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Heart rate variability analysis during hypnosis using wavelet transformation

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ABSTRACT

Hypnosis can act on the autonomic nervous system which can be presented by heart rate variability (HRV). So HRV implies many information related to hypnosis. Because HRV signal is time-variant and non-stationary, the traditional methods, such as Fourier transform and AR spectral estimation, are unable to analyze it. Hence, wavelet time-frequency analysis is applied here to not only offer superior time and frequency resolution, but also detect sudden amplitude and frequency jumps. The electrocardiograms of subjects were recorded under hypnosis, from which the corresponding HRV signals are obtained. The instant parameters including HRV, very low frequency (VLF), low frequency (LF), high frequency (HF), and the ratio of LF to HF (LF/HF) components of each HRV signal are then computed. Furthermore, mean, coefficient of variation, skewness, and kurtosis of independent frequency components in four hypnotic states (resting state, inducing state, imagining state and awaking state) were also obtained from the instant parameters to describe variation during hypnosis. The experiment results show that the parameters of HRV can reflect some physiological features of hypnosis, e.g., the LF/HF was more concentrative and steady in imagining state.

1. Introduction

Clinical hypnosis is a mind-body technique that operates at the intersection of subjective perceptions and objective physiological changes. Many researches illustrated that hypnosis can be characterized by a decreased sympathetic tone and an increased parasympathetic activity [1], where sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) are the two main branches of autonomic nervous system (ANS). In addition, autonomic cardiac tone was significantly modified during hypnosis by shifting the balance of the ANS toward an enhanced PNS modulation, accompanied by a reduction of the SNS tone and a decreased short-range similarity but without a concomitant change in heart rate [2].

Heart rate variability (HRV) is often used to assess function of ANS [3]. The measure of the ANS response to hypnosis can be obtained from analyzing the HRV parameters of frequency domain [4]. Low frequency (LF) component of HRV signal is influenced by both SNS and PNS and it may reflect the thermal control and baroreflex control of blood pressure through HRV. High frequency (HF) component is controlled by PNS and it is associated with respiratory activity. Although respiratory sinus arrhythmia occurs within the HF band, this condition can also occur at other frequencies. The ratio of LF and HF (LF/HF) is considered to reflect balance between SNS and PNS [5–7].

Some traditional methods, such as Auto-regressive (AR) spectral estimation and Fourier transformation, are the most popular methods to analyze HRV [8]. These methods to estimate spectrum presupposed that HRV is stationary and time-invariant signal. However, HRV is non-stationary signal in the long term, especially in hypnosis. The different stages of hypnosis results in the change of HRV parameters due to the individual received different external stimulus. The HRV parameters still vary even in the same stage. Therefore, traditional methods are not effective to analyze hypnotic HRV signal. On the other hand, traditional methods can only quantify the amplitude of heart rate oscillations, without providing temporal information [9]. The variability of instantaneous power of independent frequency components under hypnosis is extremely valuable, which maybe imply some important information.

Compared with traditional methods, wavelet transformation (WT) can not only analyze non-stationary signal like hypnotic HRV and offer superior time and frequency resolution, but also has the

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ability to detect sudden amplitude and frequency jumps [10]. There are three main classes of wavelet analysis: Continuous Wavelet Transform (CWT), Discrete Wavelet Transform (DWT), and Wavelet Packet Transform (WPT). DWT and WPT are useful for compact representation of data, particularly for noise reduction, and can also for analyzing power spectrum of HRV [11–14]. However, DWT and WPT do not have subtle frequency resolution in terms of time-frequency analysis. Whereas, the CWT is the best one for feature extraction [15]. Only CWT is studied here because we are interested in extracting low s/n ratio signals in time series. We recorded and analyzed the changes of independent frequency components of subjects who were under hypnosis. Then some statistical features are computed by assessing the short-time variation of frequency components including mean, coefficient of variation, skewness and kurtosis of instantaneous power of independent frequency components at all the four states (resting state, inducing state, imagining state, and awaking state). It will indicate the change rule of frequency components of HRV under hypnosis and further compare the statistical features of these components in different hypnotic conditions.

2. Statistical feature extraction using Wavelet technique

2.1. Acquisition of HRV signal

There are four states during hypnotic test. First, in resting state, subjects breathe normally with their eyes closed and lie quietly without moving before hypnosis. Second, in inducing state, subjects are guided to relax progressively and respond suggestions. Subjects are considered to be hypnotized when roving eye movements are observed or the subject respond by a hand movement that he or she feels to be hypnotized [16]. Third, in imagining state, subjects are invited to imagine pleasant and peaceful scene, and they are instructed to feel their subconscious and positive energy. This process is an alteration in perception, sensation, emotion, thought, or behavior through imagination and suggestion. Four, in awaking state, subjects return to waking state with completion of hypnosis. They breathe normally with their eyes closed and lay quietly without movement.

Electrocardiography (ECG) signals and videos of subjects in the whole tests are recorded in all the four states. The subjects are documented with a video camera for detailed analysis after recording ECG. ECG is recorded in supine position by using three-limb ECG leads (ECG-B; SAYES, Shenzhen, China) through Red DotTM Ag/AgCl disposable electrodes placed in accordance with a sample rate at 500 Hz. Then the peaks of this ECG are extracted and resampled at 4 Hz to obtain HRV signal $h(t)$. $h(t)$ is segmented into four part $h_i(t)$ according the four hypnotic states, $i = 1, 2, 3, 4$.

2.2. Time-frequency analysis of HRV signal

After the $h_i(t)$ is obtained, WT is used to compute its wavelet power coefficients WT(t,a) as follows

$$WT(a,b) = \frac{1}{\sqrt{a}} \int h_i(t)\psi^*(\frac{t-b}{a})dt \tag{1}$$

$$= \sqrt{a} \int e^{jwt} \widehat{h}_i(w)\widehat{\psi}^*(aw)dw \tag{2}$$

where * represents conjugate, the scaling factor a and shifting factor b are real and $a > 0$, the w is the angular frequency. $h_i(t)$ is the HRV signal in the ith state and $\psi(t)$ is the Morlet wavelet. After WT, a data matrix containing time, scale, and wavelet coefficients is obtained. Actually, the WT is not a function of time and frequency but time and the scaling factor a. Because scale is related to frequency, P_{WT} (t,a) is called the scalogram and it defines a joint density of time and scale [17],

$$P_{WT}(t,a) = \frac{1}{2\pi Ca^2}|WT(t,a)|^2 \tag{3}$$

The factor $\frac{1}{2\pi Ca^2}$ is inserted for proper normalization. The constant C is chosen to obtain the energy by using WT,

$$C = \int \frac{|\widehat{\psi}(w)|^2}{|w|} dw \tag{4}$$

A reference frequency w_r is chosen from $w = w_r/a$ to obtain a time-frequency density. Finally, wavelet time-frequency analysis can be expressed by [18]

$$P_{WT}(t,w) = \frac{w_r}{w^2} P_{WT}\left(t, a = \frac{w_r}{w}\right) \tag{5}$$

$$= \frac{1}{2\pi C w_r}\left|WT\left(t, \frac{w_r}{w}\right)\right|^2 \tag{6}$$

Then, the instantaneous power $P_{WT}(t,w)$ is obtained from Eq. (6), which contains the messages of time and frequency. For assessing the instantaneous power of independent frequency components of HRV, the frequency spectrum is divided into three parts: very low frequency (VLF, 0.003–0.04 Hz):

$$P_{VLF}(t) = \int_{0.003}^{0.04} P_{WT}(t,f)df \tag{7}$$

where f=2π/w, frequency interval is related to the scaling factor a, and the frequency range from 0 to 2 Hz. Low frequency (LF, 0.04–0.15 Hz) spectrum is:

$$P_{LF}(t) = \int_{0.04}^{0.15} P_{WT}(t,f)df \tag{8}$$

and high frequency (HF, 0.15–0.40 Hz) spectrum is:

$$P_{HF}(t) = \int_{0.15}^{0.40} P_{WT}(t,f)df \tag{9}$$

2.3. Statistical analysis of independent frequency components

In the process of hypnosis, the instantaneous power of independent frequency components changes with the time. In order to describe this variation, four parameters of statistical features are used: mean, coefficient of variation, skewness, and kurtosis. Mean represents mean value of instantaneous power at each hypnotic state. Coefficient of variation is defined as the ratio of standard deviation to mean, which shows the extent of variability in relation to the mean of the population [19].

$$\mathrm{Coe}[X] = \frac{\mu}{\sigma} \tag{10}$$

where X represents instantaneous power of independent frequency components, μ represents mean value and σ represents standard deviation. Skewness can reflect the degree of asymmetry in the histogram of instantaneous power:

$$\mathrm{Skew}[X] = E\left[\left(\frac{X-\mu}{\sigma}\right)^3\right] = \frac{E\left[X^3\right] - 3\mu\sigma^2 - \mu^3}{\sigma^3} \tag{11}$$

where E is the expectation operator. If the histogram is symmetrical, the skewness is zero. If the left hand tail is longer, the skewness will be negative. If the right hand tail is longer, the skewness will