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Spontaneous Variability Analysis for Characterizing Cardiovascular Responses to Water Ingestion

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Abstract— **This paper examines the effect of water ingestion on the cardiovascular system, utilizing advanced fluctuation analysis. The ingestion of water has been known to significantly raise the blood pressure in subjects with autonomic disorders, resulting in the effect of preventing syncope occurrences. For precise characterization of the effect of water ingestion, head-up tilt experiments at 80 degrees have been conducted for fourteen healthy subjects, ranging in age from 16 to 24. Systolic/ diastolic blood pressures (sBP/dBP), total peripheral resistance index (TRPI) and ECG RR intervals (RRIs) were measured for thirty minutes before and after the isotonic water ingestion of 340 ml. Blood pressures: sBP (2.8%), dBP(3.6%), and TPRI (5.3%) showed statistically significant increases after the water ingestion. RRIs also tended to increase (2.3%), although they were not statistically significant. The data analysis confirmed that the water injection of 340 ml has the acute effect against the syncope occurrences that are mainly due to the increase in TPRI. Then heart rate (HR) spectral analysis with the derivative of the cubic spline interpolation (DCSI) method, and a closed loop system identification technique, which associate fluctuations in sBP and HR, are utilized for further precise characterization of the change in recorded physiologic quantities.**

Keywords—**Water ingestion, autonomic nervous system, fluctuation analysis, heart rate, blood pressure, syncope.**

I. Introduction

Since Lu et al.[1] found that water ingestion enhances the body's ability to prevent occurrences of orthostatic syncope, the effect of this simple practice has been studied in many areas of application[2]-[4]. The effect of hydration in general is not fully understood, nor is its effect on the cardiovascular system[5]. This paper examines the effect of water ingestion on prominent physiologic quantities, continuously recorded Systolic/diastolic blood pressures (sBP/ dBP), total peripheral resistance index (TPRI) and ECG RR intervals (RRIs), taken from the fourteen healthy subjects with no syncope episodes. The head-up tilt experiment at 80 degrees was conducted, and the physiologic quantities measured before and after water ingestion were compared. In addition to comparing standard statistics, heart rate spectra based on the heart rate (HR), reconstruction by derivative of cubic spline interpolation[6] and closed loop properties between sBP and HR obtained from the multivariate autoregressive signal modeling[7] are analyzed. Those methods will be useful tools for precise characterization of the effect of water ingestion on the cardiovascular system.

II. Methods

Experimental protocol and data acquisition

The tilt-up experiment at eighty degrees was conducted for fourteen normal subjects aged sixteen to twenty four with no syncope history. Written informed consent was obtained from each subject. The experiment was conducted in the afternoon, between two and six o'clock, in the room where temperature was kept at twenty two degrees Celsius. Each subject was kept supine for five minutes, and tilted at eighty degrees for thirty minutes. Then the subject returned to supine and was kept for five minutes before the isotonic water (340 ml) was injected. The ionic composite of the water is shown in Table 1. Five minutes after the water ingestion, the subject was tilted again at eighty degrees for another thirty minutes.

Table 1. Ionic composition of the ingested isotonic water

Cation (mEq/*l*)

Na^+	K^+	Ca^{2+}	Mg^{2+}
21	5	1	0.5

Anion (mEq/*l*)

Cl^-	$citrate^{3-}$	$lactase^-$
16.5	10	1

Continuous recording of physiologic quantities, Systolic/ diastolic blood pressures (sBP/dBP), total peripheral resistance index (TPRI) and ECG RR intervals (RRIs), were made for two tilted sessions by a non-invasive monitoring device (CNSystems *Task Force Monitor* TFM-3040).

Data Analysis

In addition to the basic comparison of the mean values of the recorded physiologic quantities, the heart rate spectrum and impulse responses between systolic blood pressure and

the heart rate signals were compared before and after water ingestion. For the HR spectrum analysis, RRIs were first converted to the instantaneous heart rate time series using the derivative of cubic spline interpolation (DCSI) method[6]: The method assumes the ECG pulses are generated by the integrated pulse frequency modulation (IPFM). Hence, setting the time origin at an arbitrary ECG R wave occurrence time, the following equation holds.

$$M(t_n) = \int_0^{t_n} m(t)dt = nT \qquad \ldots(1).$$

Here, $m(t)$ and $M(t)$ are the instantaneous heart rate signal and its integration. t_n is the n -th R wave occurrence time. T is a constant, normally set to one, designating the threshold of the IPFM based pulse generation. Eq. (1) indicates that observed RRIs give unevenly sampled values of $M(t)$. The DCSI method interpolates $M(t_n)s$ by the cubic spline function which yields the continuous estimate of $M(t)$. Then $m(t)$ is estimated, taking the derivative of the interpolating cubic spline function. The method is shown to have high accuracy, especially in the region of high frequency [7]. Hence, the method is appropriate for the heart rate spectrum analysis where the HF power change is crucial. For our spectrum analysis, re-sampled heart rate signals at 4 (Hz) are utilized. The heart rate power spectrum of each tilt-up time is estimated by averaging eight half overlapped 512 point Hamming windowed data. Frequency resolution is 0.0078 Hz. For more precise characterization of the data, a closed loop feedback analysis has been carried out. The Bi-variate autoregressive model identification method[8][9] was applied to the beat-to-beat record of the heart rate sequence, *i.e.* the inverted RRIs, and sBPs. The model hypothesizes the linear mutual dependence between the heart rate $x(n)$ and sBP $y(n)$ as:

$$y(n) = \sum h_{yx}(n-k)x(k) + v_y(n) \qquad \ldots(2)$$

$$x(n) = \sum h_{xy}(n-k)y(k) + v_x(n) \qquad \ldots(3)$$

The conventional parameter estimation method requires that exogenous driving forces $v_x(n)$ and $v_y(n)$ be independent white noise. This is not the case for the heart rate analysis associated with blood pressure changes. However, it has been shown that the estimation is practically accurate even when the driving forces have common 1/*f* components[10], validating the applicability of the method for the analysis of heart rate variability.

III. RESULTS

Table 2 compares the change in average values of simultaneously recorded physiologic quantities. Each thirty minute tilt-up time was divided into three segments of ten minutes. We term each segment as early, mid and late. Table 2(a)-(c) shows the list of average value ± standard error (SE) of the recorded data (inner eight minute period data trimmed at one minute from the beginning and the end of the segment) for each segment. Table 2(a)-(c) shows that sBP, dBP and TPRI tend to increase after water ingestion. The asterisk denotes the designated quantity increased significantly ($p<0.05$) after the water ingestion. It is noted that all but RRI showed significant increases in the *late segment*. The sBP, dBP and TPRI mean values increased respectively by 2.8%, 3.6% and 5.3%. RRIs also had a tendency to increase, alhough it is not statistically significant. The average RRIs increased by 2.3% with *p* value being 0.71 at the late segment.

Table 2 Changes in recorded physiologic quantities after water ingestion

a) Early segment (1-9 min after tilt up)

	Pre Water Ingestion	Post Water Ingestion
sBP (*mmHg*)	112.0 ± 3.01	115.0 ± 3.39
dBP (*mmHg*)	78.79 ± 2.22	82.55 ± 2.69
TPRI ($dyne \cdot \sec \cdot cm^5/m^2$)	2183.7 ± 133.3 *	2286.7 ± 132.4 *
RRI (*ms*)	684.5 ± 19.4	680.7 ± 17.6

b) mid segment (11-19 min after tilt up)

	Pre Water Ingestion	Post Water Ingestion
sBP (*mmHg*)	114.3 ± 2.79	115.0 ± 2.81
dBP (*mmHg*)	79.74 ± 2.03	81.94 ± 2.16
TPRI ($dyne \cdot \sec \cdot cm^5/m^2$)	2207.5 ± 134.8	2278.7 ± 132.3
RRI (*ms*)	661.6 ± 18.6	673.1 ± 21.2

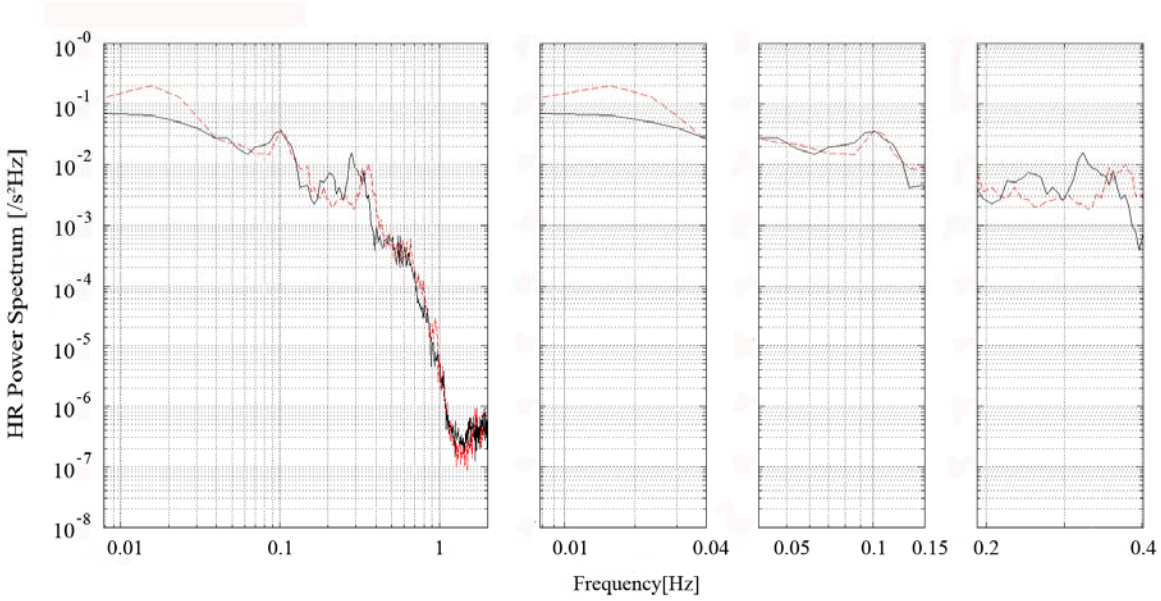
c) late segment (21-29 min after tilt up)

	Pre Water Ingestion	Post Water Ingestion
sBP (*mmHg*)	113.8 ± 2.72 *	117.0 ± 2.55 *
dBP (*mmHg*)	79.83 ± 2.32 *	82.73 ± 2.20 *
TPRI ($dyne \cdot \sec \cdot cm^5/m^2$)	2193.0 ± 140.6 *	2308.6 ± 131.5 *
RRI (*ms*)	641.0 ± 17.3	655.8 ± 24.0

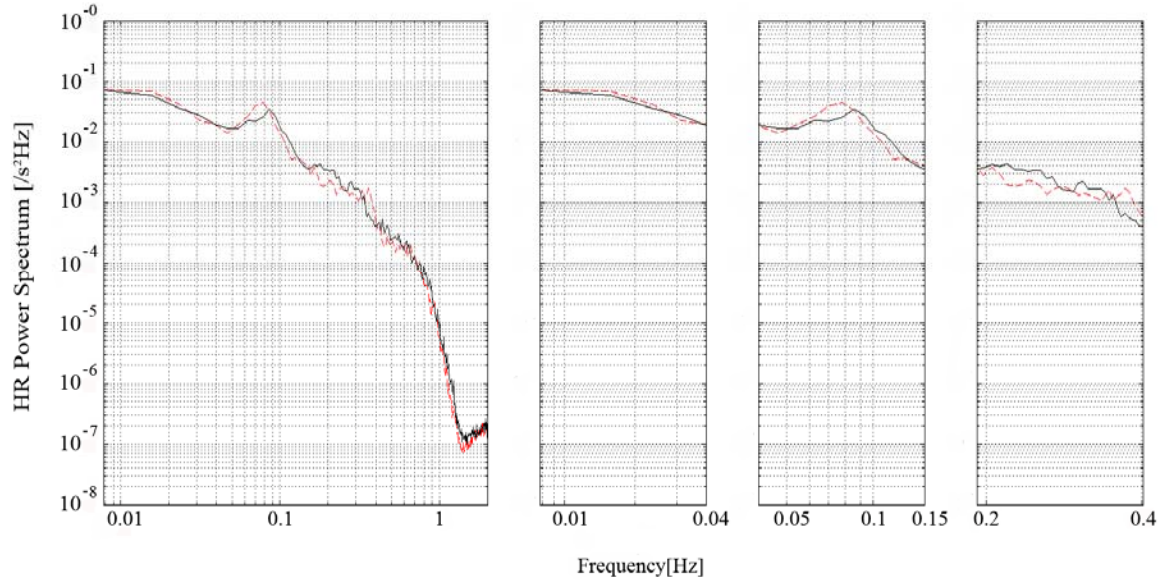
* $p<0.05$

Fig. 3(a)(b) on the next page shows power spectrum changes after water injection. Each figure, from left to right, shows a power spectrum that makes up part of the whole frequency range (0-2Hz): VLF(0-0.04Hz), LF(0.04-0.15Hz), and HF(0.15-0.4Hz). Since the continuous heart rate obtained by the DCSI method is re-sampled at 4Hz, the power spectrum up to 2Hz is estimated and shown. However, the original average heart rate at about 1 Hz implies the meaningful frequency range is restricted up to 0.5 Hz at most. Fig. 3(a) shows an example power spectrum which indicates the prominent enhancement in the LF region. Average power spectrum Fig. 3(b), however, doesn't show such a large power increase in the VLF

frequency region, yet a slight consistent increase presents. The difference may be visible in the linear data plot. It is noted in the average power spectrum, that the peak frequency at 0.1Hz, known to be the blood pressure origin, is shifted to lower frequency. Power enhancement of the high edge frequency region at around 0.4Hz is also visible both in average and in an example power spectrum. Fig. 4(a) and (b) show average impulse responses $h_{yx}(n)$, heart rate to sBP, and $h_{xy}(n)$, sBP to heart rate. The solid dark line and dotted light line, respectively, show impulse responses estimated from data before and after water ingestion. The peak value of the response of blood pressure to the heart rate $h_{yx}(n)$ significantly increased ($p<0.01$), while impulse response of the heart rate to sBP showed no change.

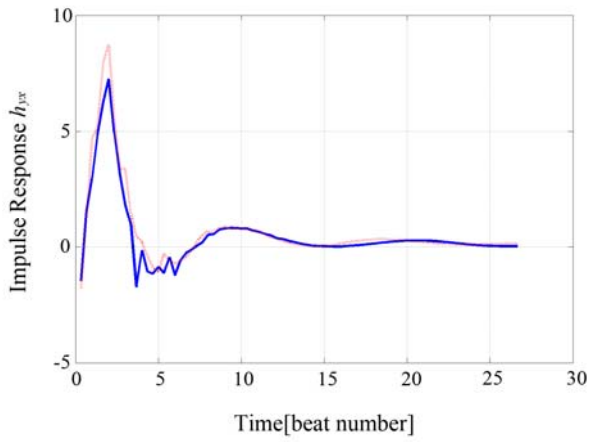


(a) An example showed the prominent power enhancement at VLF(0-0.04Hz) frequency range

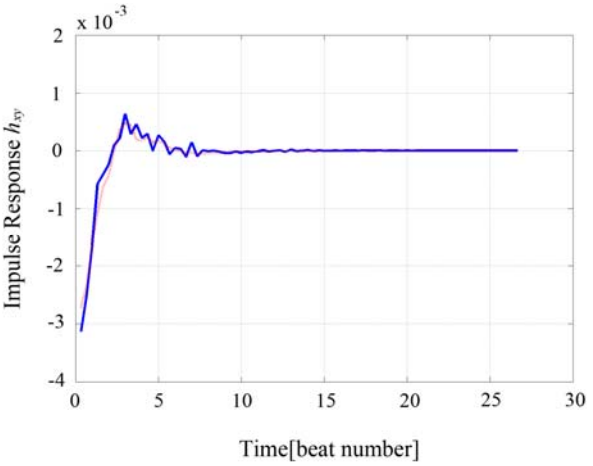


(b) Average heart rate power spectrum

Fig. 3 HR power spectrum before (solid line) and after (dotted line) water ingestion



(a) Impulse response from the heart rate to sBP



(b) Impulse response from the sBP to the heart rate

Fig. 4 Change in feedback characteristics between the heart rate and sBP.

IV. Discussion and Conclusion

The significant increase in TPRI, sBP and dBP due to the water ingestion implies that the water ingestion enhances the ability to prevent the occurrence of syncope. Although a not very significant change in the heart rate spectrum pattern was observed, a noticeable power increase at VLF and the high edge of the HF frequency band may be worth studying further. The DCSI method may be especially useful for examining the fine spectrum pattern at the high edge of the HF frequency region[7]. The peak value increase in the impulse response from the heart rate to sBP may contribute to the decrease in HR, whereas TPRI increases after water ingestion. The feedback analysis presented in this paper may be useful to examine the more precise effect of water ingestion, such as baroreceptor sensitivity changes, in a noninvasive manner. While we haven't seen the change in the impulse response from sBP to heart rate, Brown *et al.* reported the change in baroreceptor sensitivity and HF power enhancement due to the water ingestion[11]. Further research in different experimental conditions, *e.g.* the amount of water ingestion or ionic content of the water, should be conducted to reveal the cause of these discrepancies.

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