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Comparison of Cardiovascular Autonomic Responses in Elderly and Young Males During Head-Out Water Immersion

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Abstract

Objectives. To investigate the cardiovascular autonomic responses to head-out water immersion in thermoneutral water. The effects of immersion levels (neck, chest, navel) and breathing frequencies (4, 6, 10, 15 times/min) were compared with in ambient air and spontaneous breathing as a control.

Methods. Spectral analysis of heart rate variability was recorded in 11 young (mean age 20 ± 1 years) and 11 elderly (mean age 68 ± 6 years) healthy male subjects during water immersion. Modeling was employed to estimate the time course of low-frequency (LF) and high-frequency (HF) power and the ratio of LF to HF power of heart rate variability.

Results. In the young group, stroke volume and cardiac output during navel level water immersion manifested a much greater increase than during chest and neck level water immersion. Systolic blood pressure and total peripheral resistance decreased significantly in response to water immersion. The elderly group, however, showed lesser attenuation of stroke volume and cardiac output. Ectopic arrhythmias occurred in only the elderly. The elderly group showed significantly lower and higher amplitudes of HF and LF/HF components of heart rate variability due to water immersion and breathing frequency changes.

Conclusions. These findings suggest differential changes in cardiovascular autonomic responses between the young and elderly groups. These changes in integrative cardiovascular autonomic responses may account for the increased risk of ectopic arrhythmias in elderly people during water immersion. Water immersion model could be utilized to know circulatory regulation during bathing.

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Key Words

■ **Heart rate** (**power spectra analysis**) ■ **Autonomic nervous system** (**cardiovascular response**) ■ **Cardiac output** (**water immersion**) ■ **Elderly** (**vagal tone**)

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INTRODUCTION

Upright head-out water immersion (WI) shifts venous blood to the central vascular compartment and heart and subsequently increases cardiac preload from the legs and abdomen.[1−5] In young normal subjects, cardiac output ($\dot{Q}$) and stroke volume (SV) increase during WI, and by increasing the depth of immersion, the cardiac filling pressures also increase.[6] However, there is little information about arterial blood pressure adjustment in response to WI. Significant decreases occur in systolic (SBP), diastolic (DBP) and mean arterial blood pressures (MBP),[7] whereas no change in MBP and an increase in arterial pulse pressure occur during WI.[8] Thus, the effects of WI on blood pressure remain unclear.

In elderly people, cardiovascular autonomic dysfunction is likely to contribute to hemodynamic impairment in orthostatic testing and WI, with an attenuated heart rate (HR) response and augmented vascular responses.[9,10] The dynamic capacity of cardiac autonomic regulation decreases and vascular sympathetic regulation becomes augmented with increasing age.[11] The factors influencing the significant elevation of blood pressure during phase Ⅰ rehabilitation are age, physical deconditioning, imbalance of autonomic nervous activity and anxiety.[12] Therefore, a graded increase in WI could lead to a graded increase in cardiac distention and possible arrhythmias in elderly people.

The present study simultaneously measured blood pressure, HR, $\dot{Q}$ and SV, and assessed autonomic cardiovascular control during a graded WI protocol in young and elderly males using spectral analyses of HR variability. Most previous studies used spectral techniques based on the fast Fourier transform. Spectral analysis of HR variability has been used frequently as a noninvasive tool for the assessment of the autonomic cardiovascular control in recent years.[13−15] However, Fourier transform is insufficient to estimate the precise power spectral density from short time series data. Accordingly, the present analysis was carried out using the MemCalc method,[16] which allows reliable analysis of the low-frequency (LF; 0.04−0.15 Hz) component at a minimum interval of 30 sec. There is a general consensus that the high-frequency (HF; 0.15−0.4 Hz) component of HR variability, which reflects what is commonly termed respiratory sinus arrhythmia, represents a reasonably good index of parasympathetic nerve activity.[13] On the other hand, there remains considerable controversy as to whether the LF component of HR variability represents only sympathetic nerve activity or a combination of both sympathetic and parasympathetic modulation of HR, so that an alternative index is the ratio between LF to HF representing an index of sympathetic nerve activity.

Recently, HR variability analysis has been used to evaluate autonomic nervous activity, and studies have reported the relationship between coronary spasm and autonomic activity.[17,18] The present study compared the effects of changing breath frequencies during WI as well as graded WI levels between elderly and young individuals.

SUBJECTS AND METHODS

Subjects

Eleven young (mean age 20 ± 1 years) and 11 elderly (mean age 68 ± 6 years) healthy males participated in the clinical study (**Table 1**). The young subjects were well-trained and competitive swimmers in a university swimming team. Some elderly subjects had been treated for peptic ulceration, gout and gallstones. Three of the elderly subjects had hypertension and were treated with thiazide diuretics. No subject had a history of cardiovascular diseases and all were healthy as indicated by medical history, physical examination, blood pressure (< 140/90 mmHg) and 12-lead electrocardiography (ECG). The experimental protocol was approved by the ethics committee of Institutional Review Board of the School of Medicine, Kumamoto University. All subjects provided written consent for their participation after they were fully informed about the study. The investigation was performed in compliance with the Declaration of Helsinki.

Study protocol

Subjects underwent four experimental sessions in balanced random order wearing a swimsuit: 1) upright position non-immersed in the tank (air), 2) upright position at WI to the level of the sternoclavicular notch (neck), 3) upright position at WI to the level of the xiphoid process (chest), and 4) upright position at WI to the level of the spina iliaca anterior inferior (navel). The tank was pre-filled with thermoneutral warm tap water. The water temperature was maintained at 34 ℃ throughout the study. At the end of WI, the subjects were immedi-

Table 1 Physical characteristics of participating subjects

	Age (yr)	Height (cm)	Weight (kg)	Vital capacity (m*l*)
Elderly				
A	72.0	154.1	44.8	2,440
B	59.0	174.0	71.0	4,430
C	67.0	161.2	59.8	2,350
D	57.0	170.6	77.2	3,680
E	70.0	164.4	68.3	3,080
F	76.0	165.2	57.5	2,430
G	74.0	160.0	67.6	2,420
H	64.0	169.5	62.5	3,430
I	72.0	171.3	71.4	2,380
J	73.0	163.0	58.1	3,030
K	65.0	163.5	72.6	3,540
Mean±SD	68.1±6.2	165.2±5.8	64.6±9.2	3,019±691
Young				
M	19.0	170.5	57.2	4,210
N	19.0	163.0	65.5	4,260
O	21.0	164.5	80.0	4,710
P	23.0	176.0	74.0	4,600
Q	21.0	165.0	54.0	4,500
R	18.0	175.0	69.0	3,870
S	19.0	167.2	64.0	4,400
T	20.0	172.5	62.0	4,770
U	19.0	175.0	63.8	3,980
V	19.0	175.0	65.0	4,440
W	19.0	171.0	59.0	4,380
Mean±SD	19.7±1.4	170.4±4.8	65±7.4	4,375±281

ately dried and covered with towels to prevent cooling. All tests were performed at 24−27°C. No systematic difference in the room and water temperatures between the trials was observed.

Each test consisted of five different respiratory periods of 3 min each, with spontaneous breathing and four voluntary changes in the respiratory period from 4 times/min (4C) to 6 times/min (6C), then 10 times/min (10C) and 15 times/min (15C), while maintaining constant tidal volume (TV; 1,500 m*l*). The rhythm of breathing was controlled under each set of conditions by the subjects listening to a tape recording of instructions regarding the duration of inspiration and expiration. The subjects themselves also controlled TV by watching a flow meter and following instructions from the researchers. The study protocol is shown in **Fig. 1**.

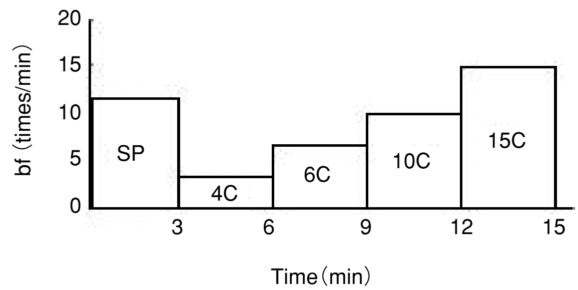

Fig. 1 Study protocol
Each test consisted of five different respiratory periods of 3 min each, with spontaneous breathing (SP) and four voluntary changes in the respiratory period from 4 times/min (4C) to 6 times/min (6C), to 10 times/min (10C) and 15 times/min (15C). Subjects underwent four experimental sessions in balanced random order, air, neck, chest and navel.
bf = breathing frequency.

Measurements and data analysis

Ventilatory flow was measured with a hot wire flow meter (RM-300, Minato Medical Sciences). The fractional concentrations of O_2 and CO_2 in samples drawn from the face mask were analyzed with a zirconium solid electrolyte oxygen analyzer and an infrared carbon dioxide analyzer, respectively (Vmax29c, Sensor Medics). This system was calibrated with a 2-*l* syringe, fresh air and an accurately analyzed gas (O_2 15%, CO_2). The time delay for gas flow to the analyzers was compensated for. The HR was measured continuously by transistor-transistor logic signal intervals synchronized with the R-wave of ECG by CM_5 leads.

At each level of immersion, ECG, $\dot{Q}$, SV, SBP, DBP, and total peripheral resistance were recorded continuously, whereas oxygen saturation (SaO_2) was measured every minute. Blood pressure was recorded with automatic oscillometric equipment (Jentow CS, Nihon Colin) at the heart level on the arm resting alongside the body. Special precautions were taken to ensure that the position of the cuff relative to the heart did not changed during the study. $\dot{Q}$ was determined during the last minute of each stage using the equilibrium acetylene rebreathing technique and pulse counter method. All data were adopted during the last minute of each 3-min stage. In all subjects, the ECG data were recorded using one channel, lead CM_5 on a DAT tape recorder during the study and analyzed with a computer-based system (AG901, Nihon-Koden). The R-R interval was measured by detecting the peak of each R-wave using a built-in analog-to-digital converter with an interval resolution of 8 msec. The data for each subject were transferred to a personal computer and stored on a 3.5-inch MO disk. These data were analyzed by the MemCalc system (Suwa Trust). We obtained the R-R interval (msec) as the time domain index of HR variability. The MemCalc system is a linearized version of the nonlinear least squares method for fitting analysis in the time domain, combined with the maximum entropy method for spectral analysis in the frequency domain.[19] The HR variability power spectrum was divided into HF (0.15−0.40Hz) and LF (0.04−0.15Hz) components. The HF component has been used to infer parasympathetic nervous activity,[20,21] whereas the LF/HF ratio of HR variability was defined as a better indicator of sympathetic nerve activity, because the LF component is typically related to a combination of parasympathetic and sympathetic influences.[22−24] For the analysis of 1/*f* fluctuations of HR, the power spectral band was focused on the range from 0.04 to 0.15. The slope of the 1/*f* fluctuations of HR was calculated by the expression on a $\log_{10}$ (frequency) − $\log_{10}$ (power density) scale; *i.e.*, the slope of the regression line between the $\log_{10}$ of frequency between 0.04 and 0.15Hz and the $\log_{10}$ of power density of the R-R spectrum was calculated. The LF, HF and LF/HF values are reported as natural logarithms (ln).

Statistical analysis

All data are expressed as mean ± SD. Statistical analysis was performed by two-way analysis of variance (ANOVA). When *F* values were significant, individual comparisons were made using the Bonferroni test. The paired Student's *t*-test was used to evaluate differences between two trials. A probability (*p*) value of < 0.05 was regarded as statistically significant. The Fisher exact probability test and unpaired *t*-test were used to compare categorical and continuous variables between the young and elderly groups, respectively. The natural logarithm transformation (ln) of each variable, which produces near-normal distribution, was applied before statistical analysis was performed, because the distribution of the frequency domain measurements of HR variability was extremely skewed.

RESULTS

Cardiovascular responses

Fig. 2 shows the circulatory responses to WI. HR tended to increase gradually with increased breathing frequency in both groups, but the increase was not significant. There was significant bradycardia during WI in the young group compared with air (navel: 61.0 ± 9.7 beats/min, chest: 59.3 ± 7.0 beats/min, neck: 61.5 ± 10.7 beats/min, air: 84.0 ± 7.7 beats/min; spontaneous breathing, $p < 0.01$), but no such change was observed in the elderly group. No significant differences were found between different WI levels, navel, chest and neck, in the young group. WI also produced a significant increase of SV at the navel level in the young group compared with air, even under spontaneous breathing (navel: 126.1 ± 39.7 m*l*, air: 79.5 ± 15.5 m*l*; $p < 0.01$), resulting in significantly increased $\dot{Q}$ at the navel level compared with chest and neck levels in the young group under 6C (navel: 10.0 ± 4.1 *l*, chest: 6.1 ± 1.2 *l*, neck: 6.9 ± 1.5 *l*; $p < 0.01$). The elderly group showed no evidence of any significant increase in SV and $\dot{Q}$ at any WI levels or with changing breathing frequency.

SBP, DBP and total peripheral resistance were significantly higher in the elderly group compared with the young group at any WI level and breathing frequency ($p < 0.01$). In the young group, both SBP and DBP increased gradually with increased breathing frequency but were not significantly different between different WI levels. In the elderly group, SBP and DBP were not significantly different between different breathing frequency and WI levels (**Fig. 3**).

No arrhythmias were observed during WI in the young group. In contrast, single supraventricular extrasystoles, including premature atrial and junctional complexes, were the most prevalent arrhythmias and were observed in 7 of the 11 elderly participants during WI. These arrhythmias occurred throughout the entire study protocol, in air and WI, spontaneous and enforced by breathing frequency, where some of the arrhythmias seemed to be related to respiratory arrhythmias.

Spectral analysis

Changes in LF, HF and the LF/HF ratio were noted in both the young and elderly groups. **Fig. 4** shows the changes in LF, HF and LF/HF ratio in

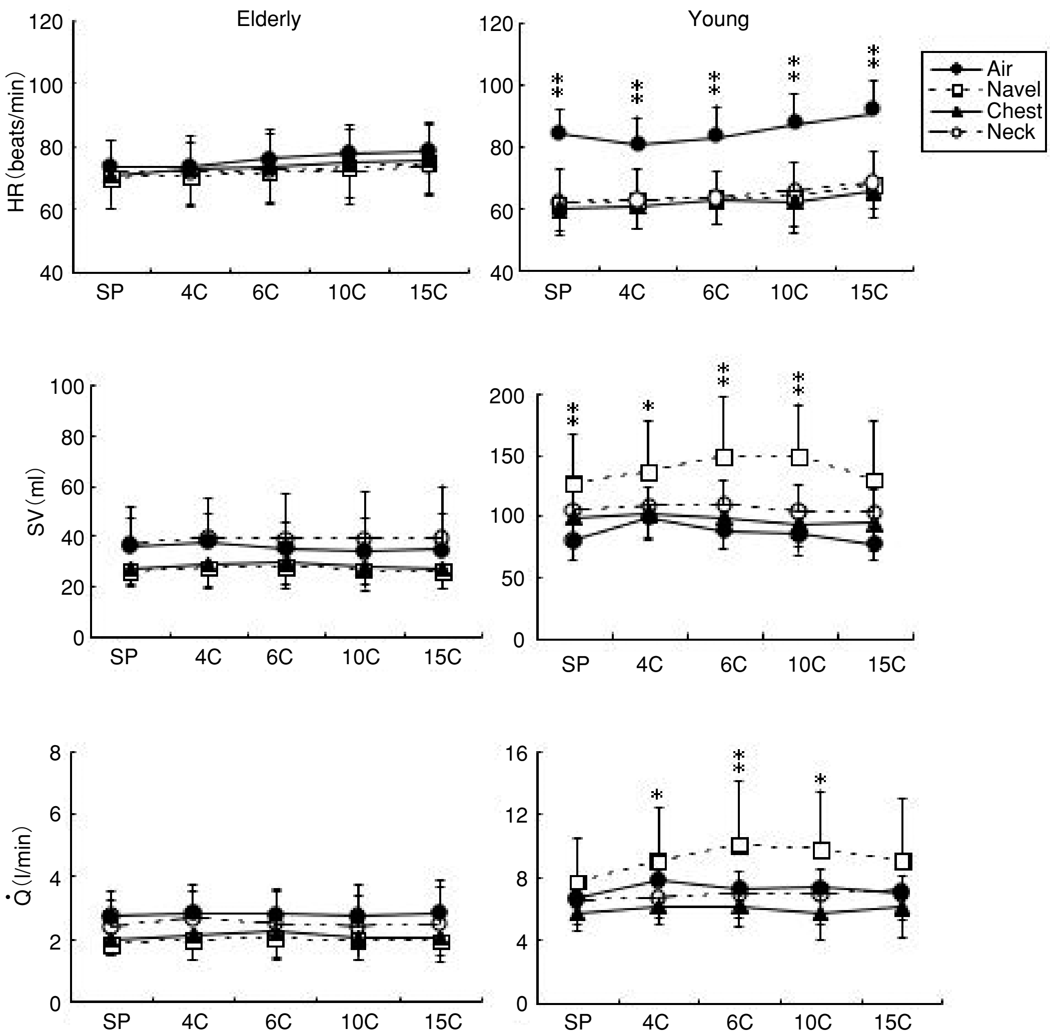

Fig. 2 Changes in heart rate (*upper*), stroke volume (*middle*) and cardiac output (*below*) with difference of breathing frequencies (spontaneous, 4, 6, 10, 15 times/min; SP, 4C, 6C, 10C, 15C) and head-out water immersion levels (air, navel, chest and neck)

Left and *right* figures show the elderly and young males, respectively. Data are expressed as mean ± SD. * $p < 0.05$, ** $p < 0.01$ vs each breathing frequency in air within group.
HR = heart rate; SV = stroke volume; $\dot{Q}$ = cardiac output. Other abbreviations as in Fig. 1.

the two groups. Compared with the young group, the elderly group had significantly lower LF ($p < 0.05$) and HF ($p < 0.01$) powers of HR variability under all conditions, including different WI levels and breathing frequency. In contrast, the LF/HF ratio of HR variability in the elderly group was significantly higher at breathing frequency of 4C and 6C than in the young group ($p < 0.05$).

DISCUSSION

The results of this study demonstrated that graded WI to navel, chest and neck levels induced adaptive changes in cardiovascular responses in the young group, and that there was less adaptation to the conditions in the elderly group. $\dot{Q}$ and SV were markedly lower in volume in the elderly group compared with the young group. Interestingly, total peripheral resistance was significantly higher throughout the study in the elderly group than in the young group. WI was associated with arrhythmias in the elderly subjects. The typical cardiovascular autonomic response to WI occurred by aging.

In the young group of this study, HR markedly decreased during all WI (diving bradycardia). Both $\dot{Q}$ and SV, however, significantly increased only between air and navel level, suggesting that

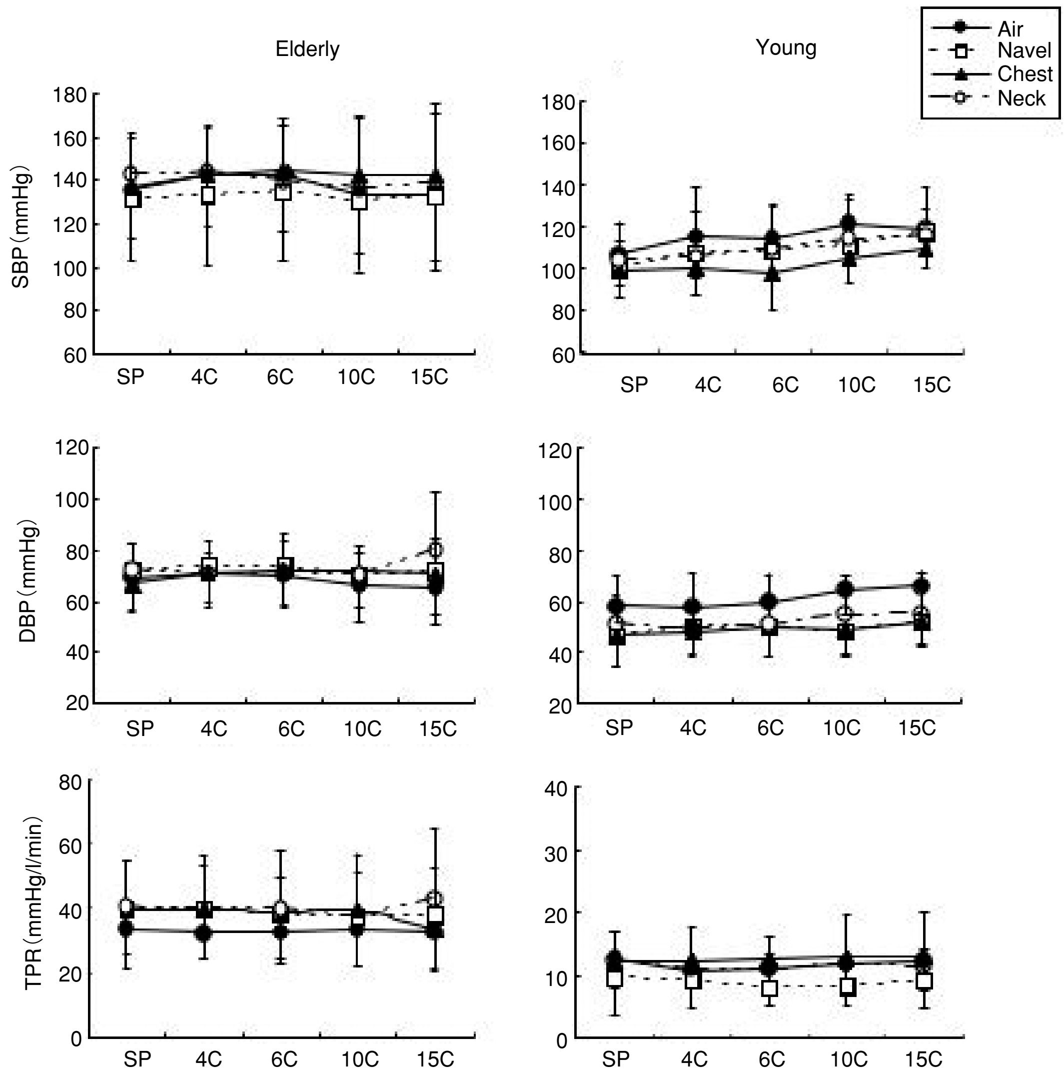

Fig. 3 Changes in systolic blood pressure (*upper*), diastolic blood pressure (*middle*) and total peripheral resistance (*below*) with differences of breathing frequencies (spontaneous, 4, 6, 10, 15 times/min; SP, 4C, 6C, 10C, 15C) and head-out water immersion levels (air, navel, chest and neck)

Left and *right* figures show the elderly and young males, respectively. Data are expressed as mean ± SD. $^{*}p < 0.05$, $^{**}p < 0.01$ vs each breathing frequency in air within group.

SBP = systolic blood pressure; DBP = diastolic blood pressure; TPR = total peripheral resistance. Other abbreviations as in Fig.1.

myocardial contractility significantly increased only during WI to the navel level, resulting in higher SV. An increase in cardiac filling pressure with graded WI induces increases in both central venous pressure and arterial pulse pressure.[25] On the other hand, we found no differences in cardiovascular responses depended upon WI levels. One of the reasons for this discrepancy is likely to be the lower increase in central venous pressure response to WI.[25] Firstly, in our study protocol, a stable and given TV (1,500 m*l*) against hydrostatic pressure may stimulate more stretch-reflexes in the lung and thorax and subsequently might exert a suppressing influence on the cardioinhibitory center (Bainbridge reflex).[26] Under conditions of WI to the navel level, however, venous return could easily and rapidly increase from the lower body into the thorax because of the absence of transmitted hydrostatic pressure. Alternatively, the significant difference in SV between air and navel WI under SP might

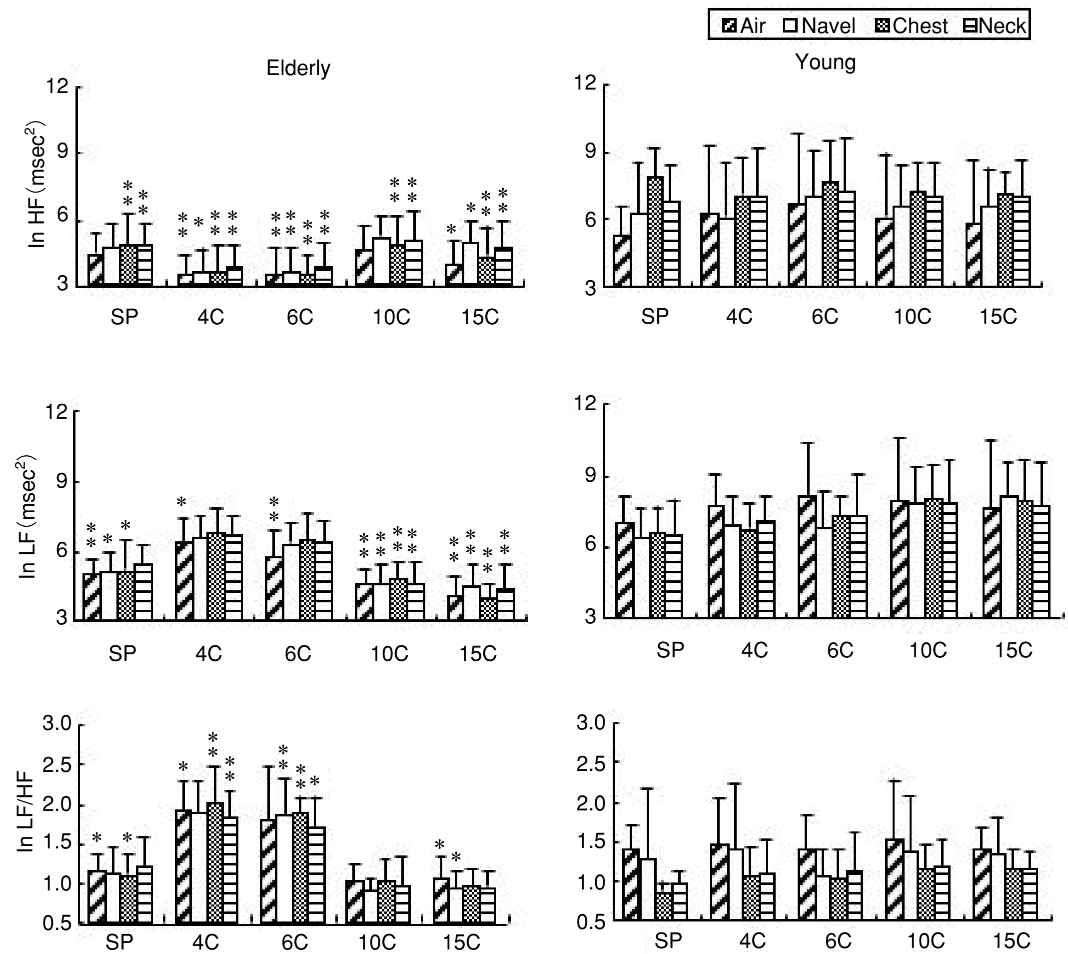

Fig. 4 Mean changes in each power of R-R interval variability (msec²) and ratio of LF/HF with difference of breathing frequencies (spontaneous, 4, 6, 10, 15 times/min; SP, 4C, 6C, 10C, 15C) and of head-out water immersion levels (air, navel, chest and neck) between the elderly (*left*) and young (*right*) groups

Upper, *middle* and *below* figures show ln HF, ln LF, ln LF/HF, respectively. Data are expressed as mean ± SD. $^{*}p < 0.05$, $^{**}p < 0.01$ vs each breathing frequency or water immersion levels between the young and elderly groups.

LF = low-frequency; HF = high-frequency. Other abbreviations as in Fig.1.

indicate that only SV or together with the hydrostatic pressure to the thorax might have greater contributions to increased central venous pressure. Another reason might be the acquired characteristic of the young subjects through physical training. The fitness and/or training of the subjects can modify the renal and hormonal responses to WI.[27] Trained young subjects probably have an intricate volume regulatory system of cardiovascular responses.[28] Under conditions of central hypervolemia induced by chest and neck levels of WI, central blood volume might be maintained by arterial baroreceptors and autonomic responses in subserving volume and circulatory homeostasis.

In contrast, HR, SBP, DBP, SV and $\dot{Q}$ in the elderly group changed less than in the young group, indicating reduced ability to withdraw from vagal influence[29] and/or decrease arterial baroreflex responses[30] with hydrostatic pressure in the elderly. Controversy still exists with regard to the response of blood pressure to WI in humans.[1,3,7] Changes in cardiovascular autonomic regulation are associated with aging under various conditions, including WI.[9,10] However, our results indicated that despite the added hydrostatic pressure, both autonomic and neuroendocrine activities were hardly necessary in circulatory homeostasis in the elderly group because of the lesser increase in central venous pressure. Blood pressure in the elderly group during WI also appropriately responded to maintain homeostasis,[31)] probably because the elderly have permanent increase of blood pressure with age-related lower vascular compliance. Moreover, total peripheral resistance in the elderly group was increased more during WI, possibly due to age-dependent reduction in suppression of muscle sympathetic nerve activity.[32)]

Spectral analysis of HR variability might allow the detection of momentary changes in both parasympathetic and sympathetic activity functions. At rest, elderly subjects exhibit increased sympathetic nerve activity and decreased parasympathetic nerve activity as well as impaired arterial baroreflex function.[11,30)] We found a marked increase in HF components of HR variability in the young group by graded WI compared with the elderly group, suggesting that parasympathetic deactivation of cardiac control during WI is important for adaption in the young group. In contrast, the LF/HF ratio in the elderly group during both 4C and 6C was significantly higher than that in the young group. In the elderly group, 4C or 6C of breathing frequency and 1,500 m*l* of TV could have elicited sympathetic nerve activity by overwork of their pulmonary capacity. HF power represents the vagal function of HR caused by the respiratory cycle and the depth of respiration.[20,21)] However, the LF/HF ratio of HR variability as a complex parameter is not a sample index of sympathetic activity.[11)]

In the present study, the rhythmic changes in activity likely elicited rhythmic variations in HR from lower to higher breathing frequency. R-R interval lengthened much less with breathing frequency change than with level of WI. The vagal control of HR in humans and respiratory sinus arrhythmia caused by reduced vagal efferent activity during the inspiration phase of the respiratory cycle is well documented.[33)] Therefore, our present findings demonstrated that bradycardia produced by parasympathetic nerve activity at lower breathing frequency was predominant during WI in the young group. On the other hand, there was less parasympathetic nerve activity in the elderly group with either changing breathing frequency or graded WI. It is important to emphasize that our results were consistent with the age-dependent attenuation of parasympathetic nerve activity previously reported.[11)]

Diving is well known to elicit brady-arrhythmias as well as premature atrial and ventricular contraction or even ventricular tachycardia.[34−36)] The potential dangers of the vagal response associated with diving include temporary sinus arrest.[37)] In the present study, the most prevalent arrhythmias were observed in 7 of 11 elderly subjects during WI. However, these arrhythmias are not likely to be solely due to increased cardiac overload (pre-load) or the Frank-Starling mechanism and baroreflex pathway. Total peripheral resistance, the so-called after-load, increased from air to all levels of WI, indicating that peripheral factors may also be related to the occurrence of arrhythmias. Therefore, at least in part, these ectopic arrhythmias during WI may be induced by augmented sympathetic nerve activity at lower breathing frequency, and by age-dependent attenuation of parasympathic nerve activity, as supported by the higher LF/HF ratio of HR variability at 4C and 6C, and lower HF power of HR variability throughout this experimental protocol. In addition, absence of augmentation of cardiac vagal activity in dogs is a risk factor for ventricular tachyarrhythmias.[38)] WI could be responsible for the increased risk of ventricular arrhythmias in elderly people despite the thermoneutral water temperature having little effect on cardiovascular responses.

Study limitations

This study does not attempt to evaluate rigorously the cardiovascular autonomic responses by difference of individual lung volume. The subjects were forced to maintain constant 1,500 m*l* of TV. Therefore, the TV ranged from 31 to 68% for each vital capacity of the subjects. Limited data in this study could not allow any clear conclusion for the difference of reflex response to lung inflation mediated thoracic stretch receptors.[39)] Further study should settle the different effects of individual physiological response accompanied by breathing.

CONCLUSIONS

The main findings of the present study are as follows. Graded WI led to different changes in cardiovascular responses between elderly and young people, with less adaptation in the elderly group. The typical response linked to parasympathetic deactivation was age-related. The occurrence of arrhythmias depends much more on autonomic activity elicited within the periphery as the dominant factor than central factors during WI in elderly people.

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要　　約

若年者および高齢者における浸水時の心血管系への自律神経応答の比較

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目　的: 中性温の浸水が心血管系に及ぼす自律神経の応答を検討するため，異なる水深(頸部，胸部，臍部)および呼吸頻度(4，6，10，15回/min)の影響を陸上および自由呼吸との比較から研究した．

方　法: 浸水時における11例の男性若年者(平均年齢20±1歳)および11例の男性高齢者(平均年齢68±6歳)の心拍変動を周波数領域から解析した．その方法では，心拍数の低周波成分(LF)，高周波成分(HF)，およびその成分比(LF/HF)を用いて評価した．

結　果: 若年者群において，浸水位が臍部での1回拍出量と心拍出量は胸部や頸部よりも顕著な増加を示した．また，最大血圧と末梢血管抵抗は浸水で有意に減少した．しかしながら，高齢者群では1回拍出量および心拍出量が減少傾向を示した． 浸水中は高齢者群のみに期外収縮の出現あるは悪化が検出された．浸水と呼吸変化によって，高齢者群には有意な低HFと高LF/HFが心拍変動から認められた．

結　論: 本研究結果で，中性温の浸水が若年者群と高齢者群間における心血管系への自律神経応答に異なる変化が示唆された．加齢による心血管系への自律神経応答の変化が，浸水中の高齢者に期外収縮の発現を増大させるのではないかと推察された．浸水の研究は，入浴時の循環調節の知見として活用できよう．

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