

Effects of Graded Load of Artificial Gravity on Cardiovascular Functions in Humans

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Abstract: An artificial gravity and ergometric exercise loading device for human use was manufactured. It has the capacity of a max 2 G-load at the heart level, and a max 150W of work-load. Eight subjects (six completed) were subjected to four repeated trials with or without 20W ergometric exercise. Anti-G score, defined as the G-load \times running time to the endpoint, was significantly higher in the exercise trials than standing trials. Heart rate (HR), mean arterial pressure (MAP), thoracic fluid index (TFI) were significantly superior during the exercise trials. Artificial gravity by centrifuge at 1.2 or 1.4 G with 40 or 60 W of ergometric workload may be an excellent countermeasure against cardiovascular deconditioning after long exposure to microgravity.

Long-term exposure to microgravity constantly induces cardiovascular deconditioning, which usually appears as orthostatic intolerance among astronauts.¹⁻³⁾ Countermeasures against this deconditioning are lower body negative pressure,⁴⁾ or ingestion of physiological saline⁵⁾ just before terrestrial re-entry, which have been proved to be ineffective or to take too much time for the prevention of deconditioning.²⁾ The cause of the deconditioning has not been well clarified so far, however, it appears to be mainly caused by cephalad fluid shift and gravitational unloading of the lower limbs.⁶⁾ Several features of the deconditioning including orthostatic intolerance were reported e.g. a 10–20% plasma volume loss⁷⁾ and an increase in fluid shift between compartments,⁸⁾ suppression of vagal activity,⁹⁾ an increase in baseline sympathetic nerve activity,¹⁰⁾ no change in sympathetic responsiveness,⁹⁾ and a decrease in vasomotor response.¹¹⁾

Artificial gravity produced by centrifuge has been investigated and reported¹²⁾ in the National Aeronautics and Space Agency (NASA), USA, for an interplanetary flight to Mars in the near future. For the prevention of cardiovascular deconditioning, the use of artificial gravity only seems to be ineffective, and a combination of other measures, e.g. exercise by ergometer, might be required as an effective countermeasure.

In the present study, we manufactured an artificial gravity loading system with an ergometer, and the effect of this device on cardiovascular variables was investigated during graded G-load.

Methods

1) Centrifuge

The centrifuge device consists of a rotating rod with a diameter of 4 m, weighing 400 kg rotation motor, and a base of 2 tons. It has a maximum rotating capacity of 302°/s within 30 s. The maximum bearing weight is 80 kg for subjects and 40 kg for the measurement devices. It is equipped with a detachable ergometer with a maximum workload of 150 W. The eyes are covered with a head-mount display (Sony Glasstron), and instructions are provided through this display. The safety of the device was approved for human studies by the ethical committee of National Space Development Agency of Japan, and the experiment was approved by the Committee of Human Research, Research Institute of Environmental Medicine, Nagoya University. The device was built according to the Code of Playing Equipment, Building Standard Law, Japan.

2) Subjects

The subjects were eight healthy male volunteers age: 22 ± 2 years old, height 170 ± 3 cm, and weight: 58 ± 6 kg, and six subjects completed the schedule. Before participation, a thorough explanation of the study protocol was given to each subject, and consent was obtained in written form.

3) Schedule

Two studies, exercise with the ergometer, or standing without the ergometer (in this case, the subjects were requested to support their bodies using the soles of their feet) were carried out. Four trials were performed in each study. The order of the exercise or standing studies was randomly selected, and an

interval of more than a week was taken between trials.

4) Protocol

Subjects were requested to come to the laboratory at 1700 in the evening. They were reclined in the centrifuge in a supine position. After more than 10 min rest, the centrifuge was rotated at 1.0 G-load for 10 min. If the subject completed the 1.0 G-load for 10 min, the G-load was increased to 1.2 G, and rotated for 5 min. The G-load was increased in a graded manner with loads of 1.4, 1.6, 1.8, and 2.0 G for 5 min each, and the trial was terminated if the subjects endured the 2.0 G-load for 5 min. Exercise of 20 W with the ergometer was requested during exercise trials.

During trials, electrocardiogram, respiration, blood pressure with Finapres, relative changes in thoracic blood volume by an impedance method were monitored, and stored in a multichannel digital audio tape (DAT) data recorder (Sony Precision Technology, PC-160 AX) for later off-line analysis.

The rotation was terminated if one of the following occurred: 1) onset of presyncopal symptoms e.g. nausea, sweating, grayout or dizziness, including a drop in systolic BP >15 mmHg and/or sudden bradycardia >15 bpm; 2) progressive reduction in systolic blood pressure to <80 mmHg, 3) the subject requested termination. The subjects hold a shutdown switch that brakes the rotation when the subjects release the switch. To rotate, the subjects have to continuously press the switch. This switch enables the centrifuge automatically to stop when the subjects lose consciousness, and release the button for safety.

5) Anti-G score

In the present study, we defined "anti-G score" as the sum of the magnitude of gravity vector toward the leg ($+G_z$) \times time (sec) for the load to the endpoint in order to quantify the orthostatic tolerance (Fig. 1).

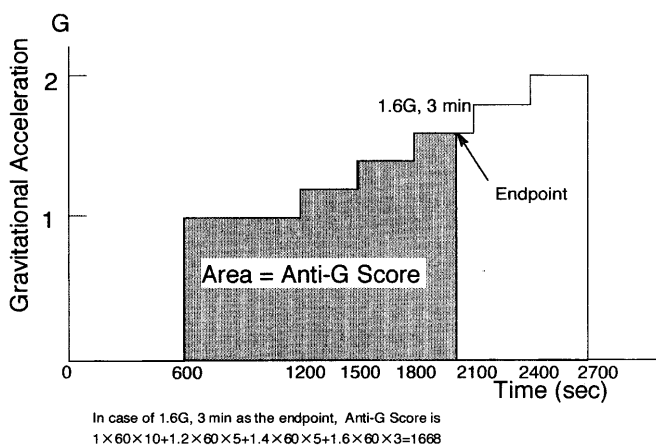


Fig. 1 The definition of Anti-G Score. Anti-G Score is the sum of the multiplication of loaded G \times running time in seconds.

6) Statistical analysis

Data on heart rate (HR), mean arterial blood pressure (MAP), intrathoracic blood volume (TFI, thoracic fluid index, a reciprocal value of the % change in an impedance value) stored in a DAT recorder were digitized with PC scan software (Sony Precision Technology, Tokyo), and averaged on personal computers (Windows 98). The variables were analyzed by a two-way repeated-measures analysis of variance. Tests for simple effects were performed with the Bonferroni-Dunn comparison procedure when the interaction term was found to be significant.

Results

Six out of the eight subjects completed the four exercise and standing trials, and the G-tolerance and cardiovascular variables were examined in graded G-load (1.0, 1.2, 1.4, 1.6, 1.8, and 2 G) with or without ergometric exercise.

1) Changes in anti-G score during centrifuge

The averaged anti-G score during centrifuge in the exercise trials was significantly higher than that during standing ($2,113 \pm 154$ vs $1,281 \pm 159$, $p < 0.05$). Inter-individual anti-G scores were significantly different among subjects ($p < 0.05$), indicating that this anti-G score is inherent to the individual subject. No significant change was observed by the repeated G-load up to four times (Fig. 2).

2) Changes in heart rate during centrifuge

The HR was increased significantly according to the G-load increase ($p < 0.00001$). HR in the exercise trials was significantly higher than in the standing trials ($p < 0.00001$). No significant change was observed by the repeated G-load up to four times ($p = 0.56$). (Fig. 3)

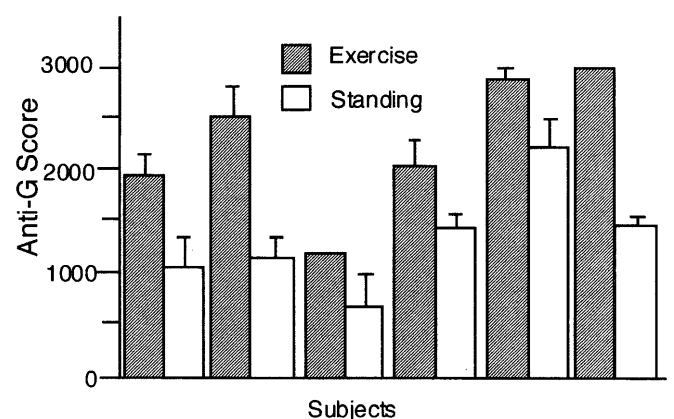


Fig. 2 Changes in anti-G score in 6 subjects. Exercise trials produced significantly higher scores than standing trials. Four repeated trials did not reveal significant differences among them.

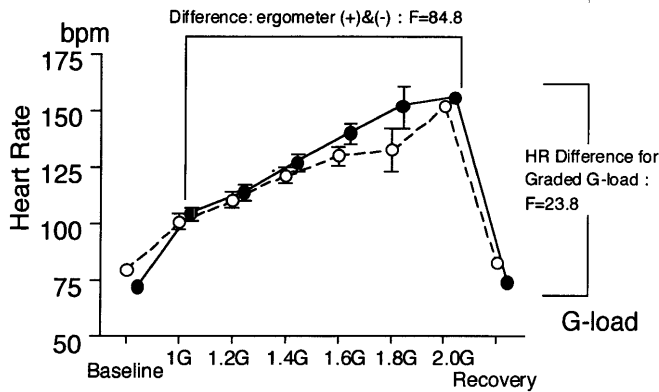


Fig. 3 Changes in heart rate in response to the graded G-load by centrifuge. There is a significant difference between the exercise and standing trials according to the G-load change. Heart rate increases in response to G-load increase.

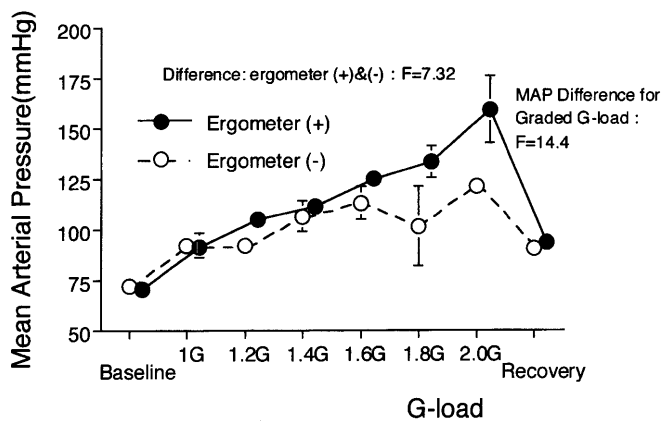


Fig. 4 Changes in mean arterial pressure in response to graded G-load. MAP is elevated as the graded G-load increases. There is a significant difference between the exercise and standing trials. MAPs in response to graded G-load increase are significantly different.

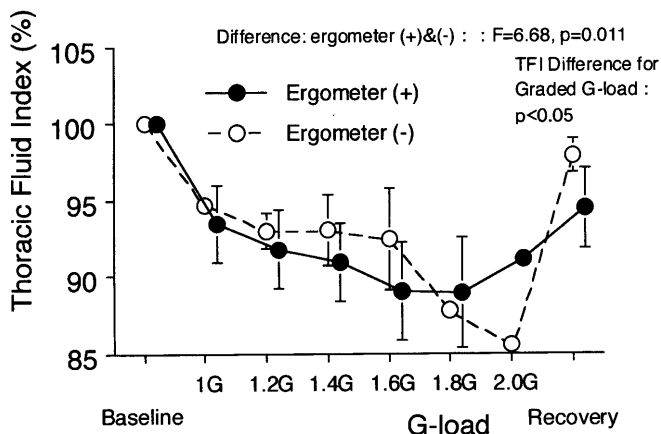


Fig. 5 Changes in thoracic fluid index ($1/[\text{chest impedance change}]$) in response to graded G-load. There is a significant difference between the exercise and standing trials. TFIs in response to graded G-load increase are significantly different.

3) Changes in mean arterial blood pressure during centrifuge

Mean arterial pressure (MAP) was calculated from the averaged values of Finapres tracings at the sampling rate of 2 kHz. MAP was significantly different among graded G-load ($p < 0.00001$). There was a significant difference in MAP between exercise and standing trials. Significant changes were observed by the repeated G-load up to four times ($p < 0.000001$). (Fig. 4)

4) Changes in thoracic fluid index during centrifuge

The blood volume change was expressed as the percent change from the supine baseline value (ohm) using impedance plethysmography. The index (thoracic fluid index, TFI) was calculated from the reciprocal number of the impedance value. TFI was significantly reduced according to the graded G-load change ($p < 0.00001$). The exercise trial exhibited a significantly different value from the standing trial ($p < 0.00001$). Significant changes in TFI were observed by the repeated G-load up to four times ($p < 0.001$) (Fig. 5).

Discussion

The present study demonstrated for the first time that artificial gravity-induced changes in HR, MAP, and TFI in response to the graded G-load up to 2G with or without ergometric workload. By using this centrifuge device, we proposed a new orthostatic tolerance index, anti-G score, and this has been proved to be inherent to individual subjects. This score is also beneficial to quantify the orthostatic tolerance or G-tolerance in humans.

The effect of hypergravity has been discussed during launching, or pilot training, and the significance of hypergravity as a countermeasure for cardiovascular deconditioning using a gondola-type centrifuge was assessed by Iwasaki et al. in 2001.¹³⁾ They reported that simulated microgravity-induced vagal suppression was avoided by 2 G-load for 30 min \times 2/day. This small effect of artificial gravity might be due to the lack of exercise combined with the G-load.

In the present study, the effect of graded G-load by artificial gravity (centrifuge) was examined with or without leg exercise before assessing the effect of this load before and after microgravity exposure.

HR was increased and MAP was elevated in accordance with the increase in graded G-load through 1.0, 1.2, 1.4, 1.6, 1.8, and 2.0G. The HR increase was probably caused by the baroreflex due to the fluid shift from the thorax to the lower leg, which induced a stroke volume decrease. MAP elevation was mainly due to the increase in peripheral resistance induced by the sympathoexcitation including vasomotor and HR increase by fluid shift to the leg. Thus, these two increases were the results of G-tolerance preservation.

As for the effect of repetition, we applied G-load on the subjects four times with or without exercise, and in both situations, training effect, an increase in anti-G score by repeated G-load was not shown. However, since MAP and TFI exhibited significant improvements by repeated G-load, an increase in the anti-G score may be achieved by more repetitions or an increase in subject numbers.

During centrifuge, exercise load by ergometer at 20W has been proved to significantly enhance the G-tolerance. It may be achieved by a suppression of the reduction in venous return with a pumping effect. Standing G-load trial sometimes caused itching or numbness at the soles of the rotating subjects, probably due to enhanced blood pooling in the feet. The +Gz value, calculated from the equation $G=r\omega^2$, where G: gravity, r is the radius, ω is the angular velocity, is 5 G when the G-load at the heart level is set at 2 G. This complaint was overcome by ergometric exercise, which shows that the ergometric exercise was beneficial not only for myoatrophic changes by microgravity exposure, but also for G-tolerance enhancement.

The next step will be to verify this artificial gravity with exercise during bed rest. From the G-tolerance test, 1.2 or 1.4 G with 60 W exercise for 30 min might be an appropriate load during bed rest.

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