Modeling of Human Heart Rate Variability Enhanced using Stochastic Sleep Architecture Properties

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Abstract

Human sleep consists of four characteristic phases: light (L), deep (D), REM sleep and almost-awake state (W) with additional arousal episodes (Exc). All of these elements create a nontrivial, complex structure, the statistical properties of which were studied here carefully. We observed a different behavior of heart rate variability for each phase. Thus, we should take these specific properties of sleep architecture into consideration while modeling heart rate variability.

We analyzed 34 simultaneous heart rate variability and 30 EEG nighttime recordings from healthy adults. EEG provides accurate information about sleep phases.

The main idea behind our sleep architecture reconstruction is to consider two properties: probabilities of transitions between all possible pairs of phases and probability distribution of phase durations. We calculated the probabilities of transition between each pair of phases and we aggregated them into two probability matrices (separately for each half of the sleep period because the character of the inter-phase transitions is different in early and late sleep). We found also that the probability distribution of L, D and REM sleep duration are described by a gamma distribution and that of the W phase - by a Pareto distribution.

To generate the RR intervals for every sleep phase, we use the model described in [1]. We consider three variants: (a) periodic sleep cycles with the sequences of phases: L, D, REM, W in each cycle, (b) a randomized distribution of phases, (c) the architecture based on our model. The results show that variant (c) gives 50% of the time series indistinguishable from real data using all standard linear and nonlinear HRV assessment methods while for variants (a) and (b) we obtain 41% and 3% accordingly.

1. Introduction

PhysioNet/Computing in Cardiology Challenge in 2002 had a topic "RR Interval Time Series Modeling". In the full papers describing best models we can find a few very interesting models of heart rate variability [2,3]. However, most of them do not consider many factors causing variability during day and night,. As we started thinking about modelling of HRV, we decided to work only with nighttime parts of the HRV, to avoid the problems of modelling human daytime activity. Moreover, sleep is a very specific time for heart activity. Each of four characteristic sleep stages: light (L), deep (D), REM sleep, almost-awake state (W) reflect different states of nervous system [4]. It manifests in changes of blood pressure, breathing variability, temperature and obviously heart rate. Unfortunately none of these factors were considered in the models from the PhysioNet/CinC Challenge in a satisfying way.

Arrangement of sleep stages creates a nontrivial, complex structure called sleep architecture. This architecture is presented usually in a form of a graph showing dependence of sleep stage on time, called hypnogram. In general, sleep is divided to 80 to 110 minute cycles with sequence of stages: light sleep, deep sleep, and REM and wake episode [5]. But this is just a very general rule; in real data we observe frequent changes inside the cycle, together with short episodes of behavior very different from the expected one, so modeling of hypnogram is not easy.

Correlation between heart rate variability (HRV) and sleep stages is clearly visible and described in the literature [6]. The most obvious example is that during deep sleep we observe decrease of mean heart rate value what is in contrast to REM and wake phase. Differences in nonlinear properties between sleep stages were also found [7, 8]. Sleep architecture is one of the factors which determine the dynamical properties of heart rate variability.

1.1. Starting point: HRV model for individual sleep stages

The starting point for our work was implementation of HRV model by Kantelhardt et al. [1] which worked for different sleep stages. Model is generally stochastic but with some additional short-range correlations introduced and with breathing rhythm applied. So it was ideal for our purposes as a first approximation. It consists of three

separate parts. First part is a constant element which defines the mean of RR-interval in each sleep stage. Second part simulates the influence of respiratory system on the HRV. This influence is implemented by sinusoidal function. Parameters of this function have direct, physiological associates: amplitude of this function corresponds to strength of the respiratory coupling and time is simply a period of respiratory cycle. This sinusoidal function has fixed respiratory period for every sleep stage, which unfortunately makes it look strict and artificial. Third part, the stochastic process with two parameters is the core of the model. This is the part which introduces short-range correlations, so important for the final result. The main equation for generating RR-interval time series is presented in eq. (1). Each sleep stage has got its own set of parameters.

$$\tau_i = \mu + 0.03\sin(2\pi t_i/3.6) + 0.025\sum_{j=1}^{i} y_i \Theta(k_j + j - i) \quad (1)$$

where: μ is a constant value, $\Theta(m) = 1$ for $m > 0$ and $\Theta(m) = 0$ for $m \leq 0$, $t_i = \sum_{j=i-(i \bmod 4)-1}^{i-1} \tau_j$ for $i \geq 5$ and $t_i = 0$ for initialization ($i < 5$). The random integer k_j following a power-law distribution, describes the variance of correlations. The random variable y_i is created by stochastic process with two parameters.

2. Data

We analyzed 34 RR interval series from healthy subjects. All data belong to anonymous Holter ECG database of the Institute of Cardiology (Warsaw, Poland) and were collected for medical purposes. Signals are sampled at 128 Hz (i.e. with a resolution of 8 ms) and were checked for artifacts by a qualified cardiologist. We used also 30 hypnograms created from complete EEG signals by a neurologist. Particular phases were defined in 5-minute windows with 20-second offset. The first set of data was used to assess generated synthetic RR time series, whereas the second one was necessary to study properties of sleep architecture.

3. Development and improvements of the model

Kantelhardt's model described HRV characteristics within a single sleep stage, but there was no way to generate complete synthetic HRV recording, because authors did not provide description how to model hypnograms. What is more, there are no hypnogram models available in the literature. One of the main aims of the development the model was then, to develop the realistic sequences of sleep stages during sleep, i.e. so-called sleep architecture.

The main idea behind our sleep architecture reconstruction is to consider two properties: probabilities of transitions between all possible pairs of phases and probability distribution of phase durations in real data. Because the character of the inter-phase transitions is entirely different in early and late sleep, we calculate all probabilities and distributions separate for the first and the second part of sleep. Then we aggregated them into probability matrices. We found that the probability distributions of light, deep and REM sleep stage duration are described by a gamma distribution and that of the wake phase - by a power-law distribution. We believe that this conclusion by itself is a very important result.

Table 1. Matrices presenting probability of transition between all possible pairs of sleep stages, together with sleep stages percentage, during the first and the second half of sleep. As we expected, results for the first and the second half of sleep are clearly different, especially for the transition between stages: L->D, L->REM, L->W, L->Exc (abbrev. Exc. comes from "exercise", which simply describes stages of repositioning). We also observed differences in sleep proportion for deep sleep, REM and wake. Probabilities of transition between pair of stages REM->D, W->D, D->L, REM->Exc and sleep proportion of light and exercise episodes do not change during sleep.

I half of sleep – matrix of probability [%]						Sleep proportion [%]
Sleep stage	L	D	REM	W	EXC	
L	-	47,8	4,9	5,2	42,2	59,3
D	75,2	-	0,01	1,7	22,1	27,6
REM	76,0	0,0	-	11,9	12,1	4,9
W	4,9	0,0	89	-	6,0	5,4
Exc	48,4	3,8	30,1	17,7	-	2,7
II half of sleep – matrix of probability [%]						Sleep proportion [%]
Sleep stage	L	D	REM	W	EXC	
L	-	22,2	9,2	11,3	57,3	66,5
D	77,6	-	2,0	4,1	16,3	10,8
REM	69,1	0,3	-	18,2	12,4	7,6
W	8,7	0,0	80,3	-	11,0	12,1
Exc	38,6	0,0	36,4	25,0	-	3,0

4. Results

We prepared a test, to determine, if our idea of hypnogram simulation, works well. The three variants were considered: (a) periodic sleep cycles with the sequences of phases: L, D, REM, W in each cycle, (b) a randomized distribution of phases, (c) the architecture based on our model. Comparison of RR time series and hypnograms between these variants and real data is showed in fig. 1.

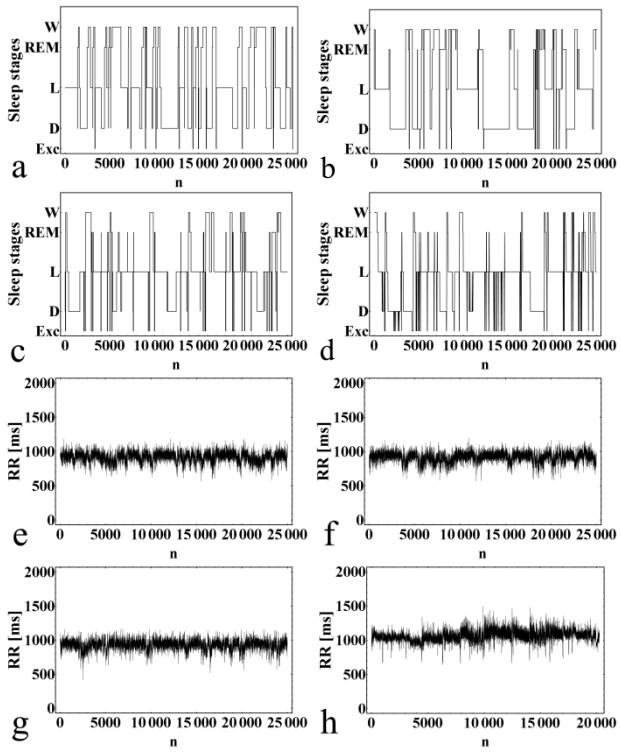

Figure 1. Hypnograms generated using three variants of sleep stage configurations: (a) periodic sleep cycles with the sequences of phases: L, D, REM, W in each cycle, (b) a randomized distribution of phases, (c) the architecture based on our model and real data (d). Below in Fig. 1 e-h, in the analogical order, we can see corresponding RR interval time series. Artificial hypnograms correspond directly to RR interval series created based on them, but note, that (d) shows real hypnogram and (h) real RR interval series, but because of lack of the data they do not come from one subject.

We found that there are no differences between HRV recordings, generated using these three variants of hypnograms. Statistic properties of the real data and three artificial recordings were so close, that none of the standard linear methods could distinguish between them (tab. 2), so we used more complex method: multiscale multifractal analysis (MMA) [9]. MMA is a time series analysis method, looking for fractal scaling of fluctuations. As a result, it gives so called Hurst surface h(q,s), depicting scaling of variance h, as a function of fluctuation magnitude q and time scale s. This Hurst surface h(q,s) for a HRV from a healthy subject has a very characteristic shape, which is automatically assessed by a program developed in our lab. Because program is prepared as a screening examination method, it gives only very simple result: healthy (1) or ill (0). Results show that variant (c) gives 50% of the series indistinguishable from real data while for variants (a) and (b) we obtain 41% and 3% accordingly. We observed the largest differences considering the shape of Hurst surfaces for low scales s (fig 2).

Table 2. Results of standard linear HRV analysis, for 34 generated night-time RR interval series in three variants of sleep architecture: (a) periodic sleep cycles with the sequences of phases: L, D, REM, W in each cycle, (b) a randomized distribution of phases, (c) the architecture based on our model. We see no clear differences between variants, because of the same statistical properties. In comparison with real data we are not able to select the best configuration of sleep stages.

linear method	(a)	(b)	(c)	real data
mean [ms]	920(5)	917(8)	929(5)	1002(127)
std [ms]	76(3)	78(3)	74(3)	104(32)
RMSSD [ms]	42(0.5)	43(0.9)	43(0.6)	63(24)
pNN50 [%]	13(0.5)	13(0.8)	14(0.5)	15(8)

There are three statistical properties of the hypnogram, that we considered trying to generate an artificial one. Probability of transition between sleep stages, sleep stages duration and sleep stages ratio. However generating hypnograms while only the first two of them are fixed, determines correct realization of the third one, because they are not independent.

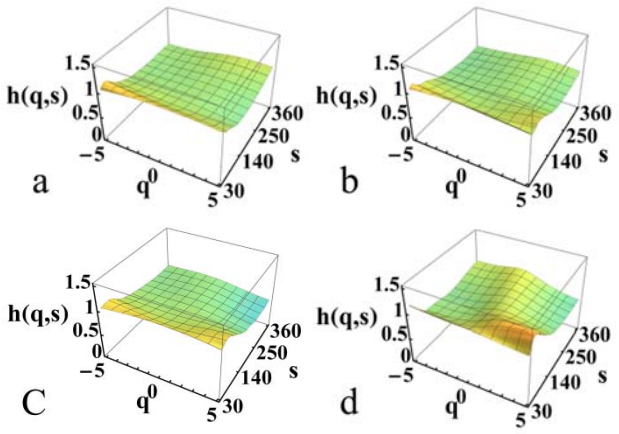

Figure 2. Average Hurst surfaces h(q,s) calculated for synthetic RR interval time series using three variants of sleep stage configurations in comparison to Hurst surface obtained from real data. (a) Periodic sleep cycles with the sequences of phases: L, D, REM, W in each cycle, (b) a randomized distribution of phases, (c) the architecture based on our model (d) real data. We observed similarity of the shape of Hurst surfaces for low scales s between our model (c) and real data (d).

5. Conclusions

We present a method for simulating healthy human sleep architecture based on properties of sleep observed in real data. In the literature similar solutions have never been developed so far.

The big advantage of our method, is providing synthetic hypnograms with good proportion of sleep stages only based on the other statistical properties of sleep architecture (see Sec. 3).

We found that the probability distributions of light, deep and REM sleep stage duration, are described by a gamma distribution and that of the wake phase - by a power-law distribution.

Results show that sleep architecture simulated by our method is the best implementation for purposes of modeling heart rate variability. It leads to noticeable improvement in the quality of generated RR signals, especially considering their dynamical properties.

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