STOCHASTIC RESONANCE IN BREATHING

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Summary The central respiratory pattern generator requires some external stimulus to trigger respiratory events. The origin of such respiratory-related inputs to the motoneuronal pools is unknown, but it is believed that the origin of the resting tone is from the sensory afferent in the airways1. Here we report a finding that inspiratory flow oscillates due to flow separation near the larynx, and the resulting periodic signal (~ 5 Hz), which is buried under a broadband flow noise, is an intrinsic property of unconscious breathing. It is also found experimentally that such signal triggers stochastic resonance, a phenomenon which occurs when the addition of noise in a nonlinear system amplifies a weak input leading to higher signal-to-noise ratio (SNR) in the output. We argue that the stochastic resonance enhanced signal serves as the external stimulus. We also found that the SNR of unconscious breathing is much higher than that of conscious breathing, indicating that the stochastic resonance mediates and controls the unconscious breathing.

INTRODUCTION

Most breathing is unconscious and displays continuous and rhythmic behaviour [1]. It is usually known that unconscious breathing is controlled primarily by the blood levels of carbon dioxide which are sensed by chemoreceptors in the carotid and aortic bodies for Ph [3]. Central respiratory control mechanisms regulate tidal volume and inspiratory and expiratory times to achieve adequate ventilation and gas exchange [4]. Input signals emanate not only from chemoreceptors but also from mechanoreceptors in the upper airways4. The upper airway has a rich sensory supply which constantly monitors mechanical changes in the lungs [5]. The mechanoreceptors in upper airways are important to the airway tonicity, compliance and calibre [6-7]. It was found that forced high-frequency (~ 30 Hz) oscillating pressure would cause an increase in the upper airway muscle activity as measured by the electromyogram (EMG), indicating that the oscillating pressure is the stimulus to trigger the reflex in the respiratory muscles [8]. Due to the narrowness of the upper airway region, the inspiratory flow is highly turbulent and fluctuating. The addition of noise in a nonlinear system can amplify a weak input so as to increase the output signal-to-noise ratio (SNR) which would improve the ability to transmit signal reliably. This phenomenon is called stochastic resonance [2] and has been found to exist in many physical and biological systems [9-13]. If the flow fluctuation is considered as a background noise, some important signal, which is buried under the noise, could be amplified through the stochastic resonance phenomenon.

RESULTS AND DISCUSSION

To investigate the role of stochastic resonance in unconscious breathing control, we measured the pressure variation in the upper airway of six human subjects in an anechoic chamber. The pressure waveform of unconscious breathing is continuous but that of conscious breathing exhibits clearly “impulsive” pattern (Fig. 1a). Here the distinction between unconscious and conscious breathing is made by the measured breathing frequency: 12/60 ~ 15/60 Hz for the unconscious breathing and ~ 20/60 Hz for the conscious. Autocorrelation is an effective mathematical tool to extract the periodic signal buried under noise and to test the randomness of the data. When the autocorrelation is near zero, it suggests the signal is random, otherwise it is non-random and contains certain fundamental frequencies. The result shows that there exists a significant negative maximum around the time interval of 0.05s for all subjects with unconscious breathing (Fig. 1b), indicating that the respiratory flow fluctuation is not random but has an intrinsic rhythm. However, during the conscious breathing this negative maximum diminishes (Fig. 1b), suggesting a lack of such natural rhythm. Spectral analysis shows that the conscious breathing has a much higher level of power spectral density (PSD) over a wider frequency range, while the PSD of unconscious breathing peaks around 5 Hz (Fig. 1c). Note that the two spectra for the unconscious and the conscious (Fig. 1c) show multiple peaks. The significance of each peak depends on the signal-to-noise ratio (SNR), which is defined as $10\log10(S/N_0)$ in decibels (dB), where S is the area enclosed above the noise background and N_0 is the intensity of noise background at the signal frequency [2]. Fig. 1d shows SNR as a function of noise intensity. The SNR of unconscious breathing is found to be much higher than that of conscious breathing. A skewed peak is found for SNR in the mid range of the noise level shown. The existence of such a peak is the principal signature of stochastic resonance. This suggests that the stochastic resonance plays an important role in the unconscious breathing as periodic signals are enhanced significantly by noise. It is believed that the enhanced periodic oscillation activates the mechanoreceptors, and this sensory input is transmitted to the central respiratory control system which regulates effectively the diaphragm and lung movements. In unconscious breathing, the highest SNR occurs around 5 Hz; and in conscious breathing, the SNR is almost constant in the spectrum between 5 and 25 Hz (Fig. 1e). This implies that the 5 Hz flow oscillation is the key factor in regulating the unconscious breathing. To further verify the flow oscillation, the pressure catheter sensor is used to measure the pressure variation at hypopharynx of one subject, and a peak PSD is also observed around 5 Hz (Fig. 1f) for unconscious breathing, i.e., the

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flow oscillations measured at different airway locations and with different methods are consistent, indicating the ~ 5 Hz flow oscillation is the intrinsic characteristics of upper airway.

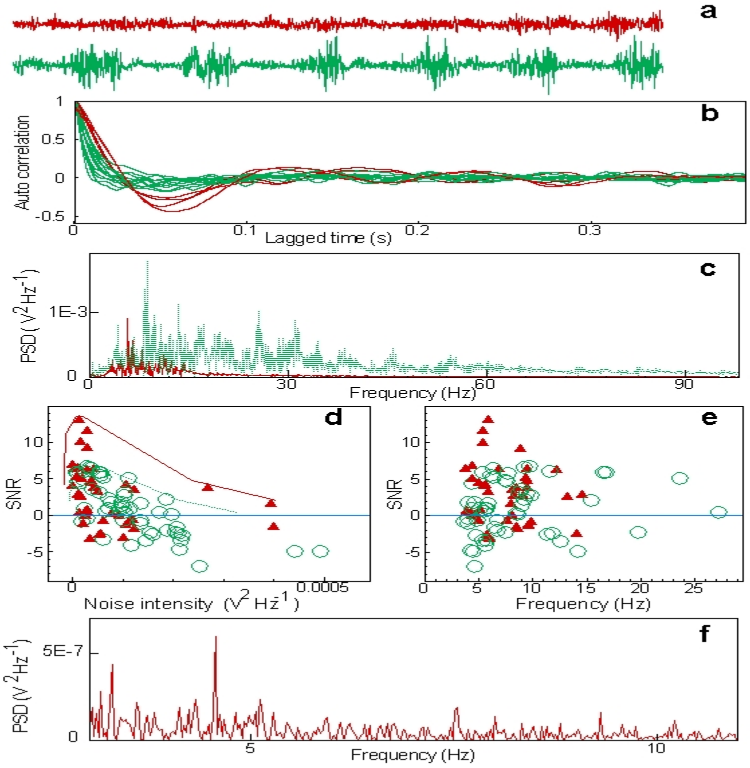

Figure 1 Time series and spectral analysis of measurements. Red lines are for the unconscious breathing, green for the conscious. a. time series of measured pressure variation for unconscious and conscious breathing; b. autocorrelation of time series; c. comparison of spectral analysis of time series between unconscious and conscious breathing for one subject; d. SNR comparison for various subjects; e. SNR comparison with Hz; f. PSD distribution of pressure variation at hypopharynx for unconscious breathing.

CONCLUSIONS

The stochastic resonance can provide a quantitative basis for breathing quality evaluation and surgery planning.

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