Hybrid Modeling of Cardiopulmonary System, HRV and Consciousness

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Abstract. Processing of Heart Rate Variability (HRV) signal becomes more and more important for functional assessment of patient’s health. When developing Hybrid Models of cardiopulmonary system we need to make possible taking into account heart rate variability. Our aim is to generate signals that have properties similar to HRV in norm and in different pathologies. Hybrid models of cardiopulmonary system with features including generation of HRV and new signal processing algorithms may be very helpful in medicine for noninvasive functional assessment. We decided to use Elman’s neural networks to generate HRV signals off-line and we are working on application of this method on-line. To evaluate if the generated signal is sufficiently good to model HRV we compare its Higuchi’s fractal dimension with that of the signal used to teach the network. While generating HRV of a person suffering with epilepsy we observed significant decrease of HRV-signal’s fractal dimension that is accompanying epileptic seizure.

Keywords: Nonlinear Signal Processing, Hybrid Models, HRV, Fractal Dimension, Biofeedback, Epilepsy, Consciousness

1. Introduction

In the hybrid model of cardio-respiratory system that we developed it was assumed that each cycle of changes of heart elastancy lasts equally long period (cf. [Darowski et al., 2007]), i.e. that there was no heart rate variability, assumptions fully applicable only to persons in the state of clinical death. So we should modify our model to make possible taking into account heart rate variability.

Living organism operates far from thermodynamic equilibrium and is ‘spaghetti-like’. Like pulling a single long thin string of spaghetti influence practically all other strings on the plate so change in one system of the organism influence other systems, changing of one process in the organism influence other processes. A change in the brain activity that manifest itself in EEG-signal may influence heart activity and have an impact on HRV-signal. So, lessening of consciousness may leave traces in decreasing complexity not only of EEG but also of HRV.

This interaction between body systems are the basis of different kinds of biofeedback. For example in respiratory biofeedback by controlling respiration one may influence heart and brain - one can observe how changes in respiratory signals are reflected in ECG (or HRV) and EEG.

2. Material and Methods

We have tried different methods of generating HRV signals, such as autoregressive methods, that would be easy to adopt on-line into the hybrid model. But human heart is, of course, nonlinear system, so nonlinear methods should work much better. Comparative analysis of different methods of modeling both HRV and EEG signals, as well as of different indexes of accuracy of the modeling process was done recently [Natarajan, 2008]. After reviewing this PhD thesis we decided to concentrate on Elman’s Neural Networks (ENN). We generated ENN using Java Object Oriented Neural Engine, Joone (http://www.jooneworld.com/)

We do not want to generate a signal that shows minimal deviation from a given HRV signal measured by statistical indexes like normalized root mean square error. It is controversial how to evaluate if any generated signals is sufficiently good to model HRV. We decided to use Higuchi’s
fractal dimension, $D_f$ (cf. [Klonowski, 2002; Klonowski, 2007]) that we have already used for analysis of HRV signals – for sleep staging (cf. [Klonowski et al., 2005; Klonowski, 2007]) and for stress evaluation ([Klonowski and Stepień, 2007]). $D_f$ in time domain is a measure of signal’s complexity.

3. Results

3.1. Generating HRV Signals Using Elman’s Neural Network

For testing the proposed method we decided to use HRV signals from Physionet data base. We have tested several cases. In each case we calculated mean $D_f$ of the signal from Physionet data base that was used for training of our ENN and $D_f$ of the signal generated by the ENN. In each case these values are close to one another while being significantly smaller than 2.0 (that is the value of $D_f$ characteristic for pure noise). Also the values for the pathological cases differed from those for healthy physiological cases. Here we present two examples - a healthy person (Fig. 1) and a case of congestive heart failure NYHA class III (Fig. 2).

![Figure 1. HRV of a healthy person (male) with normal sinus rhythm. ENN trained on data from Physionet http://physionet.org/physiobank/database/nsr2db/nhr021.ecg (blue curve), mean $D_f = 1.68$; HRV generated by ENN (red curve), mean $D_f = 1.71$](image1)

![Figure 2. HRV of a person (male) with congestive heart failure NYHA class III. ENN trained on data from Physionet http://physionet.org/physiobank/database/chf2db/chf201.ecg (blue curve), mean $D_f = 1.55$; HRV generated by ENN (red curve), mean $D_f = 1.59$](image2)

3.2 Complexity of HRV-signal and Consciousness

While analyzing a case of post-ictal heart rate oscillations in partial epilepsy we found that fractal dimension of HRV-signal sharply drops due to patient’s epileptic seizure (Fig. 3). This seizure was localized by the Physionet’s data depositors based on simultaneous EEG recording (that however is not in the database).

According to [Watt RC and Hameroff SR, 1988] consciousness may be described as a manifestation of deterministic chaos in the brain/mind; they observed on ‘phase space trajectories’ that when patients become less conscious (in those cases more anesthetized), the dimensionality of their EEG becomes more ordered, and less chaotic. We observed the same as measured by decreasing
Higuchi’s fractal dimension in anaesthesia, in physiological sleep, and in epilepsy (cf. [Klonowski, 2007]). In a ‘spaghetti-like’ living organism not only complexity of EEG-signal is lessen in the states of reduced consciousness, but as we see here the complexity of HRV-signal is lessen as well.

Figure 3. HRV of a person with post-ictal heart rate oscillations in partial epilepsy
data from Physionet http://physionet.org/physiobank/database/szdb/sz01.dat (blue curve, bottom)
$D_f(t)$ of the HRV signal (green curve, top), calculated in a moving window of 128 points shifted 14 points with $k_{max}=8$ shows significant drop in the period when, according to info in Physionet epileptic seizure, (localized by the data depositors based on simultaneous EEG recording) takes place between 1090 and 1270

4. Conclusions

We conclude that ENN are really a promising method for generation of HRV-like time series and to be used on-line in our hybrid model to vary heart rate, giving a possibility to model both physiological conditions as well as different cardio-respiratory pathologies. Works on application of the presented method on-line in our hybrid model of cardiovascular system are now in progress.

We also conclude that HRV if appropriately analyzed may be used in epileptology for localizing and maybe predicting epileptic seizures. Fractal dimension of HRV-signal may also serve as a measure of consciousness.

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