limits hb and lb in (2) and (3) will represent the upper and lower boundaries of the region (LF, HF). The ICF and the SDSE related to the LF region of the signal was also calculated, but in this case the estimate was carried out using the TFD of the HRV signal. In the case where the lower boundary of the HF component was below 0.15 Hz then this lower boundary was used in the estimation of the LF component ICF and the boundaries, otherwise the estimation was done in the frequency range of 0.04-0.15 Hz. The ICF and the boundaries were smoothed using a median filter with a length of ten seconds to avoid sharp fluctuations in these parameters. The parameters of total power (PT), power of the LF and the HF band (both in absolute and normalized units) and the ratio of the power related to the two bands (LF/HF) were estimated using the variable boundaries associated with these bands.

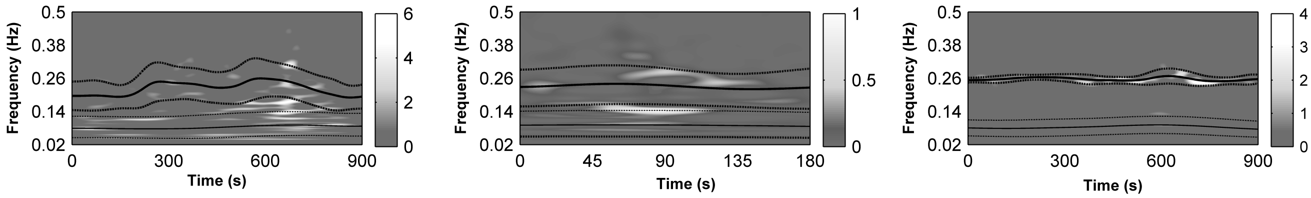
D. Statistical test

In order to quantify the results a non-parametric test (Wilcoxon, signed rank test) was used to check if the parameters values after the anesthetic block were significantly different than the value of the parameters before the application of the block. The parameters estimated for 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

The results obtained from one of the patient data set included in this study are presented in Fig. 1. The parameter values shown in Fig. 1 are the mean values calculated from a period of one minute. After the application of the local anesthetic drug (data values after the gray vertical block in Fig. 1) the LF/HF ratio shown in Fig. 1 (a) increased initially and then decreased reaching a minimum value. During the decreasing phase, the variations in the ratio values were much less than the variation in any other parts of the data. The decrease in the ratio values was observed in each case within an hour of the application of the block. Similar changes were observed in other data sets included in this study. As expected, the normalized power in the HF (Fig. 1 (e)) and the LF band (Fig. 1 (f)) show changes in the opposite direction, with HF band power showing increase after the application of the block while the LF band power showing decrease after the application of the block.

The scalogram representation along with the IF and the boundaries related to the LF and the HF band for the data set from which the results presented in Fig. 1 are obtained, is presented in Fig. 2. Figure 2 (b) shows the time-frequency representation of the data during the application of anesthetic block. Whereas, the fifteen minute data segments that were used to generate the scalogram before (Fig. 2 (a)) and after (Fig. 2 (c)) the anesthetic block were the same segments that were used in the statistical analysis. The timing of these



(a) (b) (c)

Fig. 2: Scalogram representation of the data obtained from a locally anesthetized patient; (a) fifteen minutes data segment before the application of the anesthetic block, (b) during the application of the block, (c) fifteen minutes data segment after the application of the block. In each case the ICF and the boundaries related to the HF band are represented by thick solid and dotted lines respectively. While, for the LF band the same information is presented by thin solid and dotted lines respectively

segments is indicated in Fig. 1 (a) by a pair of vertical arrows before and after the gray vertical box respectively. The decrease in total power after the induction of the anesthesia can also be seen by comparing the color bar (intensity) scale of Fig. 2 (a) and Fig. 2 (c). The shift in power from the LF to the HF band after the application of the anesthetic block can also be seen by comparing the scalogram representation for the data before the application of the block (Fig. 2 (a)) with the representation obtained from the data after the application of the block (Fig. 2 (c)). Also, as mentioned before, after the application of the block the ratio values showed decreased variability, another view of this is presented in Fig. 2. Before the introduction of the anesthetic drug the power is more spread out both in the LF and the HF region. After the introduction of the anesthetic drug the spread of power has decreased in both regions and this is evident by the reduction in the boundaries (ICF±SDSE) for the two regions after the application of the anesthetic block.

IV. Statistical test results

The HRV parameters ($^{LF}/_{HF}$ ratio, total power (PT), power related to the HF and the LF band of the signal both in the absolute (HF_p, LF_p) and the normalized units (HF_{Pnorm}, LF_{Pnorm}) and the IF corresponding to the two bands (HF_f, LF_f)) were compared in order to see if their values differ significantly after the introduction of the anesthetic drug. The parameters estimated for each patient were tested individually to check for differences before and after the block. The results presented in table I indicate that the CWT analysis has been able to detect significant changes in $^{LF}/_{HF}$ ratio values in thirteen of the fourteen patients included in this study. The significant changes occurring in the parameters related to the power of the two bands also showed strong correlation with the changes in the $^{LF}/_{HF}$ ratio values. The parameter values during the surgery were not included in the statistical analysis as in this case it might not be possible to separately identify the changes in the HRV parameter due to the local anesthetic drug and the changes occurring due to the surgical procedure.

V. Discussion and Conclusions

In this study CWT with Morlet wavelet as the mother wavelet was used for the analysis of the data obtained from patients undergoing local anesthesia (Brachial plexus block) carried out with axillary approach.

Table I: Summary of the statistical test results obtained from the CWT analysis of the data from locally anesthetized patients. $^{LF}/_{HF}$ 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 $^{LF}/_{HF}$ ratio changes.

$^{LF}/_{HF}$ ratio	PT	HF_P	LF_P
13	9, 8	10, 9	14, 13
HF_{Pnorm}	LF_{Pnorm}	HF_f	LF_f
11, 11	10, 10	10, 10	8, 7

It is well documented that the respiratory effect does not necessarily be confounded to the fixed limits (0.15-0.4 Hz) defined for the HF band of the signal [7]. In the literature, different approaches have been proposed for the estimation of the boundaries related to HRV signal components [7]–[11]. All these definitions take only the peak frequency of the respiration signal into account and the boundaries are defined without considering any other aspect (e.g. signal frequency spread) of the respiration signal. In another study [12] rate of change in respiration frequency was employed to control the length of the time smoothing window used in smoothed-pseudo Wigner-Ville distribution. The main drawback of this technique is that it might not be applicable with other frequency analysis methods.

The boundary estimation method presented in this study uses ICF±SDSE for the definition of the boundaries of the components. The boundaries related to the HF band of the signal are estimated using the cross-spectrum between the HRV signal and the estimated respiration signal whereas, the boundaries related to the LF band of the signal are directly estimated from the spectrum of the HRV signal. Unlike other previously mentioned methods, in this case the boundary values will depend on the characteristics of the HRV and respiration signals being analyzed. This represents a major advantage and the results obtained during this study suggest that this method should be able to take into account the considerable variations present in the respiration signals.

During the *in-vivo* data analysis two distinguishable changes were observed in the $^{LF}/_{HF}$ ratio values after the application of local anesthesia. Adrenaline was considered to be the major factor behind the initial increase in the ratio values, while the drop observed after this transient increase was considered to be due to the effect of local anesthesia on sympathetic/parasympathetic activity. The effect of Adrenaline present in the local anesthetic mixture, on heart rate and blood pressure has been shown in previous studies [13], [14]. In all these studies the increase in heart rate and peak concentration of Adrenaline was obtained within ten minutes of the application of the anesthetic mixture. Another important observation in these studies was the fact that even the patient's anxiety due to the anticipation of having minor surgery or having the local anesthetic injection might produce some Adrenaline in the system. However, the Adrenaline present in the local anesthetic mixture was the major cause of increase in plasma concentration of Adrenaline and hence the increase in heart rate.

The effect of the local anesthetic mixture (Bupivacaine and/or Lignocaine) used in this study on the autonomic nervous system activity during Brachial plexus block has also been studied previous using Laser Doppler Flowmetry (LDF) signals [15], [16]. In this case, the first recording was made for an interval of thirty minutes before the application of the block and a second thirty minutes recording was carried out with a gap of fifty minutes after the application of anesthesia. The results from this study indicate an inhibitory effect of the Brachial plexus block on the sympathetic and the endothelial activity.

There are some differences in the results obtained from the LDF signal study and the results reported here. In our study opposite changes were observed in the LF (decrease) and the HF (increase) bands of the HRV signal. However, in the Landsverk *et al.* study [15] the band approximately equal to the LF band of the HRV did not show any changes while, the respiratory related band showed a significant increase. This change would also result in a decrease in the $^{LF}/_{HF}$ ratio indicating a shift of sympathovagal balance towards vagal enhancement. A possible explanation of this difference could be due to the fact that in the present study, parameters were estimated continuously after the application of the block while, Landsverk *et al*. [15] started the post-block measurement of the LDF signal fifty minutes after the application of the block. Also, as in the LDF signal analysis, the changes were observed in the frequency range that nearly approximate the VLF band of the HRV signal therefore further analysis of the HRV data from patients undergoing brachial plexus block could also include this frequency band. This will allow the opportunity to see whether the changes occurring at skin microcirculation level as detected through the LDF signal could have a significant impact on the VLF region of the HRV signal.

The studies mentioned in this section provide some evidence in support of the two postulates that were made from the results obtained during this study. Firstly, the presence of Adrenaline in the local anesthetic mixture could cause a transient short live increase in the $^{LF}/_{HF}$ ratio which was observed in almost all the patients included in this study. Secondly, the anesthetic mixture would cause a sympathetic impairment and/or vagal enhancement resulting in a decrease in $^{LF}/_{HF}$ ratio values.

In conclusion, 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 ($^{LF}/_{HF}$ ratio decreases) which can be detected through HRV analysis.

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