Influences of Gravitational Stress and Total Muscle Mass on Human Cardiovascular Adjustments during Prolonged Dynamic Exercise

Yoji SUZUKI

*Department of Health Administration, School of Health Sciences, Faculty of Medicine, University of Tokyo,
Hongo, Bunkyo-ku, Tokyo 113, Japan*

To investigate cardiovascular adjustments to combined stress of gravity and exercise during dynamic exercise prolonged over 60 minutes in upright position, the three experiments were carried out. In Experiment I, as performing moderate upright bicycling (66 % $\dot{V}O_2$ max) until exhaustion (average 86 minutes) in 4 trained men, changing manners of cardiovascular adjustments were shown in three phases, which were (1) regulating set-point body temperature, (2) making to maintain suitable blood pressure, and (3) failing to control the blood pressure. In Experiment II, as performing moderate supine cycling (55 % $\dot{V}O_2$ max) for 50 minutes under several LBNP conditions in 5 sedentary women, there were correspondingly similar changing manners of the cardiovascular adjustments to each of the phases given in Experiment I. In Experiment III, as examining tolerance of orthostatic circulatory regulation, the tolerance was significantly correlated to $\dot{V}O_2$ max and lean body mass (LBM) (both $p < 0.05$) in 8 sedentary women. When a moderate upright exercise is performed over 60 minutes in upright position, the performance should be influenced by total muscle mass indicated by LBM as well as by $\dot{V}O_2$ max, because the muscle mass could play a valuable role in the tolerance of orthostatic circulatory regulation vs. gravity.

Key words: Lower body negative pressure (LBNP), Lower body blood retention, Tolerance of orthostatic circulatory regulation, Blood pressure, Sympathetic nervous activity.

One of physical stressors during prolonged upright exercise is gravity. In the laboratory, as man is stimulated by 5-6 degree head-down tilting, the influence of gravitational stress on cardiovascular adjustments is eliminated and the base lines of the variables are established (Blomqvist and Stone 1983). When the body position is changed to the upright, the gravitational stress alters factors of cardiovascular adjustments (Abboun et al. 1979, Amberson 1943, Bevegård 1963, Blomqvist and Stone 1983, B.-Petersen et al 1983, Edholm 1967, Gauer and Thron 1965, Hesse et al. 1978, Johnson and Rowell 1974, Oparil 1970, Poliner et al. 1980, Rowell 1973, Samueloff 1966) so that central venous pressure is lowered, and sympathetic nervous activity, plasma norepinephrine concentration and

vasoconstriction increase, and then as the exposing time goes on, arterial blood pressure decreases, heart rate (HR), plasma renin activity (angiotensin II-aldosterone secretion) and vasopressin secretion increase. As a moderate upright exercise is prolongly performed, the alteration of the factors should affect on cardiovascular functions adjusted to supply blood flow to exercising muscles (Bevegård et al 1963, Oparil et al 1970, Poliner et al 1980). However, this affection has been hardly demonstrated, because there were not any proper devices for combining stresses of exercise and gravity on cardiovascular functions. By using an apparatus of which a cycle-ergometer is set in the interior of a lower body negative pressure (LBNP) production box (Suzuki et al 1984, Torikoshi et al 1984, 1988,

1989), in the present study, cardiovascular responses to the combined stresses were investigated to know the adjustments to gravitational effect during upright exercise prolonged over 60 minutes, and the effects of lean body mass and aerobic power on LBNP tolerance were also studied (Torikoshi et al 1987).

Methods

Experiment I

4 male student long-distance runners were participated in the experiment as subjects, whose age averaged 20 years old, body height averaged 168 cm, and the maximum oxygen uptake ($\dot{V}O_2$ max) averaged 70.3 ml/kg/min. In the environmental temperature regulation chamber controlled at 20°C and at about 60% humidity under approximately 760 mm Hg atmospheric pressure, an upright pedalling exercise of 1,080 kpm/min load by Monark cycle ergometer was performed until exhaustive situation occurred in each subject. For a control study to know the influence of exvironmental temperature on the performance, the same exhaustive exercise was also done in the two different temperature conditions of cold (0-4°C) and hot (40°C). Mean level of oxygen uptake ($\dot{V}O_2$) during the exercise corresponded to 66% of $\dot{V}O_2$ max. Through the experiments, there were 7 measurements which were heart rate (HR) with ECG method at every minute, left ventricular systolic time interval (STI) with a mechano-cardiogram method depending on synchronous recordings of ECG, carotid sinus pulse and cardiac sound at every five minutes (Lewis et al 1977, Susuki 1980a), arterial blood pressure in the left upper arm with an auscultation method using a sphygmomanometer at every two minutes, right forearm blood flow (FBF) with a mercury-in-Silastic strain-gauge method at every two minutes (Whitney 1953), cardiac output (CO) with CO_2 gas rebreathing method (Magel and Andersen 1967) corrected by simple one-step rebreathing technique (Farhi et al 1976) or/and by the acetylene-argon gas rebreathing method (B.-Peter-

sen 1980) at every ten minutes, and $\dot{V}O_2$ with Douglas' bag method at every five minutes. Every gas fraction was analyzed by a mass spectrometer, and the expired gas volume was measured by a standard gas-meter. Variable calculated by the given data were mean arterial pressure $\{MAP = [systolic\ arterial\ pressure\ (SAP) - diastolic\ arterial\ pressure\ (DAP)]/3 + DAP\}$, systemic arteri-venous O_2 difference ($A - \dot{V}O_2\ diff = \dot{V}O_2/CO$), total peripheral resistance ($TPR = MAP/CO$), stroke volume ($SV = CO/HR$), and left ventricular ejection time (LVET) and pre-ejection phase (PEP) scaling from STI.

Experiment II

Subjects participated were 5 female students, who averaged 21 years old, 155 cm body height, and 42.5 ml/kg/min $\dot{V}O_2$ max. In as such the laboratory environment as 25°C temperature and 65% humidity, a supine cycling exercise of 450 kpm/min load was performed for 50 minutes by a cycle ergometer set within a LBNP apparatus which was able to simulate the gravitational stresses so as to suck up blood volume to lower body part (Wolthus et al 1970). The averaged exercise intensity was 55% $\dot{V}O_2$ max. The subjects took informations of the purpose and minute details of the study prior to the experiment. The LBNP loads given during the exercise were -8 mm Hg to -60 mm Hg with series of steps involving the modified system of the NASA method after 15 minutes period of non-LBNP as shown in the lower part of Figure 2. The measurements and their methods through the experiments were almost the same as those in Experiment I, excluding STI measurement, and the methods for determining CO and $\dot{V}O_2$. The CO was measured by means of acetylene-argon gas rebreathing with a mass-spectrometer (B.-Petersen et al 1980) and the $\dot{V}O_2$ by the breath-by-breath method with a combined system of mass-spectrometer and air flow-meter. Because the acetylene-argon method has such a limit that it needs at least a period of over 8

minutes to washout the previous gases from the blood in vivo, CO was not measured at two LBNP loading levels of -30 mm Hg and -50 mm Hg through the protocol.

Experiment III

8 female sedentary students participated in the experiments as subjects, who averaged 21 years old, 154 cm of body height, and 42.02 ml/kg/min of $\dot{V}O_2$ max. Environmental conditions in the laboratory were approximately 760 mm Hg atmospheric pressure, 26°C temperature and 65 % humidity. The three experiments were carried out in different days for each subject. In the first experiment body composition and $\dot{V}O_2$ max were measured. The $\dot{V}O_2$ max was determined as a peak $\dot{V}O_2$ during treadmill running which made subject exhaustive between 6th and 12th minute by means of gradually increasing speed and slope of the treadmill. The % fat in the body weight was calculated by using the equation by Brožek et al. (1963) depending on body density measured from the under water body weight and residual volume air determined with a tech-

nique of argon-gas rebreathing in head-up water immersion. The averaged % fat of the subjects was 22.16. Lean body mass was calculated by the equation of (body weight—% fat $\times$ body weight). In the second experiment, the tolerance against graded lower body blood suction was examined after a 15 minutes rest by using LBNP apparatus set on a tilting bed in the supine position. In the third experiment, the tilting bed was changed to make the body position of 5 degree head-down tilting after a 15 minutes supine rest. Then, after the body position had been kept for 6 hours in the rest, the same tolerance examination as in the second experiment was also carried out. The method of the both tolerance examination was fundamentally in accordance with NASA's LBNP loading system, but if the criterion judging the intolerable situation (Table 1) was not attained by the loads, the subject would be further loaded by series of step of -5 mm Hg of LBNP every 5 minutes until the criterion (Figure 1). The method employed in the present study was described as a modified NASA system. Ability of the tolerance was represented by two indices of

Table 1. Criteria of Intolerable Physical Condition vs LBNP

Measurements	Criteria of NASA Method	Criteria in Present Study
1. ECG	1. Arrhythmias (Conduction Disturbance) 2. S-T Depression 1). Horizontal Depression Over 1.0 mm Depression at 80 msec from J point 2). Down-slope Depression 1.0 mm lower than resting level	1. Same as NASA Criterion 2. "
2. Heart Rate (HR)	1. Non-changing HR vs LBNP 2. Abnormal HR responses to LBNP (within 60 sec)	1. Same as NASA Criterion 2. "
3. Arterial Pressure	1. Continued Three Records of abnormal arterial pressure responses to LBNP 1). Below 70 mm Hg SAP 2). Below 50 mm Hg DAP 3). Below 10 mm Hg PP	1. Continued two records of abnormal arterial pressure responses to LBNP 1). Below 70 mm Hg SAP 2). Below 50 mm Hg DAP 3). Below 20 mm Hg PP
4. Clinical Symptom	1. Syncope/Faint (Bad Feeling) 2. Chest Pain 3. Dyspnea	1. Same as NASA Criterion 2. " 3. "

Figure 1. Protocol of examination of tolerance against Lower Body Negative Pressure (LBNP) after 6 hours rest in 5 degree of head-down tilting, and one case of time course of variables in subject A.

CO; cardiac output, SAP; systolic arterial pressure, DAP; diastolic arterial pressure, MAP; mean arterial pressure, $\dot{V}O_2$; oxygen uptake, FBF; forearm blood flow, C.V. Change; calf volume change

intolerable LBNP and total exposing time until intolerable point. Through experiments, $\dot{V}O_2$, CO, arterial blood pressure, HR, FBF, and changing rate of calf volume (CV Change) were measured by the same method as those in Experiment I and/or II, except CV change which was measured by means of a mercury-in-Silastic strain gauge (Whitney 1953) and represented by percentage against the resting value.

Figure 2. Responses of cardiac output (CO), total peripheral resistance (TPR), and arterial blood pressures during moderate upright exercise (66% $\dot{V}O_2$ max) in three different environmental temperatures. In using data given in 20°C, consideration would be carried out in the present study.

SAP; systolic arterial pressure, DAP; diastolic arterial pressure, MAP; mean arterial pressure

In all experiments, statistical analysis used standard T-test to determine the difference between each mean values, and level of significance was set at $p < 0.05$.

RESULTS

Experiment I

The time courses of arterial blood pressures, CO and TPR responses during exercise in subject A are represented in Figure 2. Except the performance in 40°C condition, exercise time was gone on over 60 minutes in every subjects (average 87 minutes in 20°C), and each manner of changing in the variables was similar in two conditions of 0°C and 20°C,

although each altering point of variables on the time courses was shifted between the two temperature conditions. In normal temperature as well as 20°C, note that the peaks of SAP and MAP were reached at around 10 min. of exercise, while increased CO and TPR were reached to the steady state levels.

In Figure 3, manners of change in cardiovascular

Figure 3. Cardiovascular responses to prolonged moderate upright exercise (66% $\dot{V}O_2$ max) in neutral temperature (20°C) environment. The exercise was performed until exhaustive situation in each subject. Plots expressed are the averaged percentages of the 10th minutes values of variables at each point in the subjects.

FFB; forearm blood flow, HR; heart rate, A- $\dot{V}O_2$ differ; systemic arterio-venous oxygen difference, $\dot{V}O_2$; oxygen uptake, CO; cardiac output, DAP; diastolic arterial pressure, MAP; mean arterial pressure PEP/LVET (reflects left ventricle ejection fraction, Lewis et al. 1974); pre-ejection phase/left ventricle ejection time, SV; stroke volume, TPR; total peripheral resistance, SAP; systolic arterial pressure

variable from 10 min to exhaustive point during exercise in 20°C are represented by the mean of percents against the 10th min values, which were identified as the basal value in all subjects. The basal CO was 18.41 (± 0.8) l/min and then maintained, while $\dot{V}O_2$ and A- $\dot{V}O_2$ diff. were preserved in almost the same as the each basal value of 2.56 (± 0.11) l/min and 139.7 (± 6.51) ml respectively until around 50 min. and then together gradually increased only 3% of the values at exhaustive point. MAP lowered about 4% of the basal value of 112 (± 5.1) mm Hg until 40 min, and then suddenly became to increase with increasing DAP after 50 minutes. After 70 minutes, then, it decreased again and 11% lower ($p < 0.05$) than the basal value with dropping DAP until exhaustive point. HR gradually increased from the basal value of 147 (± 9.5) bpm and was 14% higher ($p < 0.01$) at 80 min., and then a little bit decreased from the peak at exhaustive point. SV and PEP/LVET together decreased and respectively about 17% lower ($p < 0.01$) of the basal value of 125.6 (± 12.6) ml and 12% lower ($p < 0.01$) than 0.39 (± 0.04) at exhaustive point. TPR greatly decreased to be about 12% lower ($p < 0.01$) at 30 min than the basal value of 6.16 (± 0.27), and then became to increase until 60 min. Following that, it turned to decrease again and 18% lower ($p < 0.01$) than the basal value at exhaustive point. FBF greatly increased about 4.5 times ($p < 0.001$) of the basal value of 2.2 (± 1.6) ml/100 g tissue at 40 min and then became almost steady, but after 80 min it turned to increase again.

As the exercise time was going on beyond 50 minutes, note that dramatically increasing in MAP, DAP and TPR together was suddenly presented, but after 70 minutes the tendencies were rather changed to decrease significantly.

Experiment II

In the figure 4, cardiovascular responses during supine exercise are shown in which values of each point were averaged percents of the value given at

Figure 4. Cardiovascular responses to moderate exercise (55% $\dot{V}O_2$ max) in 5 degree of head-down tilting as lower body negative pressure (LBNP) was gradually loaded by a series of steps in a neutral temperature (20°C) environment. Plots expressed are the averaged percentages of the 10th minutes values of variables at each point in the subjects. HR; heart rate, A- $\dot{V}O_2$ differ; systemic arterio-venous oxygen difference, $\dot{V}O_2$; oxygen uptake, DAP; diastolic arterial pressure, CO; cardiac output, SAP; systolic arterial pressure, FBF; forearm blood flow SV; stroke volume

10th min when LBNP is 0 mm Hg. The 10th min values of the variables were also identified as the basal values in the present LBNP study. As LBNP was gradually intensified during supine exercise of 55% $\dot{V}O_2$ max, $\dot{V}O_2$ and CO together maintained their basal values of 1.10 (± 0.08) l/min and 9.82 (± 0.92) l/min respectively until -55 mm Hg, while beyond -55 mm Hg $\dot{V}O_2$ gradually increased 6% and in turn CO decreased 7%. Systemic A- $\dot{V}O_2$ diff maintained its basal value of 112.0 (± 8.7) ml/l until -55 mm Hg, while beyond -55 mm Hg it

Figure 5. Comparisons of tolerable pressure and exposing time between two examinations vs. lower body negative pressure (LBNP) at post 15 minutes rest in supine position and at post 6 hours rest in 5 degree of head-down tilting. Both of the pressure and time given in the examination of the tilting position together were significantly decreased as compared with these in the supine position (both $p < 0.01$).

suddenly increased about 14 % ($p < 0.05$). MAP decreased until -30 mm Hg and returned to the basal value of 94.6 (± 3.8) mm Hg until -40 mm Hg, while beyond -55 mm Hg it was dropped down about its 8% ($p < 0.05$). SAP and SV gradually decreased and were about 14% lower than the basal value of 136 (± 10.2) mm Hg ($p < 0.01$) and 20% of the 87.4 (± 14.2) ml until -60 mm Hg, respectively. DAP returned to the basal value of 74 (± 5.2) mm Hg from

the bottom value by -30 mm Hg, and then gradually increased about 17% higher ($p < 0.01$) than the basal value of $74 (\pm 5.2)$ mm Hg until -55 mm Hg, while it was suddenly dropped down near to the basal level after -60 mm Hg. HR gradually increased about 23 % higher ($p < 0.01$) than the basal value of $112.4 (\pm 6.4)$ bpm until -55 mm Hg, while it became to decrease from the peak at -60 mm Hg. TPR maintained almost its basal level of $9.36 (\pm 0.25)$ through the experiment. FBF suddenly decreased from the peak higher than the basal value of $4.21 (\pm 1.02)$ as starting LBNP loading, and became 50% lower ($p < 0.01$) than it until -50 mm Hg, while beyond -55 mm Hg it rather increased.

Experiment III

Figure 6. Relationships between maximum oxygen uptake ($\dot{V}O_2 \text{ max}$) and tolerable pressure and exposing time vs. lower body negative pressure (LBNP). Using all data given in the two examinations of LBNP, each of the relationships is significantly correlated (each $p < 0.05$).

In Figure 5, the mean values of tolerable pressure and tolerable time against LBNP examination in 8 subjects are shown. In the supine test, the tolerable LBNP was -56.3 mm Hg and the time was 18.5 minutes. In the 5 degree head-down tilting test, the LBNP was -47 mm Hg which was significantly lowered ($p < 0.01$) from it of the supine test, and the time was 11.8 minutes which was also significantly shortened ($p < 0.01$). Using all of data given in the two tests, the relationships between $\dot{V}O_2 \text{ max}$ and the tolerable LBNP and the time are shown in Figure 6. The both relationships together were significant (both $p < 0.05$). As shown in Figure 6,

Figure 7. Relationships between lean body mass (LBM) and tolerable pressure and exposing time vs. lower body negative pressure (LBNP). Using all data given in the two examinations of LBNP, each of the relationships is significantly correlated (each $p < 0.05$).

LBM and the tolerable LBNP and the time significantly correlated (both $p < 0.05$).

DISCUSSION

Cardiovascular responses during moderate prolonged exercise in upright position

When moderate upright exercise was performed until exhaustive situation, it is found that changing manners of cardiovascular responses along exercising time were divided into three phases depending on the basal values given at the 10th min. The first phase was from 10 min. to 50 min., when despite the maintenances of the basal $\dot{V}O_2$ and CO there were significant decreases in MAP and TPR while SAP, SV, and PEP/LVET which was considered to be inversely correlated to myocardial contractility gradually decreased. The responses of cardiovascular variables were similar to those given during 50 minutes and/or 60 minutes upright exercise in previous studies (Castenfors 1977, Ekelund 1967). In this phase, even if splanchnic blood flow (SpBF) is proportional to norepinephrine and inversely to HR and % $\dot{V}O_2$ max, it would be maintained at about 50 % of the resting value in man (Rowell 1978). Further, body temperature would be established to the set-point, and blood loss would be only 2% of the total blood volume (Ekelund 1967), while skin blood flow would be increased (Bregelmann 1983, Johnson et al 1974, Johnson and Rowell 1975, Johnson et al 1974, Suzuki 1980a). In the first phase, therefore, cardiovascular functions should be adjusted not only to keep the steady $\dot{V}O_2$ and CO but also to make skin blood flow increase for maintaining the set-point temperature.

The second phase was from 50 minutes until about 10 minutes prior to following exhaustive situation, when despite keeping the CO level $\dot{V}O_2$ and systemic A- $\dot{V}O_2$ diff were a little bit increased, MAP returned to the basal level depending on increasing DAP, increasing rate in HR was smaller, and FBF reached to almost steady state, while SAP, SV and PEP/LVET were further decreased. In this

phase, probably SpBF does not decrease below 40% of the resting level (Rowell 1973) and body temperature increase beyond the set-point (Johnson and Rowell 1975, Suzuki 1980a), but the increments in skin blood flow and HR should become smaller (Suzuki 1980a), although there is little evidence to compare because in most of previous studies (ex. Bregelmann 1983, Castenfors 1977, Ekelund 1967, Johnson and Rowell 1975) the prolonged exercise performed was within 60 minutes period. The changes in the variables should be due to an affect of gravitational stress with prolongly maintained upright position more than 50 minutes in spite of active muscular contraction. At least, by the influence of the gravity, the decrease in SV and the increase in HR should be resulted from decreasing central venous pressure and central blood volume (Bevegård et al 1963, Poliner et al 1980, Risch et al 1978), and the increases in DAP and peripheral vascular resistance suggested by the changes in TPR and FBF should be brought with increasing sympathetic nervous activity (Abbound et al 1979), and thus plasma norepinephrine concentration (Hesse et al 1978), vasoconstriction (Edholm 1942, Johnson Rowell 1975, Johnson et al 1974, Rowell 1973, Samueloff et al 1966) and angiotensin II-also-steron system activity (Goldsmith et al 1982, Grimby 1965, Oparil et al 1980).

The third phase was indentified in 10 minutes prior to the exhaustion, when DAP, MAP, SAP and TPR together were significantly dropped from the levels in the second phase, HR decreased and FBF increased from the previous level. The changes in the variables should be brought by the decline of the sympathetic nervous activity, as much as by so much decreases in venous return and thus central blood volume because of elevating lower body blood retention (Abbound et al 1979, Blomqvist and Stone 1983) by further prolonged upright position in spite of muscle activity. It is therefore considered that the exhaustion of moderate upright exercise in the normal environmental temperature should be brought

by the fail of maintaining blood pressure, because sympathetic nervous activity is probably broken by porolong exposure to gravitational stress, while $\dot{V}O_2$ and CO apparently maintained the exercise levels.

Simulation of gravitational stress on cardiovascular adjustments during moderate supine exercise

Lower body blood suction with LBNP load should be able to simulate lower body blood retention by gravity (Blomqvist and Stone 1983, Wolthus et al 1970), even if supine leg exercise is performed. When LBNP was loaded by series of certain steps, the effect of mild LBNP smaller than -30 mm Hg was weak on the cardiovascular adjustments during supine exercise, even though there were a little decreases in SAP and FBF, and increase in DAP. Going further than -30 mm Hg LBNP, however, the decrease in SV was manifested. This should be due to the decrease in venous return with increasing lower body blood retention by the lower body suction producted (Abbound et al 1979, Ahmad et al 1977, Blomqvist and Stone 1983, Nagano et al 1987, Poliner 1980, Torikoshi et al 1988, 1989). It is considered that as LBNP was intensified from -30 mm Hg to -50 mm Hg, the increase in the blood retention brings more negative effect on cardiovascular adustments to the exercise although muscle activity effectively fuctions on venous return. Under such LBNP loading, therefore, the facts that the increase in DAP and the decrease in FBF with increasing HR were greatly observed should be resulted from the increase in sympathetic nervous activity which promotes to adjust MAP to keeping the blood supply to exercising muscle against increasing lower body blood retention and decreasing venous return. $\dot{V}O_2$ slightly increased and CO was kept during the exercise. However, as LBNP was gone on beyond -55 mm Hg, although not only DAP and MAP but also HR and CO suddenly became to decrease lower than the values given at the previous stage of LBNP, the facts that $\dot{V}O_2$ did not change, and

systemic A- $\dot{V}O_2$ diff. and FBF together significantly increased should be due to the decline of the sympathetic nervous activity against extremely increasing lower body blood retention with such strong LBNPs.

Effect of lower body blood retention on cardiovascular adjustments during prolonged upright exercise

To demonstrate to a reliable detection that cardiovascular adjustments to prolonged upright exercise should be affected by gravitational stress with the position (Amberson 1943, Bevegård et al 1963, Edholm 1942, Gauer and Thron 1965, Oparil et al 1980, Poliner et al 1980), the results given by the two Experiments of I and II were combined and considered. In Experiment II, the profiles of cardiovascular responses to combined stresses of moderate exercise and simulation of gravity were divided into three stages by the grade of LBNP, that is, mild stage until around -30 mm Hg, moderate stage from -30 mm Hg to -50 mm Hg, heavy stage beyond -50 mm Hg. In the mild stage, cardiovascular adjustments were mainly affected by exercise and the increase in skin blood flow but little by lower body blood retention with the suction, which were similar to the adjustments given in the first phase in Experiment I, as observed especially in decreases in DAP and MAP and increase in FBF. In the moderate stage, the adjustments were not only for exercise but also against the blood retention with the suction, which should be considered likely to be similar to these given in the second phase in Experiment II, as presented by the alterations of changing tendencies in DAP, MAP, and TPR. In the heavy stage, the adjustments were much more greatly affected by the blood retention with the suction than by exercise, which should be almost the same as these in the third phase in Experiment I, as looked like to be the break down of the control of sympathetic nervous activity. The correspondences between the Experiment I and II should permit to demonstrate such a

deduction that as a moderate exercise goes on beyond 60 minutes in the upright position, cardiovascular adjustments during the exercise are affected by the volumatic degree of lower body blood retention caused by gravitational stress rather than by the muscular activity, and the exhaustive situation comes from the decline of sympathetic nervous activity as manifested by the fail to keep MAP against the great increase in the retention.

Tolerance of orthostatic circulatory regulation

Through LBNP test which is able to examine the tolerance of orthostatic circulatory regulation, it was shown that the both of tolerable LBNP and exposing time together significantly decreased after cardiovascular adaptation to simulation of zero gravity which could be made by 6 hours rest in 5 degree head-down tilting, as compared with the supine rest (both $p < 0.01$). The decrease in the tolerance is probably due to the sympathicotonia. The tolerance was mainly evaluated by raised orthostatic hypotension (Blomqvist and Stone 1983, Lightfoot et al 1989), which came from significant decrease in SAP, DAP and pulse pressure below the certain levels which appeared to be the fail in the maintenance of peripheral resistance with sympathetic nervous activity against the increase in lower body blood retention.

On the other hand, the positive correlations between $\dot{V}O_2$ max and the tolerable LBNP and exposing time (both $p < 0.05$) (Convertino et al 1984, 1986, Greenleaf et al 1988) are not supported in several studies (ex. Raven and Stevens 1990 in printing, Smithe et al 1987, Stegemann et al 1974, Vorman et al 1988), which have demonstrated the inverse correlation between $\dot{V}O_2$ max and the tolerance against orthostatic hypotension as much as the decrease in the tolerable capacity and the increase in $\dot{V}O_2$ max with aerobic exercise training in man (Raven and Stevens 1990 in printing, Smithe et al 1987). However, LBM which reflected total muscle

mass in the body (Brozek et al 1963) was significantly correlated not only to the tolerable LBNP but also to the exposing time. The muscle mass which is increased due to positive physical activity should be a basal and beneficial factor for making peripheral resistance and thus function for maintaining arterial blood pressure (Smith et al 1987, Smith and Raven 1986, Suzuki 1980b, Torkoshi 1987). The LBM was also significantly correlated to $\dot{V}O_2$ max. It is therefore considered that the positive correlations between $\dot{V}O_2$ max and the tolerable LBNP and exposing time presented should be come from the fact that in sedentary young women the degree of physical activity of life should affect not only on $\dot{V}O_2$ max but also muscle mass and be beneficial for the tolerance. Even if it is not clear whether or not $\dot{V}O_2$ max is a beneficial factor for the tolerance against orthostatic circulatory regulation (Lightfoot 1989, Raven et al 1984, Seals and Chase 1989), it would be possible that the positive correlations were arised from the degree of physical activity because the subjects were sedentary young women. Therefore, it has to be noted as an important finding that the tolerable capacity of the orthostatic circulatory regulation increased with increase in total muscle mass observed by LBM in sedentary women.

Effect of LBM on maintaining the certain level of blood pressure during prolonged moderate upright exercise

As time goes on beyond 50 minutes in moderate upright exercise, according to the present results, the positive activity of sympathetic nervous system made peripheral resistance increase and maintained blood pressure against the decreases in central venous return and central blood volume with increase in lower body blood retention, which were brought by almost the same lower body suction as -40 mm Hg to -55 mm Hg LBNP. The maintenance of blood pressure causes to keep CO, and $\dot{V}O_2$ is thus delivered to exercising muscles steadily and satisfactorily. Coming up to the upper limit of the

function as going on over certain exercise period, the fail of maintaining the blood pressure should make the exercise reach the exhaustive situation, even though $\dot{V}O_2$ and CO were kept almost as the same as the steady levels. This upper limit is probably given by lower body blood retention increasing with lower body suction equivalent to -60 mm Hg LBNP as simulation of gravity, because there were similarity in cardiovascular responses between the third phase in Experiment I and the heavy grade of LBNP in Experiment II. The upper limit against such a gravitational simulation should be stepped up by increasing total muscle mass (Torikoshi et al 1987), because whole muscle pump was strengthened and venous return increased helping sympathetic nervous activity.

In conclusion, there are several findings in the present study as follows: (1), When a moderate upright exercise (average 66% $\dot{V}O_2$ max) was performed until exhaustive situation (average 87 minutes) in 4 male distance runners, total cardiovascular adjustments changed by three phases along the exercise, that is, the first phase of regulating set-point body temperature, the second phase of regulating blood pressure level, and third phases of failing to regulate the blood pressure. (2), When a moderate supine exercise (average 55% $\dot{V}O_2$ max) was performed for 40 minutes period from 0 to 60 mm Hg LBNP in five female students, total cardiovascular adjustments were represented by three phases due to the degree of lower body blood retention with LBNP, that is, the mild stage of small influence until -30 mm Hg, the moderate stage of regulating blood pressure level from -30 until -50 mm Hg, and the heavy stage of break-down of the regulation beyond -55 mm Hg. (3) In moderate and exhaustive exercise, cardiovascular adjustments should be affected by graded increase in lower body blood retention as going on over 50 minutes, and the exhaustion should come from the fail of maintaining blood pressure due to gravitational stress. (4), The tolerance of orthostatic circulatory regulation

against simulation of gravity with LBNP test was affected not only by $\dot{V}O_2$ max but also by LBM in 8 sedentary young women. (5), When a moderate upright exercise is prolongly performed, the exercise performance is probably influenced by the level of $\dot{V}O_2$ max and further similarly by the total muscle mass in the body, because the muscle mass can play a valuable role in the tolerance of orthostatic circulatory regulation against lower body blood retention increasing with gravitational stress in the upright position.

REFERENCES

- Abboud, F.M., et al (1979). Carotid and cardiopulmonary baroreceptor control of splanchnic and forearm vascular resistance during venous pooling in man. *J. Physiol. London*, 286: 173-184
- Ahmad, M., et al. (1977). Left ventricular function during lower body negative pressure. *Aviat Space Environ Med* 48, 512-515.
- Amberson, W.R. (1943). Physiologic adjustments to the standing posture. *Maryland Univ. Sch. Med. Bull.* 27, 127-145.
- Bevegard, S., A. Holmgren, and B. Jonsson (1963). Circulatory studies in well-trained athletes at rest and during heavy exercise with special reference to stroke volume and the influence of body position. *Acta Physiol Scand* 57, 26-50.
- Blomqvist, C.G., and H.L. Stone (1983). Cardiovascular adjustment to gravitational stress. In *Handbook of Physiology, American Physiological Society, Bethesda, MD. The Cardiovascular System. Peripheral Circulation and Organ Blood Flow.* (J. T. Shepherd, F.M. Abboud, and S.R. Geiger, eds), sect. 2, vol. III, part 2, chapt. 28, p.1025-1063.
- Bonde-Petersen, F., P. Norsk, and Y. Suzuki (1980). A comparison between freon and accetylene re-breathing for measuring cardiac output. *Aviat Space Environ Med* 51, 1214-1221.
- Bonde-Petersen, F., Y. Suzuki, and T. Sadamoto (1983). Cardiovascular effects of simulated zero gravity in human. *Acta Astronautica* 10(9), 657-661.

- Brengelmann, G.L. (1983). Circulatory adjustments to exercise and heat stress. *Annu Rev. Physiol* 45, 191-212.
- Brožek, T., et al. (1963). Densitometric analysis of body composition: Review of some quantitative assumptions. *Ann. N.Y. Acad. Sci.* 110: 113-140.
- Castenfors, J. (1977). Renal function during prolonged exercise. In *the Marathon: Physiological, Medical, Epidemiological, and Psychological Studies* (P. Milvy, ed.). *Ann NY Acad Sci* 301:151-159.
- Convertino, V.A., et al. (1984). Cardiovascular responses during orthostasis: effect of an increase in VO_2 max. *Aviat. Space Environ. Med.* 55: 702-708.
- Convertino, V.A., et al. (1986). Aerobic fitness does not contribute to prediction of orthostatic intolerance. *Med. Sci. Sports Exercise* 18: 551-556.
- Edholm, O.G. (1942). The compensatory mechanism of the splanchnic circulation during changes of posture. *J Physiol (Lond.)* 101: 1-10.
- Ekēlund, L.-G. (1967). Circulatory and respiratory adaptation during prolonged exercise. *Acta Physiol Scand* 70 (Suppl. 292): 1-38.
- Farhi, L.E., et al. (1976). Cardiac output determination by simple one-step rebreathing technique. *Respir Physiol* 28: 141-159.
- Gauer, O.H., and H.L. Thron (1965). Postural changes in the circulation. In *Handbook of Physiology*. American Physiological Society. Circulation. (W.F. Hamilton and P. Dow. eds.), sect. 2, vol. III, chapt. 67, pp.2409-2439.
- Goldsmith, S.R., et al. (1982). Response of vasopressin and norepinephrine to lower body negative pressure in humans. *Am J Physiol* 243 (Heart Circ Physiol 12): H970-H973.
- Greenleaf, J.E., et al. (1988). Effect of longitudinal physical training and water immersion on orthostatic tolerance in men. *Aviat. Space Environ. Med.* 59: 152-159.
- Grimby, G. (1965). Renal clearances during prolonged supine exercise at different loads. *J Appl Physiol* 29: 1294-1298.
- Hesse, B., et al. (1978). Renin stimulation by passive tilting: the influence of an anti-gravity suit on postural changes in plasma renin activity, plasma norepinephrine concentration and kidney function in normal man. *Scand J Clin Lab Invest* 38: 163-169.
- Johnson, J.M., L.B. Rowell, and G.L. Brengelmann (1974). Modification of the skin blood flow-body temperature relationship by upright exercise. *J Appl. Physiol* 37: 880-886.
- Johnson, J.M., and L.B. Rowell (1975). Forearm skin and muscle vascular responses to prolonged leg exercise in man. *J Appl Physiol* 39: 920-924.
- Johnson, J.M., et al. (1974). Human splanchnic and forearm vasoconstrictor responses to reduction of right arterial and aortic pressure. *Cir. Re.*, 34: 515-524.
- Lewis, R.P., et al. (1977). A critical review of the systolic time intervals. *Circulation* 56: 146-158.
- Lifhtfoot, J.T., S. Febles, and S.M. Fortney (1989). Adaptation to repeated presyncopal lower body negative exposures. *Aviat. Space Environ. Med.* 60: 17-22.
- Lifhtfoot, J.T., et al. (1989). Ten weeks of aerobic training do not affect lower body negative pressure responses. *J. Appl. Physiol.*, 62: 894-901.
- Magel, J.R., and K.L. Andersen (1967). Cardiac output in muscular exercise measured by the CO_2 rebreathing procedure. In *Ergometry in Cardiology* (H. Denolin, K. Konig, R. Messin, and S. Degre, eds.) (GmbH: Boehringer Mannheim). pp. 147-157.
- Nagano, J., et al. (1987). Effect of LBPP stocking on cardiovascular responses during rest and exercise in LBNP and upright position in woman. *The Physiologist* 30 (1): Suppl. 72-73.
- Oparil, S., et al. (1970). Role of renin in acute postural homeostasis. *Circulation* 41: 89-95.
- Poliner, L.R., et al. (1980). Left ventricular performance in normal subjects: a comparison of the responses to exercise in the upright and supine positions. *Circulation* 62: 528-534.

- Raven, P.B., D. Rohm-Young, and C.G. Blomqvist (1984). Physical fitness and cardiovascular response to lower body negative pressure. *J. Appl. Physiol.* 56: 138-144.
- Raven, P.B., and G.H.J. Stevens (1990). Endurance exercise training reduces orthostatic tolerance in humans. *The Physiologist*. (in printing).
- Risch, W.D., et al. (1978). The effect of graded immersion on heart volume, central venous pressure, pulmonary blood distribution, and heart rate in man. *Pfluegers Arch* 374: 115-118.
- Rowell, L.B. (1973). Regulation of splanchnic blood flow in man. *The Physiologist* 16: 127-142.
- Samueloff, S.L., N.L. Browse, and J.T. Shepherd (1966). Response of capacity vessels in human limbs to head-up tilt and suction on lower body. *J. Appl. Physiol* 21: 47-54.
- Seals, D.R. and P.B. Chase (1989). Influence of physical training on heart rate variability and baroreflex circulatory control. *J. Appl. Physiol* 66(4): 1886-1895.
- Smith, et al. (1987). Effect of muscle tension on the cardiovascular responses to lower body negative pressure in man. *Med. Sci. Sports Exercise* 19: 436-442.
- Smith, M.L., and P.B. Raven (1986). Cardiovascular responses to lower body negative pressure in endurance and static exercise trained men. *Med. Sci. Sports Exercise* 18: 545-550.
- Stegemann, J., A. Busert, and D. Brock (1974). Influence of fitness on the blood pressure control system in man. *Aerosp. Med.* 45: 45-48.
- Suzuki, Y. (1980a). Human physical performance and cardiocirculatory responses to hot environments during sub-maximal upright cycling. *Ergonomics* 23: 527-542.
- Suzuki, Y. (1980b). Mean arterial pressure, O_2 -uptake, and muscle force time during dynamic and rhythmic-static exercise in men with high percentages of fast-and slow-twitch fibers. *Eur. J. Appl. Physiol* 43: 143-155.
- Suzuki, Y., et al. (1984). Blood pressure related with muscle activity and/or carotid artery compression during mild supine exercise exposed to LBNP. *The Physiologist* 27 (6): Suppl. 55-56.
- Suzuki, Y., et al. (1980). Effect of alteration of peripheral blood flow on the central circulation in man during supine cycling in different ambient temperatures. *Eur. J. Appl. Physiol* 45: 69-80.
- Torikoshi, S., et al. (1989). Difference in cardiovascular responses to blood pooling patterns between LBNP and head-up tilting stimulated after supine cycling in woman. *The Physiologist* 32(1): Suppl. 88-89.
- Torikoshi, S., et al. (1988). Effect of acutely exposing to 40 mm Hg LBNP on cardiovascular responses during rest and mild exercise after 6 hrs rest in 5° head down tilting (HDT). *The Physiologist* 31(1): Suppl. 16-17.
- Torikoshi, S., et al. (1987). Effect of lean body mass and aerobic power on LBNP tolerance in woman. *The Physiologist* 30(1): Suppl. 75-76.
- Torikoshi, S., et al. (1984). Cardiovascular responses to +G or -G stimulated during post-exercise in mild supine pedalling in -60 mm Hg LBNP. *The Physiologist* 27(6): Suppl. 53-54.
- Vorman, N.B., J.A. Hearly, and R. Kertzer (1988). Cardiovascular response to lower body negative pressure (LBNP) following endurance training. *Aviat. Space Environ. Med.* 59: 330-334.
- Whitney, R. J. (1953). The measurement of volume change in human limbs. *J. Physiol (London)* 121: 1-45.
- Wolthus, R.A., G.W. Hoffler, and R.L. Johnson (1970). Lower body negative pressure as an assay technique for orthostatic tolerance. II. A comparison of individual response to incremental vs. constant level of LBNP. *Aerosp. Med.* 41: 419-424.

(Received March 1, 1990)