Investigation of the influence of swallowing, coughing, and vocalization on heart rate variability with respiratory-phase domain analysis

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Abstract-- **In this study, external influence on heart rate variability was investigated using the respiratory-phase domain analysis. Swallowing, coughing, and vocalization (conversation and reading aloud) were adopted as external influences. It was found that swallowing induces tachycardia that recovers within one respiration. Coughing also induces tachycardia but it doesn't recover within one respiration. Vocalization shortens the mean RRI, which is caused by the activity. The changing respiratory pattern by vocalization had no statistical significant influence on amplitude of RSA.**

Keywords--**Heart rate variability, Respiratory phase, Respiratory sinus arrhythmia**

I. Introduction

Heart rate variability (HRV) has been well studied because of its clinical and physiological importance [1]. We previously proposed a method to extract respiratory sinus arrhythmia (RSA), which is known as an index of cardiac vagal activity [1-3], as a waveform in the respiratory-phase domain [4,5]. Amplitude of RSA by this method has the interchangeability to commonly used power of 0.15-0.5Hz, by frequency analysis. By selecting the data that correctly reflect vagal activity breath-by-breath, accuracy of estimated vagal activity rises in theory and it was confirmed by the mental arithmetic experiment [5].

Measurement of RSA has also been used in the field of human engineering and it is expected to evaluate the difficulty of task, to optimize the working environment, and to improve health-care system. However, for the measurement of RSA in the real situation; such as deskwork, debating, and relaxation; some other external influences disguise the results. Consequently, it is important to investigate the external influence on HRV and extracted RSA. Generally for the investigation of how HRV reflects external force, time separated experiments are assigned and their results are compared. But, there is a possibility that condition differ between the experiments. Moreover, the short-time variability, induced by event, cannot be evaluated because it is hidden by RSA, which is the dominant variability in short time.

The objectives of this paper were (a) to focus on swallowing, coughing, and vocalization as external influence because these behaviors are observed normally even in sitting-rest condition and they can be detected by the motion of throat, (b) to analyze their influence on HRV in the respiratory-phase domain by extracting the stable waveform of RSA and comparing them with that of normal respiration.

II. Methods

A. Experimental procedures

We obtained RR-intervals (RRI) of the electro-cardiogram (AC-601, Nihon-Koden) by a sampling frequency of 1kHz, and instantaneous lung volume (ILV) by sampling elastic chest band (TR-755T, Nihon-Koden) at the rate of 100Hz. Further, we put the accelerometer (8304B2, Kistler) on the larynx and sampled the motion of the laryngeal prominence to detect the time of swallowing, coughing, and vocalization.

Five experiments were performed under rest and sitting position, two were for swallowing, one was for coughing, and remaining two were for vocalization. In Exp.1-1, swallowing was allowed to be performed at free timing by the subject, while in Exp.1-2, it was also allowed at free timing but only between inspiration and expiration. In Exp.2, coughing was made once in a minute on purpose. In Exp.3-1 and 3-2, vocalization was performed in two 90s sessions (110-200s and 290-380s). For vocalization, reading aloud and conversation was performed in Exp.3-1 and 3-2, respectively. Both of Exp.3-1 and 3-2 were arranged symmetrically against time in order to cancel linear trend of RRI and RSA. Experimental protocols and number of subjects are summed up in Table 1.

B. Signal processing algorithm

Fig.1 shows the diagram of signal processing algorithm. First, the data of RRI was interpolated by the derivative of cubic spline interpolation (DCSI) [6] according to the following equation:

$$M(t_k) = \int_{t_0}^{t_k} m(t)dt = k\,, \tag{1}$$

where $t_k (k = 0,1,2,..., n)$ are times at which heartbeats were observed and $m(t)$ is the instantaneous heart rate obtained from the first derivative of the interpolated $M(t_k)$ using a cubic spline function. Here, we used $1/m(t)$ as instantaneous RRI. An instantaneous respiratory phase was estimated by analytic signal by using Hilbert transform [7] after filtering ILV. ILV was passed by a linear-phase FIR band-pass filter whose pass-band was 0.15-10.0 Hz. Instantaneous RRI was re-sampled in each $\pi/10$ rad of respiratory phase. We set the phase between $\pi/2$ rad and next $\pi/2$ rad as one respiration, which was the same as [5], for whole inspiratory period (i.e. from π rad to 2π rad) and induced tachycardia were contained in one respiration. The data were divided into

TABLE I
EXPERIMENTAL PROTOCOLS

Experiment	Experimental condition	Measuring time (s)	Timing	No. of subject
1-1	swallowing	420	free	6
1-2	swallowing after inspiration	420	free (after inspiration)	6
2	coughing	420	once in a minute	7
3-1	reading aloud	490	two 90s sessions	7
3-2	conversation	490	two 90s sessions	7

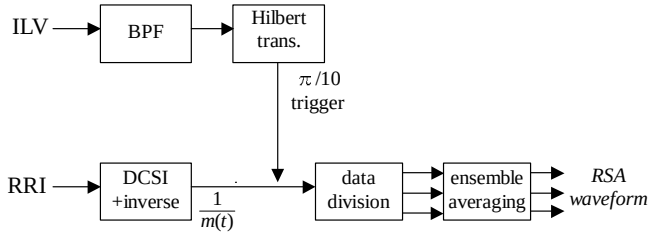

Fig. 1. Diagram of signal processing algorithm

respiration with event occurring, after one respiration of event and normal respiration (in Exp.3-1 and 3-2 next respiration of event was not extracted). After that, in each subsets waveforms of equi-sampled RRI were ensemble averaged in the same phase and stable waveform of RSA was extracted.

In this method, the variability of RSA (which is the largest in the short-time fluctuation of HRV) can be separated and the other effects, such as Mayer wave related sinus arrhythmia and low frequency fluctuation, can be minimized by ensemble averaging. By the random event occurring it is expected that low frequency trend of RRI and RSA can be further minimized. In addition, it is also the merit of this signal processing that measurements were performed in natural conditions that didn't need paced breathing.

For the statistical analysis, mean RRI and amplitude of RSA were calculated in each waveform. Amplitude of RSA was the subtraction of maximum in the RSA waveform from the minimum. Statistical difference was tested by repeated measures ANOVA with post hoc test of Bonferroni correction in Exp.1 and 2, and paired t-test in Exp.3. In all experiments, both of first and last 20s were eliminated by filtering, and the remaining part was used for analysis.

III. RESULTS

A. Influence of swallowing

In Exp.1-1, all swallowing was observed after the expiration (i.e. around π rad in respiratory phase). The number of swallowing of Exp.1-1 and 1-2 were 6.2±1.5 and 8.0±4.0, respectively. Physiologically, swallowing generates sudden change of intrathoracic pressure. Fig.2 shows the results of Exp.1-1. By RSA waveform,

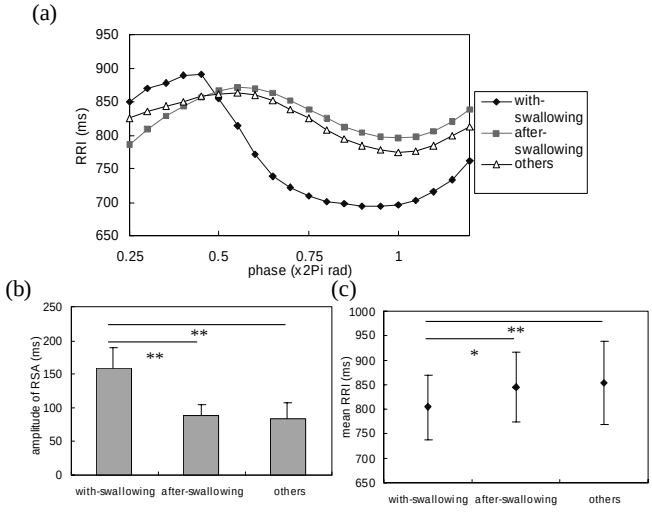

Fig. 2. Results of Exp.1-1. (a) RSA waveforms of the typical subject, (b) amplitude of RSA of all subjects, (c) mean RRI of all subjects. Data are mean values with error bar of standard deviation. ** indicates $P<0.01$ and * indicates $P<0.05$

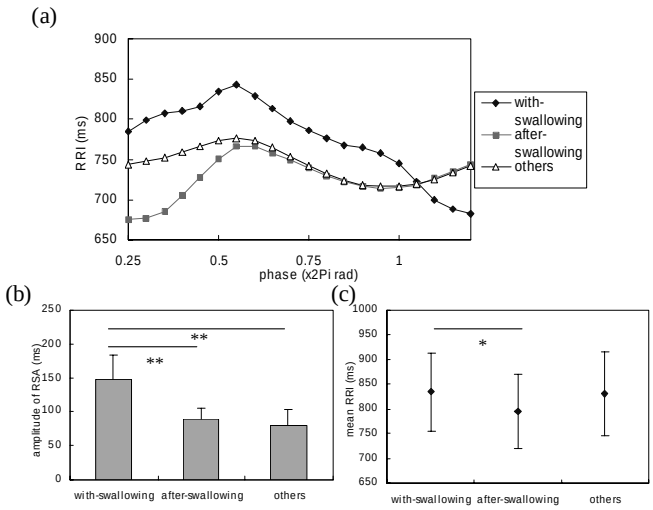

Fig. 3. Results of Exp.1-2. (a) RSA waveforms of the typical subject, (b) amplitude of RSA of all subjects, (c) mean RRI of all subjects. ** indicates $P<0.01$ and * indicates $P<0.05$.

it can be seen that swallowing induced tachycardia and after-swallowing respiration had almost the same waveform as normal respiration. The comparison between the amplitude of RSA with swallowing and that of normal respiration was statistically significant ($P<0.01$). The amplitude of RSA of after-swallowing, however, showed no statistical significant difference when compared with normal respiration (Fig.2(b)). These results show that swallowing caused tachycardia, and that the tachycardia recovered quickly. Mean RRI of with-swallowing respiration had lower value because of tachycardia but that of after-swallowing respiration had non-significant difference from the normal respiration (Fig.2(c)).

Fig.3 shows the results of Exp.1-2. It can be seen that swallowing induced tachycardia around 2π rad in

respiratory phase and it recovered in the after one respiration. Therefore, the same statistical features as Exp.1-1 were observed in the results of RSA amplitude, though the results of mean RRI were different because the influence of tachycardia remained at the beginning of after-swallowing respiration.

B. Influence of coughing

Coughing also generates sudden change of intrathoracic pressure but it associates with strong inspiration and expiration. After coughing, if there were disturbed respirations (such as rapid inspiration) that are considered as the effect of previous coughing, these data were discarded and the first normal respiration was selected as after-coughing respiration. Fig.4 shows the results of Exp.2. Tachycardia caused by rapid inspiration was observed in the RSA waveform of coughing and this tachycardia didn't recover within one respiration. Therefore, mean RRI of after-coughing respiration was shorter than normal respiration (P<0.01). Amplitude of RSA with coughing was large but non-statistically significant because magnitude of coughing differed between individuals.

C. Influence of vocalization

In vocalization, respiration becomes short inspiration and long expiration. Reading aloud continues its state, while conversation has some silent (listening) periods. Figs.5 and 6 show the results of Exp.3-1 and 3-2, respectively. These results were almost the same. Mean RRI of vocalization was shorter than rest condition and statistically significant. However, non-significant difference was found between the amplitude of RSA of vocalization and rest condition. In order to investigate whether the differences appeared in short time transition of vocalizing and silent, the waveform of conversation was divided into speaking and listening, and were compared. Data of one subject, who had almost no listening period, was discarded and data of six subjects were analyzed. Results are shown in Fig.6 (d) and (e). Mean RRI of speaking period was shorter than listening, but statistically difference was non-significant.

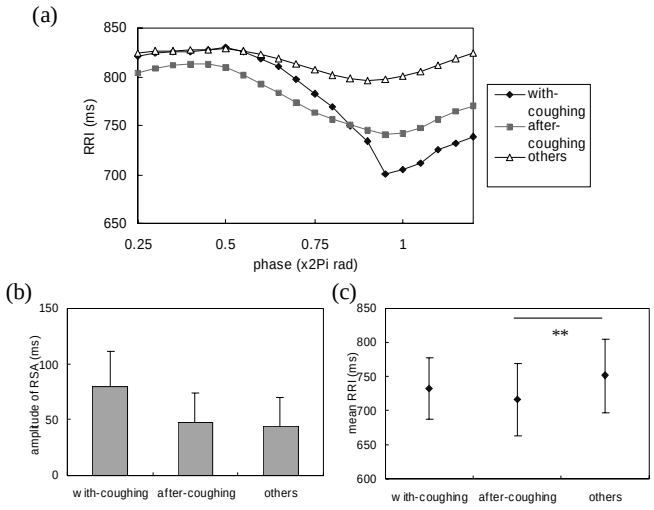

Fig. 4. Results of Exp.2. (a) RSA waveforms of the typical subject, (b) amplitude of RSA of all subjects, (c) mean RRI of all subjects.
** indicates P<0.01.

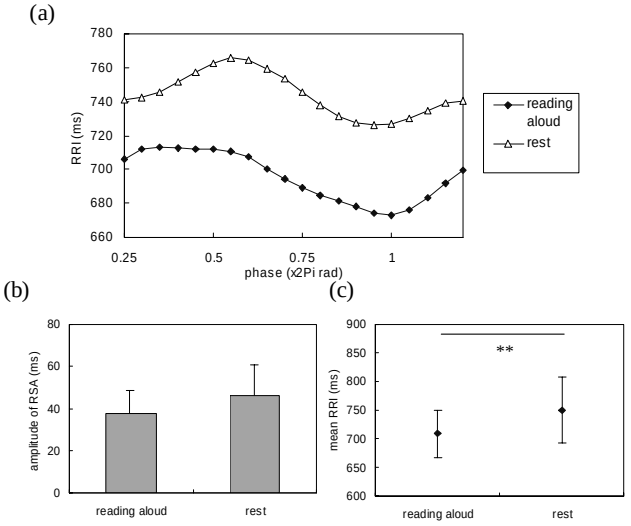

Fig. 5. Results of Exp.3-1. (a) RSA waveforms of the typical subject, (b) amplitude of RSA of all subjects, (c) mean RRI of all subjects.
** indicates P<0.01.

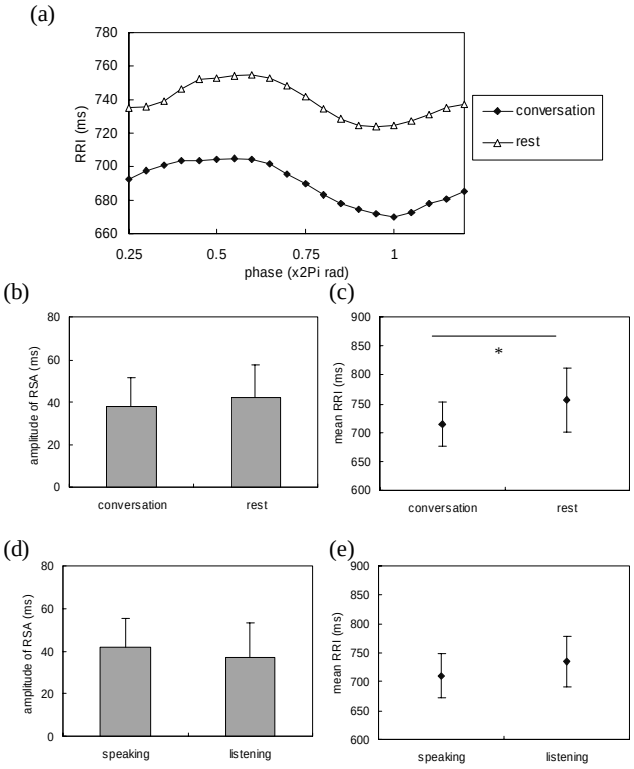

Fig. 6. Results of Exp.3-2. (a) RSA waveforms of the typical subject, (b) amplitude of RSA of all subjects, (c) mean RRI of all subjects, (d) amplitude of RSA of speaking and listening during conversation period, (e) mean RRI of speaking and listening during conversation period.
* indicates P<0.05.

IV. Discussion

In Exp 1-1 and 1-2, we observed swallowing-induced tachycardia that might be caused by the sudden change of intrathoracic pressure. Change of intrathoracic pressure affects venous return and blood pressure, and they change heart rate by Bainbridge reflex and baroreflex, respectively. It is found that this tachycardia recovers within one respiration. Swallowing-induced tachycardia shows rapid change and it disguises the RSA extraction by usual frequency analysis. Coughing also associates sudden change of intrathoracic pressure. However, it needed more strong activity of respiratory organs and that resulted in short mean RRI after-coughing respiration. Short mean RRI was observed in the cases of vocalization. This may reflect the activity of vocalization (i.e. sympathetic nervous activity increases and vagal decreases). Changing the respiratory pattern in vocalization has no statistical significant influence on amplitude of RSA. For the purpose of accurate extraction of RSA amplitude, the respiration with swallowing must be discarded and the respiration with coughing is also needed to be discarded for safety.

Respiratory-phase domain analysis is an effective method for analyzing the external influence on HRV and this method could detect even short time influence, which is hidden by RSA. The same procedure can be adapted for precise investigation of other influences, such as visual or auditory stimulus on HRV by stimulating in the same respiratory phase.

Furthermore, recently the complexity of healthy human HRV has been investigated in the sense of statistical physics and interesting features, such as multifractality [8] and scale invariance property [9], were observed. But the mechanism of these features isn't fully understood. Therefore, investigation of how HRV reflects external force is also important for physical science. For further understanding of these findings it would be necessary to study the effects of swallowing, coughing, and vocalization in detail because they would appear even during constant routine protocol [10]. Results of this study indicate that swallowing may result in strong singularity and coughing may result in relative weak singularity. Conversation also results in relative weak singularity, whose strength depends on its timing and length.

V. Conclusion

We investigated the influence of swallowing, coughing, and vocalization on HRV using respiratory-phase domain analysis. The results show that the swallowing induced rapid tachycardia that recovers quickly, while tachycardia of coughing continues in after-respiration. In the case of vocalization, mean RRI becomes short because of activity, and the amplitude of RSA has no statistically difference. Respiratory pattern of vocalization has no influence on the amplitude of RSA.

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