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Wearable ECG Recorder with Acceleration Sensors for Monitoring Daily Stress*: Office Work Simulation Study

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Abstract— **A small and light-weight wearable electrocardiograph (ECG) equipment with a tri-axis accelerometer (x, y and z-axis) was developed for prolonged monitoring of everyday stress. It consists of an amplifier, a microcomputer with an AD converter, a triaxial accelerometer, and a memory card. Four parameters can be sampled at 1 kHz for more than 24 h and a maximum of 27 h with a default battery and a memory card of one giga byte (1 GB). Off-line data processing includes motion information along three axes and autonomic nervous system (ANS) activity bispectral analysis and the tone-entropy method (T-E method) from HRV data. The availability of the system was tested through simulated office work and three-day monitoring by replacing the battery and the memory card every 24 h. Both short-term and circadian rhythms of ANS activity were clearly observed. In addition, sympathetic nervous activities gradually increased from the second to the third day. The experimental data presented verifies the functionality of the proposed system.**

I. Introduction

In Japan, according to the government's Comprehensive Survey of Living Conditions (2005), 48.2% of those surveyed had trouble and stress caused by everyday life or work. For such chronic stresses, it is important and beneficial to monitor the level of stress because it is the cause of lifestyle-related and/or mental diseases. There are two non-invasive approaches to measure and evaluate chronic stresses. One is the measurement of plasma catecholamine and cortisol as stress biomarkers [1]. Although such biomarkers can easily be measured by using a simple instrument, continuous sampling of such biomarkers is not realistic. In addition, after stress stimulation, a certain time delay from several minutes to several hours occurs, and the time resolution of a stress response is poor because it appears as an integral calculus value a long time before and after stress stimulation [2, 3]. The other non-invasive approach is the measurement of autonomic nervous system (ANS) activity, which is observed by changes such as blood pressure, heartbeat, and temperature [4, 5]. Among them, spectral analysis of heart rate variability (HRV) is the method most frequently used [6, 7, 8].

Recent ECG monitors are small and high performance. Telemetry enables a real-time monitoring of cardiac condition for an alarm [9, 10], and acceleration sensors are used for activity monitoring [9] as well as motion artifact reduction in ECG [11]. Combination of telemetry and accelerometer is also useful for monitoring sleep activity at home [12]. Even one lead wireless ECG monitoring system is available [13]. However, the present work is intended to develop an ECG monitor which can be used by anybody, not only by specialists but also by normal office workers, housewives, etc. For this purpose, the conventional lead system with disposable electrodes is enough and one lead system is not necessarily needed. Though telemetry is another option for ECG recordings, our system is designed for off-line analysis not for real-time analysis. The restricted range of motion because of the radio wave interference with other instruments and the packet lost in an electromagnetic environment with full of unwanted emissions are also of our concern. A matter of prime importance of the present work is that the system is easy to manage for normal people including the replacement of battery and memory card for a long-term monitoring at workplace, home and everywhere.

This paper describes the experimental results of monitoring subject's stress level for three days and demonstrates its validity for assessing the long-term stress response at work, household duties, etc., in everyday life.

II. Stress Monitoring System

A. ECG Recording

Figure 1 shows an electrocardiograph with the case open (left) and closed (right). The body is collapsible and made of plastic. The electrocardiograph is 44 mm long, 58 mm wide and 17 mm thick, and weighs 45 g including a battery and memory card.

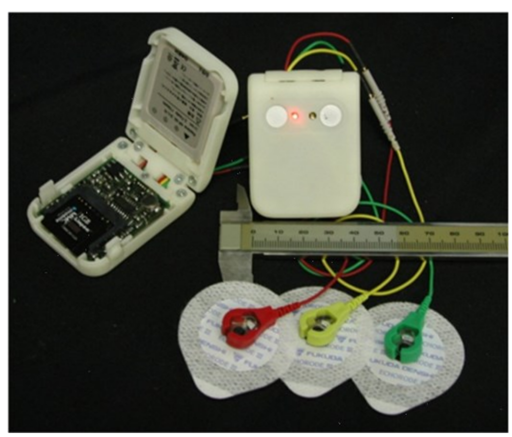

Figure 1. Developed ECG recorder with disposable electrodes. The ECG monitors with the case open (left) and closed (right). The body is collapsible and made of plastic. The ECG is 44 mm long, 58 mm wide and 17 mm thick, and the weight is 45 g, including a battery and memory card. There are two switches (ON/OFF, START/STOP) and two light emitting diodes (LEDs).

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There are two switches (ON/OFF, START/STOP) and two light emitting diodes (LEDs). The red LED is an operation indicator, and the green LED is a detection indicator. The green LED flashes when each R-wave is detected. The memory card and battery can be easily replaced within 15 seconds with just a little practice. A printed-circuit board has a four-layer structure which sandwiches the power source and ground layers. ECG and acceleration data are recorded at a 1 kHz sampling rate for more than 24 h (up to 27 h). After measurement, the memory card is dismounted, and the data are transferred to a personal computer (PC) for signal processing (off-line analysis).

B. Signal Processing

After measurement, the memory card is removed from the electrocardiograph and is set into a card reader which is connected to a PC (Pentium Dual Core, 2 GHz). Transferred data are converted from binary to text data (CSV format). The ECG is processed for R wave detection and HRV spectrum/T-E analyses. MATLAB (2007b) was used for the analysis. Details of the stable R-wave detection are given elsewhere [14].

A heart rate variability spectrum was calculated with a serial FFT (Fast Fourier Transform) using a Hanning window. A conventional LF/HF power ratio was used as an index of the sympathovagal valance [6]. Frequency ranges are as follows: LF = 0.04 - 0.15 Hz, HF = 0.15 - 0.40 Hz. RRI data are re-sampled at 4 Hz after spline interpolation. A ratio of HF/All (All=LF+HF) was used as an index of parasympathetic activity. The data points for FFT were 512 points (128 sec) and the FFT range was shifted 240 points (60 sec) over entire data. The length of data points for FFT can be set to any integer in this algorithm.

Tone-Entropy analysis was also used for the evaluation of cardiac stress level. The methodology is described in detail elsewhere [15, 16]. In brief, obtained RRIs (heart periods) are transformed into a percentage index time series (PI time series), and tone is defined as:

$$\text{Tone} = \sum \text{PI}(n) / N \quad (1)$$

where n is a serial number of heart period and N the total number of PI terms. Entropy is defined as the PI probability distribution based on information theory:

$$\text{Entropy} = -\sum p(i)\log 2p(i) \quad (2)$$

where p(i) is the probability that PI(n) has a value in the range of $i \leq \text{PI}(n) < i+1$. Tone is an index of the sympathovagal balance and entropy an index of total ANS activity. Larger entropy seems to indicate a more relaxed state of heart and circulatory function.

III. Experimental Methods

Subjects were two healthy male college students (subject B and C, 23.5 ± 0.5 years) used for an office work simulation and a long-term monitoring experiment. The two subjects were requested to abstain from drinking, smoking, or taking drugs, including caffeine, during experiments. The aim and details of this experiment were explained to the subjects, and they provided written informed consent in protocols approved by the ethics committees of University of Shizuoka.

On the first day (Day-1), subjects were given the operating instructions of the ECG recorder and led a normal life (not office work). Monitoring was started from 11:30 a.m. only on Day-1. On the second (Day-2) and third day (Day-3), they were given the PC-related tasks (data input) as a simulated office work from 9:00 to 17:00, except for lunchtime. They took a 10-min rest every hour. An electrocardiogram and 3-axis acceleration data were recorded for 3 days except while taking a bath. Memory cards and batteries were replaced every 24 h. The electrocardiograph was fixed with tape to the chest. ECG electrodes were placed on the chest wall according to the NASA induction method (Fig. 2). Disposable ECG electrodes were used.

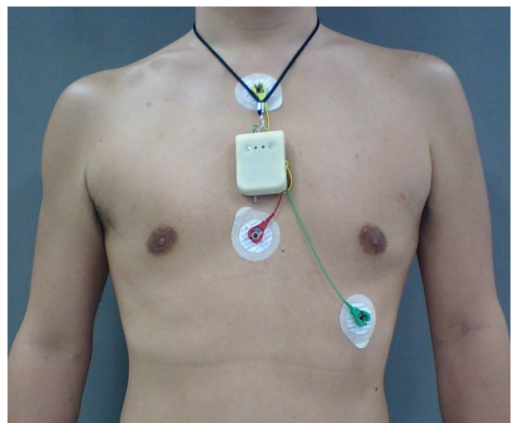


Figure 2. ECG recorder and electrode placement.

The monitor was either taped to the chest wall or placed in the subject's breast pocket. Electrodes were arranged according to the NASA method.

IV. Results and Discussion

Figure 3 shows 24-h data on Day-3 in subject C. Fig. 3 (a) shows the time series data of RRI and sympathetic nervous activity (LF/HF) for 24 h. LF/HF was averaged every 15 min. Fig. 3 (b) shows RRI and LF/HF variations for 3 h in the morning during work (typing task). Fig. 3 (c) shows raw ECG data and three accelerations in the evening and (d) during sleeping at around 3:00. A waveform of acceleration data represents the pattern of a subject's movement or posture. The rhythmical variations of three acceleration signals in Fig. 3 (c) show that the subject was walking at this time of the day. The acceleration data in Fig. 3 (d) show that the subject was sleeping, but was turning over in bed. The bold line in Fig. 3 (a) shows a slow change of sympathetic nervous activity, which shows a clear circadian rhythm, lowest in the early morning (3:00–6:00) and highest in the late afternoon (14:00–18:00). Fig. 3 (b) clearly shows rising tension during typing task and easing tension during rest. No problems were reported by the subject about the recording device during the experiment.

Figure 4 shows the result of a 24-h recording for three days in subject C. The uppermost part of the figure is RRI, the second and the third parts are tone and entropy, the fourth and

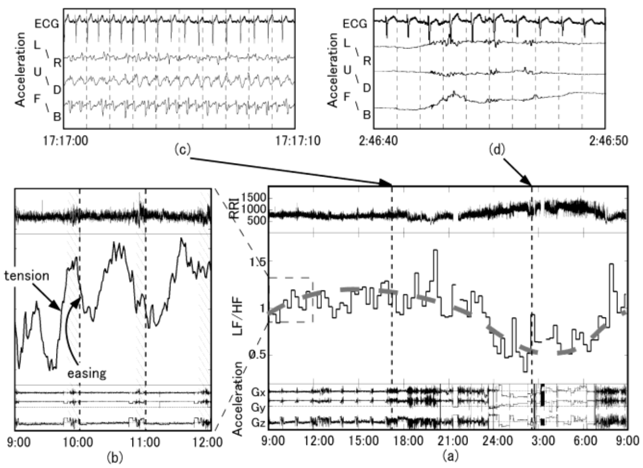
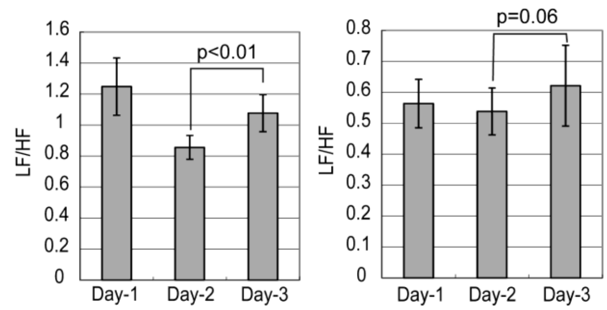


Figure 3. One-day time series data of RRI, acceleration and sympathetic nervous activity.

(a) 24 h variations of RRI, LF/HF and acceleration signals. LF/HF was lower at night and higher during the day. (b) Enlarged variation of LF/HF in the morning. An increase and decrease in LF/HF were clearly observed in response to typing work and break. (c) ECG and acceleration signals when the subject was walking. (d) ECG and acceleration signals during sleeping. A roll over was observed in the acceleration signals.

fifth parts are sympathovagal balance (LF/HF) and parasympathetic (HF/All) indexes, and the lowermost part is acceleration signals (Gx: left-right, Gy: ups-downs, Gz: forward-back). The subject took a bath at around 21:00 (Day-1), 22:00 (Day-2), 21:00 (Day-3) and changed the battery and the memory card. Rough circadian rhythms were observed in the variations of RRI, T-E and spectral ANS activity (LF/HF and HF/ALL). Sympathetic activity during sleep hours was lower than during the daytime while parasympathetic activity was higher with a constant churn. We think that these results demonstrate that the HRV analysis (LF/HF or HF/ALL) reflects the broad outline of stress level of the subject. An increasing number of roll-overs was observed at around 3 a.m. (Day-3) and this may be the cause of decreased parasympathetic activity. The increase in sympathetic activity most likely precedes the appearance of the roll over. Entropy was higher (almost 5 bits) during sleeping and lower (about 2 bits) during the day. Entropy dips were observed for three days during morning commute (around 7:30). The other dips around 19:30 for Day-1, 22:00 for Day-2 and 20:00 for Day-3 seemed to show the subject's evening commute.

Figure 5 shows the comparison of LF/HF values among three days. The subject was not assigned any task on Day-1, and he was just wandering around for the confirmation of the system operation. Sympathetic nervous activities on Day-3 were higher than those on Day-2 in office hours ($p<0.01$, paired-t). Though there was no significance, LF/HF during sleep hours had a tendency to increase on Day-3 compared to Day-2 ($p=0.06$). Entropies on Day-3 were lower than those on Day-2 both in office hours ($p<0.05$) and in sleep hours ($p<0.05$). This suggests that fatigue or stress was worsened on Day-3 because of repeated typing tasks. Significant test on Day-1 was not performed because of the difference of recorded data points.



(a) Office hours (b) Sleep hours

Figure 5. Comparison of sympathetic nervous activity.

Significant difference was observed between Day-2 and Day-3 in office hours (**$p<0.01$) while there was no difference in sleep hours ($p=0.06$). Statistical test was not performed on Day-1 because of the difference of recorded data points.

Subjects who participated in the 3-day experiments reported no problems in handling the monitor including changing the battery and memory card. The time required to replace the battery and memory card, and to start measurement was almost within 30 sec at worst, but usually 15 sec with just a little practice. The ECG recorder was either secured on the chest wall with tape or placed in a breast pocket. Since it is

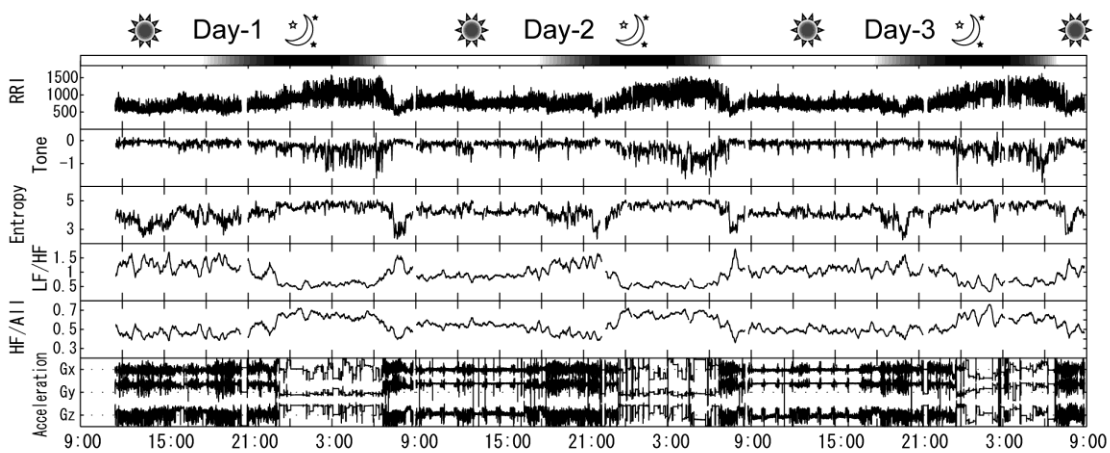


Figure 4. An example of three-day monitoring.

From the top, RRI, tone, entropy, LF/HF, HF/ALL, and three acceleration signals are shown. The subject changed the battery and memory card when taking a bath. Rough circadian rhythm was observed on each day. Sympathetic activity was lower during sleep buy higher during the day. An increase in the number of roll overs was observed at round 3 a.m. (Day-3) and this may be the cause of the decreased parasympathetic activity at that moment.

compatible with the activities of general daily life, we believe that the developed monitor can be used by all people such as office workers, shift workers (drivers, factory workers, medical staff, etc.), housewives, etc. Three acceleration signals successfully indicated the subjects' movements and postures during experiments. Especially, it was interesting to observe that the increase in sympathovagal balance index (LF/HF) tended to precede the roll-overs during sleep hours. This relationship remains to be investigated.

Two methods were used for HRV analysis: one is a conventional spectral method [6] and the other is the T-E method [15, 16]. Although both LF/HF and entropy varied in much the same fashion throughout the whole experiment, they differed in their details. At the beginning of movement, a rapid increase in LF/HF was observed which tended to decrease soon even though the subject was still walking (Fig.7, Day-3, around 19:00). The former is suitable for observing the rapid variation of ANS while the latter for a prolonged, stable variation. Therefore these two different methods seemed to be complementary and are needed for accurate monitoring of physical and/or psychological stresses of everyday life. The level of the sympathetic nervous activity in the daytime on Day-1 is the highest because the subject wandered around. Entropy change also indicates the less relaxed state of heart and circulatory function on Day-3 compared to Day-2. From the above, we believe that the developed system is useful for monitoring daily stress level for a prolonged period of time, and it can be used by everyone and everywhere.

V. Conclusion

A wearable electrocardiograph with a tri-axis accelerometer and its analysis program for monitoring ANS changes and body movements for an extended period of time were developed. The availability of the system was demonstrated by a consecutive three-day experiment. Clinical applications for monitoring the pathological conditions of vertigo patients with the present system are in progress.

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