Respiration-Posture Feedback System for Breathing Control

A challenge to develop an ambient health care system

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***Abstract*—We developed a respiration-posture feedback system to control breathing involuntarily. In this system, a rubber air chamber placed under a subject's back inflates or deflates to adjust a subject's chest position slightly. By adequately regulating the movement of this air chamber in synchrony with actual respiration, respiration was successfully lengthened and deepened, just like voluntary deep breathing. Moreover, the analysis of the heart rate signal indicated that the parasympathetic nervous system, which is a prominent nervous system in the body, was also activated. This respiration-posture feedback system can be used for an at-home adaptive health care interface as part of an ambient system.**

Keywords-ambient feedback; heart rate variability; respiration; vagal nervous system

I. INTRODUCTION

Across generations and continents, breathing control has been introduced as one of the easiest and most effective approaches toward controlling the mental and somatic states. The unique breathing styles are developed when doing activities such as yoga, martial arts, marathon running, and even religious meditation. There is increasing scientific evidence in the field of biofeedback showing that breathing control affects behaviour, mental state, physiology, etc., such as the performance of tasks [1], quality of sleep, anxiety [2-5], heat rate [6-8], blood pressure [5, 9] and even immune functioning [10-12].

Moreover, the numerous medical observational and clinical studies have revealed that adequate breathing control of patients who experience a breathing-related disorder, such as obstacle sleep apnoea (OSA) or central sleep apnoea (CSA), which are prominent risk factors of cardiovascular disease [13], can significantly reduce this risk [14, 15]. Thus, developing a breathing control method is quite beneficial for maintaining health clinically and in daily life.

The wide-ranging physiological effects of breathing control are mediated by vagus nerve (parasympathetic nervous system) activation [16]. The vagus nerve, the most important nervous system in the body, is a single transduction pathway of the nerve signals that convey physiological information to the brain stem. Respiration is regulated via the parasympathetic nervous system as follows: (1) respiration induces changes in the pressure in the lung and pH in the blood, (2) these physiological changes are detected by mechanoreceptors and chemoreceptors, respectively, and then (3) the signal from each receptor is conveyed to the respiratory centre at the brain stem via the (afferent) parasympathetic nervous system (Fig. 1). Because nerves innervating the body and brain interconnect at the brain stem, respiration may be able to regulate the entire body and even mind. In other words, voluntary control of respiration could affect the entire body and the mind.

The challenge of this study is to develop a system to involuntarily (or unconsciously) control respiration. The voluntary control of respiration, e.g., biofeedback training, sometimes requires substantial effort and concentration.

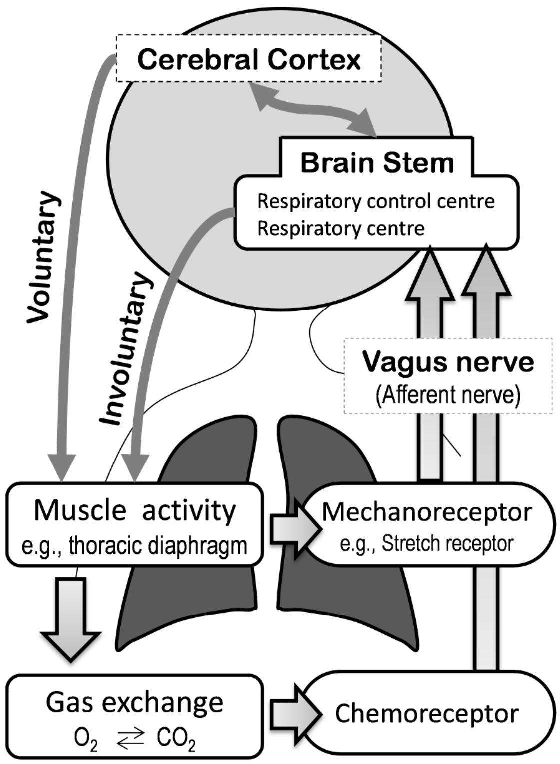

Figure 1. Respiration physiology.

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Moreover, the mechanical respiration control systems that physically provide airflow to patients in the clinic, such as Continuous Positive Airway Pressure (CPAP) and Adaptive Servo-Ventilation (ASV), require patients to be fitted with a nasal cannula or respirator. Although CPAP and ASV can be the most effective treatments for patients with OSA and CSA [14, 15], they are not suitable for daily, at-home use.

We, thus, propose a respiration-posture feedback system as a novel and easy-to-use home health care system. With this system, we hypothesized that regulation of the user's posture stimulates mechanoreceptors, which then induces vagus nerve activation, unconsciously.

In the following sections, we describe the schema of our respiration-posture feedback system, present the experiment to verify the feasibility of this system and its results, and conclude by discussing the results and limitations of the study.

II. METHOD

A. *Respiration-posture Feedback System*

We developed a respiration-posture feedback system to control subject's respiration. This system comprises a respiration sensor unit, a posture regulation unit, and an interface, as shown in Fig. 2. The respiration sensor unit uses a force-sensing device (FSR400, Interlink Electronics, Inc., USA, [17]) and an electric signal amplifier to convert the movement of the subject's chest that accompanies respiration into an electric signal. The interface (NI USB-6008 DAQ, National Instruments Co., USA, [18]) converts the analogue signal derived by the respiration sensor unit into a digital signal (12-bit resolution, 1000-Hz sampling rate). Using our algorithm (described later), the digital respiration information can be used for the posture regulation unit. Posture is regulated by a rubber air chamber (Fig. 3a) placed under the subject's back and is inflated and deflated by a pair of air pumps (Fig. 3b) (YP-20A, Yasunaga Air Pump Inc., Japan, [19]).

B. *Regulation of Respiration-posture Feedback System*

The challenge of this feedback system is to lengthen and deepen a subject's breathing. To achieve this goal, we introduced posture regulation because physical movement accompanies respiration, and posture, to some extent, affects respiration. We then designed an algorithm in which the inflation and deflation of the air chamber is appropriately regulated as follows: (1) the air chamber is inflated when the subject's respiration is about to reach its peak of inspiration to extend slightly the inspiration time, and on the other hand,

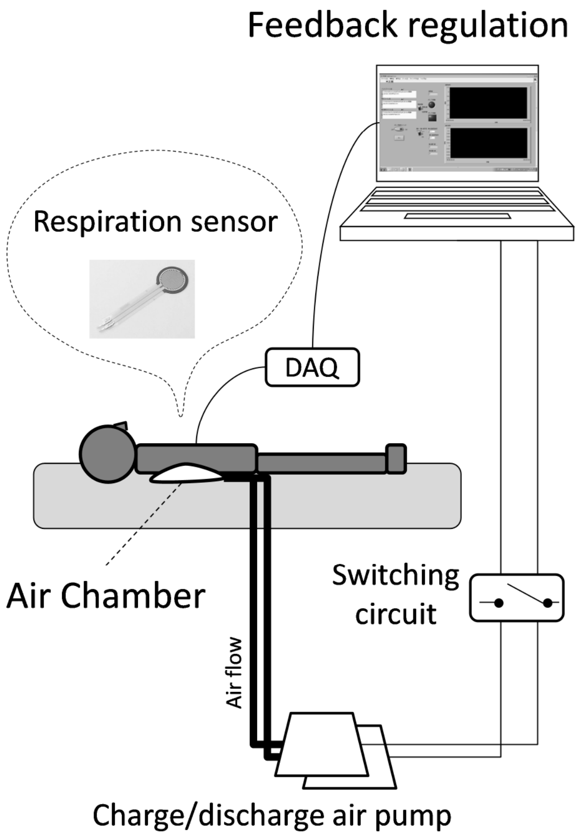

Figure 2. Schematic diagram of our respiration-posture feedback system.

(a)

(b)

Figure 3. (a) Rubber air chamber placed beneath the subject's back, and (b) air pump to inflate and deflate the rubber air chamber.

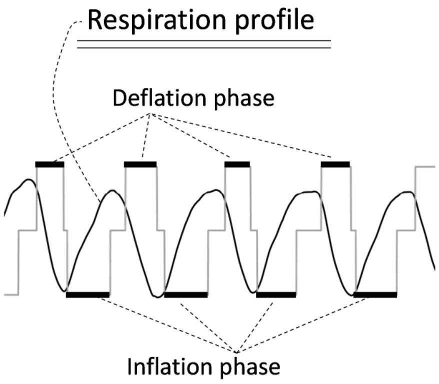

Figure 4. Profile of respiration and the feedback regulated inflation/deflation phases of the air pump.

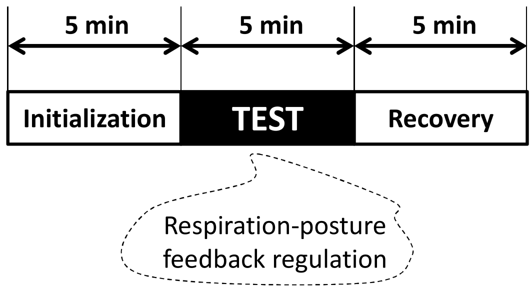

Figure 5. Experiment schedule.

and (2) the chamber is deflated gradually to slow the subject's expiration. It is not necessary for human respiration to be a regular cycle, so this regulation is implemented as a real-time feedback system. The system continuously monitors the subject's respiration via the respiration sensor unit. The signal is differentiated to determine the change in breathing speed during inspiration and overall respiration. By comparing this breathing speed signal with the subject's normal breathing speed profile that is recorded in advance, the system predicts the timing of peak inspiration and respiration during the relevant respiration cycle. The air chamber is inflated or deflated to shift this predicted respiration peak later.

Typical respiration and air pump regulation profiles are shown in Fig. 4. It should be noted that the airflow to the rubber chamber via the pump has a certain time delay, so the On/Off signal of the pump does not imply the time of inflation and deflation. Moreover, the inflation of the rubber chamber is limited to avoid placing too much pressure on the subject's back.

The regulation algorithm described here was developed using a visual programming language (LabVIEW, National Instruments Co., USA, [18]). We then conducted an experiment to confirm the effectiveness of the feedback system.

C. *Experiment*

Four male undergraduate students (age, 20–22 years) voluntarily participated in the experiment. After electrodes for obtaining the electrocardiogram (ECG, the heart beat signal) and the respiratory sensor unit were attached, the subjects were instructed to lie on a bed with the posture regulation unit (the rubber air chamber) placed under their back. As shown in Fig. 5, the experiment consists of a 5-min initialization period, followed by the regulation period, and then a 5-min recovery period (15 min in total). The respiration-posture regulation algorithm functioned only during the target period. There was no regulation at all during the initialization and recovery periods.

Subjects were instructed to stay calm and relax on the bed for the entire 15-min period, and were informed that the air chamber would be inflated and deflated during the middle of the experimental period. However, they were not told in advance how the chamber was regulated.

The experiment was conducted in the afternoon in an environmentally controlled room.

III. RESULTS

Fig. 6a and 6b shows the results of the peak-to-peak interval and the amplitude of the respiration, respectively. It should be noted that the amplitude in Fig. 6b is shown in the form of an electric potential observed by the sensor unit of our system; it proportionally increases as the chest circumference increases. As these figures show, the peak-to-peak interval and the amplitude of the subjects' breathing lengthened and increased in magnitude, respectively, during the target period compared with initialization and recovery periods. This indicates that the subjects' respiration was slowed and deepened using our system, as we expected.

Fig. 7a shows the results of the heart rate. The heart rate declined during the period of regulated respiration compared with the initialization and recovery periods. The frequency component analysis of the heart rate variability (HRV) was also performed. Fig. 7b shows the results of the high-frequency component. The high-frequency component (range, 0.15–0.40 Hz) of the variation in the peak-to-peak interval of the heart beat in a time series, called the HRV, represents the activation of the heart-related parasympathetic nervous system [20, 21]. The vagus nerve works to slow the heart beat and increase the variation in heart beat intervals, called respiratory arrhythmia. Therefore, these heart beat profiles imply the increment of vagus nerve activity during respiration regulated by our respiration-posture feedback system.

Fig. 8 shows the ratios of the test period over the initialization and recovery periods. Although a decline in the heart rate was not observed for all subjects, a significant change in the respiration and the vagus nerve activation was observed.

With regard to subjective scoring, no subject reported any discomfort with the air chamber placed under his back.

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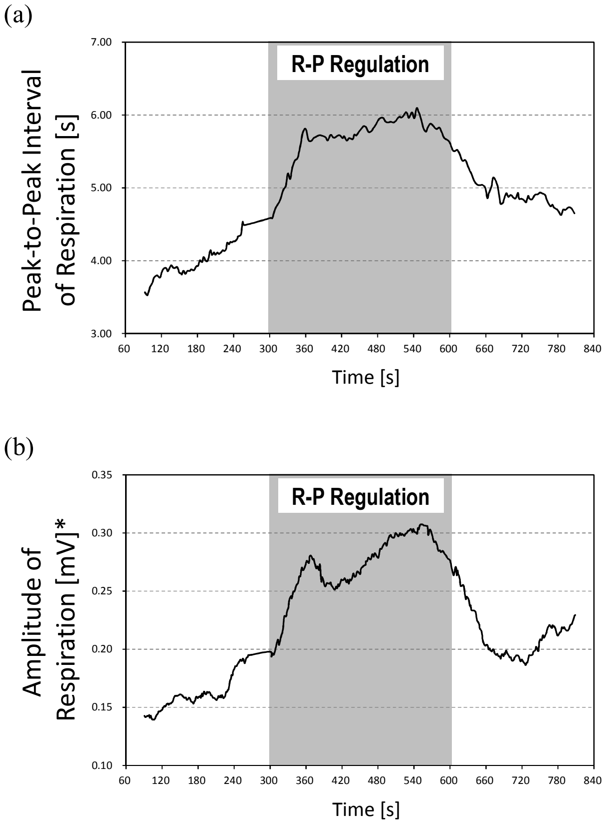

Figure 6. Profile of (a) peak-to-peak interval and (b) amplitude of respiration, respectively. The amplitude is shown in the form of electric potential measured by the sensor unit of our system.

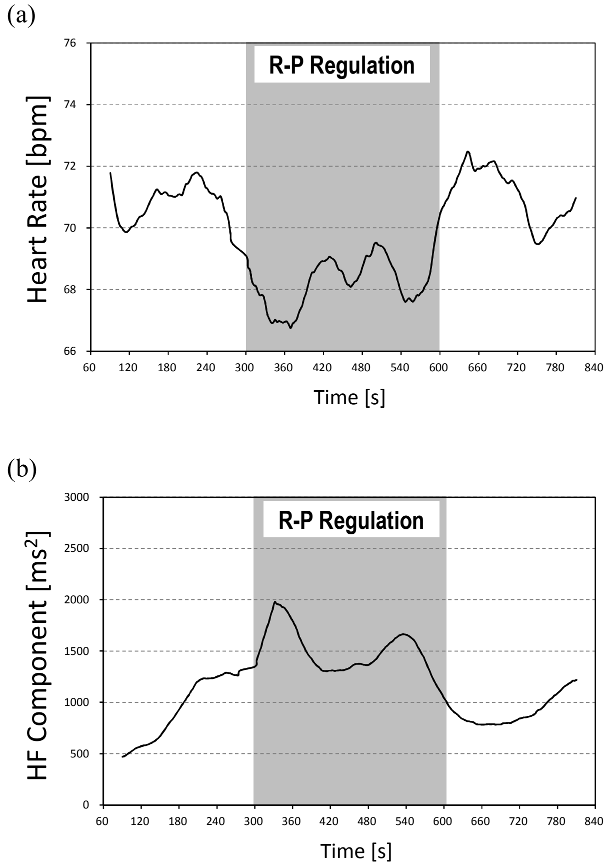

Figure 7. Profile of (a) heart rate and (b) high-frequency component of the heart rate, respectively.

The subjects were not aware of the feedback regulation of the system.

IV. DISCUSSION

The aim of this study was to test the plausibility of our respiration-posture feedback system for controlling a subject's respiration, and, in turn, the accompanying vagus nerve activation. By regulating the inflation and deflation of the rubber air chamber in relation to inspiration and expiration peak timing, the subject's breathing was lengthened and deepened, as we expected. Moreover, the heat rate and its variability profile indicated that the parasympathetic nervous system was activated simultaneously. Therefore, it is suggested that respiration-posture feedback regulation could affect not only breathing but also human parasympathetic nervous system activity.

The parasympathetic nervous system is a prominent system of afferent nerves in the body, and conveys and aggregates the internal states of the entire body to the brain stem. Vagus Nerve Stimulation (VNS) technology, for example, employs this afferent property to stimulate the brain of a patient with symptoms of epilepsy. This is accomplished, not by stimulating the brain itself, but by stimulating the patient's vagus nerve using an electrical device implemented in the neck [22, 23]. However, it has been reported that VNS could have a side effect of the symptoms of apnoea syndrome, a pathological respiration disturbance [24]. This comes from the wide and complex network of the parasympathetic nervous system in the body, and it represents the risk of direct electrical stimulation. In contrast, our system controls the respiration, which is also closely related to parasympathetic nervous system activation, and thus stimulates the vagus nerve indirectly. Therefore, our system might stimulate the brain stem indirectly via parasympathetic nervous system activation. To verify this theory, further study is needed on a variety of physiological functions. For example, in the endocrine system, secretion of stress-related hormones [25, 26] using respiratory control is envisioned.

Implementing our respiratory control system as an ambient system for promoting daily health care at home would have an advantage compared with yoga, meditation, or conventional biofeedback training introducing breathing control. Respiration is controlled both voluntarily and

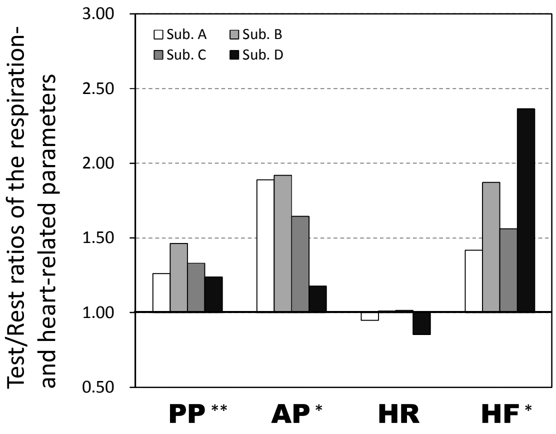

Figure 8. Ratios of the test period over the initialization+recovery period. PP, AP, HR, and HF represent peak-to-peak interval of respiration, amplitude of the respiration, heart rate, and high-frequency component of the heart rate variability, respectively. ** and * represent statistical significance by the *t*-test at $p < 0.01$ and $p < 0.05$, respectively.

involuntarily. Individuals use these relaxation activities to control their breathing by voluntary ventilation, so it requires a sufficient effort and higher concentration to maintain ideal breathing. In contrast, our system targets controlling involuntary ventilation by respiration-posture feedback regulation, which should stimulate mechanoreceptors in the body that sense the change in the air pressure and induce a variety of reflex responses needed to maintain respiration involuntarily. The user would achieve breathing control with less conscious effort, and for a longer time.

A recent population-based sleep study reported that approximately 20% of business men at a company had at least one symptom of severe or moderate OSA, and that the severity of OSA is related to metabolic syndrome [27]. A direct airflow apparatus such as CPAP or ASV is not practical for installation in a large number of patients' and/or pre-patients' homes. In contrast, because our system is a real-time feedback system that monitors the subject's respiration continuously, it could easily detect OSA and adequately inflate or deflate the air chamber to change posture and stimulate recovery from apnoea. Therefore, by developing our system, it could contribute to the field of public health and preventive medicine at both the clinic and at home.

The limitations of our study are the small number of subjects, the use of the same air chamber and its regulation algorithm for subjects with different physical attributes, and the use of a wired respiration sensor. These limitations should be improved in future studies.

V. CONCLUSION

Our respiration-posture feedback system successfully lengthened and deepened subjects' respiration, which implied vagus nerve activation.

The number of health care devices used at home is increasing, many of which can be interconnected via a wireless network [28]. Thus, the integration of biomedical engineering and information and communication technology for home health care would be an important and future direction for an ambient system, of which our system could be a part.

REFERENCES

[1] A. Solanky, "Respiration biofeedback assisted controlled breathing training to enhance shooting performance," Br. J. Sports. Med., vol. 44, 2010, pp. i27-i28.

[2] A. P. Sutarto, M. N. Wahab, and N. M. Zin, "Resonant breathing biofeedback training for stress reduction among manufacturing operators," Int. J. Occup. Saf. Ergon., vol. 14, no. 4, 2012, pp. 549-561.

[3] W. Wu, Y. Gil, and J. Lee, "Combination of wearable multi-biosensor platform and resonance frequency training for stress management of the unemployed population," Sensors (Basel), vol. 12, no. 10, 2012, pp. 13225-13248.

[4] Y. H. Su, J. J. Luh, H. I. Chen, C. C. Lin, M. J. Liao, and H. S. Chen,, "Effects of using relaxation breathing training to reduce music performance anxiety in 3rd to 6th graders," Med. Probl. Perform. Art, vol. 25, no. 2, 2010, pp. 82-86.

[5] Q. A. Morarend, M. L. Spector, D. V. Dawson, S. H. Clark, and D. C. Holmes, "The use of a respiratory rate biofeedback device to reduce dental anxiety: an exploratory investigation," Appl. Psychophysiol Biofeedback, vol. 36, no. 2, 2011, pp. 63-70.

[6] I. Bergstrom, S. Seinfeld, J. Arroyo-Palacios, M. Slater, and M. V. Sanchez-Vives, "Using music as a signal for biofeedback," International Journal of Psychophysiology, 2013 [Epub ahead of print].

[7] L. Guan-Zheng, H. Bang-Yu, and W. Lei, "A wearable respiratory biofeedback system based on generalized body sensor network," Telemedicine and e-Health, vol. 17, no. 5, 2011, pp. 348-357.

[8] P. M. Lehrer, E. Vaschillo, and B. Vaschillo, "Resonant frequency biofeedback training to increase cardiac variability: rationale and manual for training," Appl. Psychophysiol Biofeedback, vol. 25, no. 3, 2000, pp. 177-191.

[9] S. Z. Wang, S. Li, X. Y. Xu, G. P. Lin, L. Shao, and Y. Zhao, "Effect of slow abdominal breathing combined with biofeedback on blood pressure and heart rate variability in prehypertension," J. Altern. Complement. Med., vol. 16, no. 10, 2010, pp. 1039-1045.

[10] M. S. Rider, J. Achterberg, G. F. Lawlis, A. Goven, R. Toledo, and J. R. Butler, "Effect of immune system imagery on secretory IgA," Biofeedback Self Regul., vol. 15, no. 4, 1990, pp. 317-333.

[11] R. G. Green and M. J. Green, "Relaxation increases salivary immunoglobulin A1," Psychol. Rep., vol. 61, no. 2, 1987, pp. 623-629.

[12] M. L. Jasnoski and J. Kugler, "Relaxation, imagery, and neuroimmunomodulation," Ann. N. Y. Acad. Sci., vol. 496, 1987, pp. 722-730.

[13] H. K. Yaggi, J. Concato, W. N. Kernan, J. H. Lichtman, L. W. Brass, and V. Mohsenin, "obstructive sleep apnea as a risk factor for stroke and death," N. Engl. J. Med., vol. 353, 2005, pp. 2034-2041.

[14] J. M. Marin, S. J. Carrizo, E. Vicente, and A. G. N. Agusti, "Long-term cardiovascular outcomes in men with obstructive sleep apnoea-hypopnoea with or without treatment with continuous positive airway pressure: an observational study," Lancet, vol. 365, 2005, pp. 1046-1053.

[15] P. C. Hastings, A. Vazir, G. E. Meadows, M. Dayer, P. A. Poole-Wilson, and H. F. McIntyre, "Adaptive servo-ventilation in heart failure patients with sleep apnea: A real world study," International Journal of Cardiology, vol. 139, 2010, pp. 17-24.

[16] K. E. Barrett, S. M. Barman, S. Boitano, and H. Brooks, Ganong's Review of Medical Physiology, 24th ed., McGraw-Hill Medical, 2012.

[17] Interlink Electronics, Inc., http://www.interlinkelectronics.com [retrieved: September, 2013]

[18] National Instruments Co., http://www.ni.com/ retrieved: September, 2013]

[19] Yasunaga Air Pump Inc., http://www.fine-yasunaga.co.jp [retrieved: September, 2013]

[20] G. G. Berntson, J. T. Bigger Jr, D. L. Eckberg, P. Grossman, P. G. Kaufmann, and M. Malik, "Heart rate variability: Origins, methods, and interpretive caveats," Psychophysiology, vol. 34, 1997, pp. 623-648.

[21] B. Pomeranz, R. J. Macaulay, M. A. Caudill, I. Kutz, D. Adam, and D. Gordon, "Assessment of autonomic functions in human by heart rate spectral analysis," Am. J. Physiol., vol. 248, no. 1, 1985, pp. 151-153.

[22] S. Ogbonnaya and C. Kaliaperumal, "Vagal nerve stimulator: Evolving trends," Journal of Natural Science, Biology and Medicine, vol. 4, no. 1, 2013, pp. 8-13.

[23] M. Bao, J. Zhou, and G. Luan, "Treatment of drug-resistant epilepsy with vagus nerve stimulation . review of 45 cases," Chin. Med. J., vol. 124, no. 24, 2011, pp. 4184-4188.

[24] F. Parhizgar, K. Nugent, and R. Raj, "obstructive sleep apnea and respiratory complications associated with vagus nerve stimulators," Journal of Clinical Sleep Medicine, vol. 7, no. 4, 2011, pp. 401-407.

[25] D. H. Hellhammer, S. Wüst, and B. M. Kudielka, "Salivary cortisol as a biomarker in stress research," Psychoneuroendocrinology, vol. 34, no. 2, 2009, pp. 163-171.

[26] S. S. Dickerson and M. E. Kemeny, "Acute stressors and cortisol responses: A theoretical integration and synthesis of laboratory research," Psychological Bulletin, vol. 30, no. 3, 2004, pp. 335-391.

[27] K. Chin, T. Oga, K. Takahashi, M. Takegami, Y. Nakayama-Ashida, and T. Wakamura, "Associations between obstructive sleep apnea, metabolic syndrome, and sleep duration, as measured with an actigraph, in an urban male working population in Japan," Sleep, vol. 31, no. 1, 2010, pp. 89-95.

[28] Continua® Health Alliance, http://www.continuaalliance.org [retrieved: July, 2013]