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High-intensity interval aerobic exercise training (HIAT) in occupational health

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Abstract An astronaut's maximal oxygen intake ($\dot{V}O_{2max}$), along with cardiac function, decreases during space life; and many astronauts experience unhealthy weight loss due to energy imbalances. In fact, excessive exercise may promote an energy deficit. Moreover, a typical scheduled exercise program (2.5 hours per day) appears to be excessive for time-pressed astronauts. Hence, more efficient exercise programs need to be developed for future space missions. With this background, the study of “*high-intensity interval aerobic exercise training (HIAT)*” was initiated. The HIAT protocol in our study consisted of 3 sets of 3-min high-intensity cycling with 2-min active rest between sets. Two intervention studies conducted with sedentary male adults revealed that $\dot{V}O_{2max}$ improvement by HIAT was significantly higher than improvement by moderate-intensity continuous aerobic training (MICT); and that cardiac function significantly improved in HIAT, but not in MICT, even though the exercise duration and volume of HIAT (15 mins, 180 kcal) were substantially lower than those of MICT (42 mins, 360 kcal). Further studies on general workers with metabolic syndrome also showed the superior effect of HIAT to MICT on $\dot{V}O_{2max}$. Studies conducted on astronaut health may provide clues to solving lifestyle-related public health issues because the microgravity environment is similar to physical inactivity in reducing the load on the heart. Lack of time is a significant barrier to exercise habituation in our time-pressed society. Therefore, time-efficient exercise may contribute to the prevention of health risks not only in astronauts, but also in working adults in a modern society with time constraints and sedentary lifestyles.

Keywords : cardiorespiratory fitness, EPOC, HIIT, exercise training, MICT

Background

The Japan Aerospace Exploration Agency (JAXA) is trying to obtain technologies needed for an astronaut's extended stay in space. Astronauts in space need to keep their activities safe and healthy. Research on “*high-intensity interval aerobic exercise training (HIAT)*” was initiated as a JAXA project mainly focused on astronaut exercise programs for future long-term space missions. In a microgravity environment, the volume load on the left ventricle is reduced, and cardiac function deteriorates¹⁾. Consequently, an astronaut's cardiorespiratory fitness (CRF), which relates directly to physical working capacity and is evaluated by maximal oxygen intake ($\dot{V}O_{2max}$), decreases during spaceflight²⁾; and exercise, such as with a cycle ergometer, can be a useful countermeasure for this deterioration.

On the other hand, some researchers indicate that excessive exercise may promote an energy deficit and have a negative impact on long-term space missions³⁾. Many astronauts experience controversial, unhealthy weight loss during space missions because of energy imbalances⁴⁾. The issue of an astronaut's energy balance also influences food-transportation costs since an excessively exercising astronaut will require extra calories (food) to maintain their energy balance, thus increasing the spaceship's load. Therefore, reducing total energy expenditure (EE) induced by exercise should have a meaningful impact on long-term space missions. Moreover, the scheduled exercise program at the international space station (ISS) (approximately 2.5 hours per day, six times per week⁵⁾) may be excessive for time-pressed astronauts. Hence, a more efficient exercise program is crucial for future missions. And, high-intensity interval training (HIIT), which is an activity conducted within a short period but with a substantial impact on the $\dot{V}O_{2max}$, is considered a potential

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countermeasure for addressing these problems.

HIIT protocols

HIIT has gained attention recently, not only as an efficient training method for athletes, but also as an appropriate exercise prescription in public health⁶⁾. Recent review papers^{7,8)} indicate that the HIIT protocols are divided into two main types: sprint and aerobic types. Sprint-type HIIT improves $\dot{V}O_{2\max}$ mainly through increased oxidative capacity in peripheral muscles⁷⁾, whereas aerobic-type HIIT improves $\dot{V}O_{2\max}$ mainly through improved cardiac function⁸⁾. Studies have reported that existing HIIT protocols, namely the Wingate-based HIIT protocol⁷⁾ or the 4 × 4-min aerobic-type HIIT⁸⁾, were not optimal and high in intensity for astronauts whose CRF level decreases during space missions. Therefore, at JAXA we conducted a study to find a suitable HIIT protocol that can be routinely performed even by individuals whose CRF level is relatively low.

Through our preliminary experiments, two candidate HIIT protocols using a cycling ergometer, i.e., a sprint-type (sprint interval training: SIT) and an aerobic-type named the HIAT, were proposed (Table 1). We hypothesized that these candidate protocols are suitable for controlling EE and still have a significant positive impact on $\dot{V}O_{2\max}$ and cardiac function. We verified this hypothesis by conducting two types of a ground-based experiment as follows:

Experiment 1 compared the total EEs of SIT and HIAT with moderate-intensity continuous exercise training (MICT), which is one of the most common exercise protocols recommended for public health and is used on the ISS as the primary exercise protocol.

Experiment 2 compared the effects of SIT and HIAT on $\dot{V}O_{2\max}$ and cardiac function with that of MICT.

Experiment 1 (energy expenditure of HIAT)⁹⁾. When we discuss issues concerning total EE induced by exercise, we need to investigate not only the duration of the exercise but also the post-exercise recovery period. During this period, there is an increase in EE due to excess post-exercise oxygen consumption (EPOC). It has been reported in previous studies¹⁰⁾ that exercise intensity impacts the magnitude of EPOC. Our candidate protocols (SIT and HIAT) include not only shorter exercise durations, but also higher exercise intensities compared to MICT. Therefore, we need to determine the total EEs induced by SIT and HIAT, including their EE during EPOC.

In Experiment 1, ten young male adults (healthy, but non-athletes) completed three cycling trial sessions, i.e., SIT, HIAT, or MICT in random order, separated by approximately one week between each session. For each session, participants performed one of the three exercise trials and returned to the resting position to measure 180 mins EPOC. The net exercise EE during MICT, HIAT, and SIT was 350 ± 49 kcal, 161 ± 20 kcal, and 77 ± 8 kcal, respectively. However, EPOC's EE increased along with an increase in exercise intensity, i.e., SIT (32 ± 19 kcal), HIAT (21 ± 16 kcal), and MICT (13 ± 13 kcal). Furthermore, the total EE (net exercise EE + EPOC) during MICT, HIAT, and SIT was 363 ± 45 kcal, 182 ± 17 kcal, and 109 ± 20 kcal, respectively, in decreasing order, suggesting that EPOC did not affect the total EE for the entire session.

The differences in total EE between our interval protocols (SIT and HIAT) and the common cycling protocol (MICT) were approximately 180-250 kcal in this study. It corresponds to approximately 100-200 g of ISS foods (e.g., Japanese curry). When applied to the Mars500 mission, which is a simulation of a human-crewed flight to Mars over a 520-day (75-week) isolation period of six crew members, the selection of daily exercise protocol may mean a difference of about 270-540 kg ($100\text{-}200 \text{ g} \times$

Table 1. Exercise protocols used in JAXA's and J-NIOSH's studies.

	SIT (candidate 1)	HIAT (candidate 2)	MICT (reference)
Protocol	Warm-up (30 watts, 1~3 mins, 40-60 rpm) * $\left[\begin{array}{l} 120\% \text{ WL at } \dot{V}O_{2\max} \quad 30 \text{ seconds} \quad >85 \text{ rpm} \\ \text{rest} \quad 15 \text{ seconds} \end{array} \right.$ * Repeat 7 times (no rest at 7th) Cool-down (30 watts, 1~3 mins, 40-60 rpm)	Warm-up (30 watts, 1~3 mins, 40-60 rpm) I) 85% WL at $\dot{V}O_{2\max}$ 3 mins 70-80 rpm II) 50% WL at $\dot{V}O_{2\max}$ 2 mins 60 rpm III) 85% WL at $\dot{V}O_{2\max}$ 3 mins 70-80 rpm IV) 50% WL at $\dot{V}O_{2\max}$ 2 mins 60 rpm V) 80% WL at $\dot{V}O_{2\max}$ 3 mins 70-80 rpm Cool-down (30 watts, 1~3 mins, 40-60 rpm)	Warm-up (30 watts, 1~3 mins, 40-60 rpm) 60-65% WL at $\dot{V}O_{2\max}$ 40 mins 60 rpm Cool-down (30 watts, 1~3 mins, 40-60 rpm)
Total time	7~ mins	15~ mins	42~ mins
Volume†	110 kcal	180 kcal	360 kcal

† Previous study⁹⁾ shows the exercise volume including 3-h excess post-exercise oxygen consumption.

HIAT, high-intensity interval aerobic exercise training; MICT, moderate-intensity continuous exercise training; SIT, sprint interval training; $\dot{V}O_{2\max}$, maximal oxygen consumption; WL, workload

6 times/week exercise $\times$ 75 weeks $\times$ 6 members) in food requirements. Thus, the choice of exercise protocol may save significant food-transportation costs. Detailed information for experiment 1 are shown in the article⁹.

Experiment 2 (effect of HIAT on $\dot{V}O_{2\max}$ and cardiac function)^{11,12}. Experiment 2 compared the effects of SIT and HIAT on $\dot{V}O_{2\max}$ and cardiac function with those of MICT. Two randomized-control trials (RCT) were conducted in Experiment 2.

In the first trial (Study 1)¹¹, 42 healthy but sedentary male adults participated in an 8-week, 5 times/week, supervised exercise (cycling ergometer) intervention. They were randomly assigned to the SIT, HIAT, or MICT group. $\dot{V}O_{2\max}$ measurement and cardiac MRI were performed before and after the intervention. Significant increases in $\dot{V}O_{2\max}$ were observed in all three groups (SIT, $16.7 \pm 11.6\%$; HIAT, $22.5 \pm 12.2\%$; MICT, $10.0 \pm 8.9\%$) (Fig. 1-1, Study 1), while a significant group difference was only observed between HIAT and MICT. There were significant changes in left ventricular (LV) mass, stroke volume (SV) and resting heart rate (HR) in both SIT (LV mass, $6.5 \pm 8.3\%$; SV, $5.3 \pm 8.3\%$; HR, $-7.3 \pm 11.1\%$) and HIAT (LV mass, $8.0 \pm 8.3\%$; SV, $12.1 \pm 9.8\%$; HR, $-12.7 \pm 12.2\%$), but not in MICT (LV mass, $2.5 \pm 10.1\%$; SV, $3.6 \pm 6.6\%$; HR, $-2.2 \pm 13.3\%$).

In the second trial (Study 2)¹², to further reduce exercise volume, the exercise frequency was changed from 5 times to 3 times per week. SIT was omitted in this trial because of an insignificant group difference between SIT and MICT observed in the first trial. Here, 24 healthy but sedentary male adults participated in an 8-week, 3 times/week, supervised exercise intervention. We observed similar results (Fig. 1-1, Study 2) confirming the conclusions of the first trial that $\dot{V}O_{2\max}$ improvement with HIAT was more significant than that with MICT. Furthermore, the $\dot{V}O_{2\max}$ improvements (percentage changes) by HIAT in Study 2 were similar to those in Study 1 despite the reduction in training frequency by 2 days per week. Study 2 also showed that HIAT affected autonomic nervous system function in sedentary adults.

The significant group difference in $\dot{V}O_{2\max}$ improvement between HIAT and MICT in Experiment 2 is noteworthy because previous studies^{13,14} comparing a HIIT protocol with a MICT revealed that the increase in $\dot{V}O_{2\max}$ of their HIIT exceeded that of their MICT when the exercise volumes were matched. In our previous study, however, the exercise duration and volume of HIAT (15 mins, 180 kcal) were substantially less than (approximately half) those of MICT (42 mins, 360 kcal) (Table 1). These results emphasize the importance of exercise intensity rather than duration and volume in improving $\dot{V}O_{2\max}$. Detailed information for Experiment 2 (Studies 1¹¹ and 2¹²) is shown in the articles.

Results from Experiment 2 suggest that HIAT in our study would be a “time-efficient” exercise protocol and

a useful countermeasure for deterioration in CRF and cardiac function in space missions. In fact, a Japanese astronaut tried to incorporate HIAT in a recent ISS mission, and JAXA is considering utilizing HIAT as a routine exercise program for future missions.

HIAT for metabolic syndrome^{15,16}

Lack of time is a major barrier to exercise in our time-pressed society¹⁷. HIIT is considered to be a highly effective, time-efficient strategy for public health⁶. The HIAT protocol in our study, in particular, was developed for low-fitness individuals, so may be applied to sedentary office workers with low fitness. Accordingly, the National Institute of Occupational Safety and Health, Japan (J-NIOSH) conducted two RCT studies^{15,16} incorporating HIAT for workers with metabolic syndrome (MS). In the first study (Study 3)¹⁵, a time-efficient intervention strategy consisting of a HIAT intervention (8 weeks, 3 times/week) followed by a short-term (4 weeks) calorie restriction (CR) intervention was developed as an MS treatment method. Twenty-six male workers with MS (including pre-MS) were randomly assigned to either the HIAT or MICT group. After the 8-week exercise (i.e., HIAT or MICT) intervention, all participants both in HIAT and MICT groups participated in a 4-week CR without exercise intervention. The study reported that adding a CR intervention of only 4 weeks after an exercise intervention, either to HIAT or MICT, had a favorable effect on MS, and that HIAT ($25.4 \pm 14.6\%$), compared to MICT ($14.9 \pm 12.8\%$), had a more significant effect on $\dot{V}O_{2\max}$ (Fig. 1-1, Study 3), even though the exercise volume of HIAT was substantially less than that of MICT. The study also reported that the effect sizes for some MS risk factors in the HIAT group, compared to the MICT group, were relatively larger during the CR period, suggesting that positive effects from high-intensity exercise may continue during the CR period without exercise. Furthermore, the study revealed that the HIAT advantage on $\dot{V}O_{2\max}$ was promptly lost during the 4-week detraining period.

Referring to the results in Study 3, the second intervention study (Study 4)¹⁶ investigated the influence of the intervention order, i.e., HIAT followed by CR or CR before HIAT, on MS risk factors. The study tested the hypothesis that once-weekly HIAT would prevent a rapid decrease in $\dot{V}O_{2\max}$ during the post-intervention period. Thirty-two male and female workers with MS (including pre-MS) were randomly assigned to either the ‘HIAT-then-CR’ or ‘CR-then-HIAT’ group. This study reported that intervention order had no influence on changes in MS risk factors, i.e., both intervention methods improved MS risk factors similarly and that $\dot{V}O_{2\max}$ decreased when HIAT was discontinued, whereas once weekly HIAT could maintain the improved $\dot{V}O_{2\max}$ (Fig. 1-2, Study 4). Thus, our studies with MS workers again confirmed that time-efficient HIAT had a significant effect on $\dot{V}O_{2\max}$. Additionally, the

Fig. 1 Changes in $\dot{V}O_{2max}$ of four randomized-control trials.

Study 1 (Fig.1-1): forty-two sedentary young male adults participated in an 8-week, five times per week exercise (SIT, HIAT, or MICT) intervention. Study 2 (Fig.1-1): twenty-four sedentary young male adults participated in an 8-week, three times per week exercise (HIAT or MICT) intervention. Study 3 (Fig.1-1): twenty-six middle-aged male workers with MS participated in an 8-week, 3 times per week exercise (HIAT or MICT) intervention (they further participated in a 4-week CR intervention after the exercise intervention). Study 4 (Fig.1-2): thirty-two middle-aged male and female workers with MS participated in either HIAT-then-CR or CR-then-HIAT intervention.

SIT, sprint interval training; HIAT, high-intensity interval aerobic exercise training; MICT, moderate-intensity continuous exercise training; CR, calorie restriction; MS, metabolic syndrome

other interventional study¹⁸⁾, involving sedentary obese men with nonalcoholic fatty liver disease, showed that HIAT positively affected an improvement in hepatic stiffness. Detailed information for the aforementioned above studies are described in the articles referenced here^{15,16,18)}.

HIAT procedure for low-fitness individuals

This section explains some tips for HIAT intervention for low-fitness individuals. Table 1 shows that the intensity during the last high-intensity stage of HIAT (80% $\dot{V}O_{2max}$ at Stage V) was lower than the other two high-intensity stages (85% $\dot{V}O_{2max}$ at Stages I and III). This is because we observed that 5% workload (WL) reduction from the second high-intensity stage (Stage III) to the third high-intensity stage (Stage V) markedly relieved the subject's leg (also mental) stress while their HR remained at a higher level. We consider that the lower intensity during the last stage could be an effective expedient when HIAT is performed as a routine exercise method in sedentary individuals. In our intervention studies^{11,12,15,16,18)}, $\dot{V}O_{2max}$ measurement data were used to determine each participant's WLs of HIAT. Generally, for the first few weeks on intervention, most participants with low fitness cannot complete pre-determined WL. Therefore, the WLs are set 10-30 watts lower than pre-determined, making the absolute WLs for these individuals low level (for example, under 100 watts) even during the high-intensity

stages. WLs would then be gradually and progressively increased until they reach the pre-determined WLs. Actually, in our studies, averaged WL at the end of the intervention (the highest WL during intervention) was 208 ± 38 watts for young male participants¹²⁾ whereas it was 180 ± 20 watts for middle-aged male workers with MS¹⁵⁾.

HIAT in occupational health

Exercise habituation is generally recommended in public health. Nevertheless, the CRF level of adults has been declining internationally for the past several decades¹⁹⁾. In today's time-pressed society, finding time for exercise is difficult. Besides, working adults are more likely to be placed in sedentary situations²⁰⁾. Countermeasures for this problem is necessary. Although astronauts' health issues are not a common topic in occupational health, this field may provide clues in solving lifestyle-related health issues because the microgravity environment in space is similar to physical inactivity in reducing the load on the heart. Astronauts must schedule enough time for exercise despite their extremely busy schedules since a decline in CRF can quickly become life-threatening in their environment. However, this is not a problem only for astronauts. CRF is known as a vital health marker²¹⁾, and studies^{22,23)} have indicated that midlife CRF for the average person plays a significant role in health-related incidents in later life.

As lack of time is a major barrier to exercise habituation in our time-pressed society¹⁷⁾, promoting health “*within the workplace*,” as demonstrated by astronauts, may be vital in maintaining workers’ optimal health. So far, in our studies, some advantages of HIAT have been revealed from laboratory-based experiments. However, the reproducibility of the advantages in the real world is unknown. Recently, we tried to apply HIAT to sedentary office workers as a social implementation research in which the participants (employees) performed HIAT during their working hours in a temporary fitness room in their office building (Fig. 2). The participants’ positive comments in the interviews after the experiment included, “I was motivated to exercise because I had the permission of the company”; while negative comments included, “I didn’t want to exercise during work”, “I was worried about colleagues’ eyes, and didn’t want them to see me exercising,” and “Sweating after exercise affected my work”. Even under an environment where a fitness room is set up in the workplace and exercising is allowed during working hours, “exercising in the workplace” seems to have challenges. To overcome these challenges, not only providing facilities such as fitness rooms and training equipment, but also developing a culture that can be understood by managers and colleagues is important. Generally, in Japan, such a culture has not yet been widely accepted. Researchers in this field need to suggest ways to prevent the deterioration of CRF for people living in modern society, which tends to be dominated by a sedentary lifestyle with less load on the heart.

Fig. 2 Sedentary office workers participated in a HIAT intervention in their company building.

Employees performed the HIAT in a small, temporary fitness room, which had been usually used as a meeting room by the company.

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Conflict of Interests

The authors declare no conflict of interests in this article.

Author Contributions

The contributions of each author were as follows. TM contributed to developing the study concept and design, data acquisition, data analysis, and manuscript writing. RS contributed to developing the study concept and design, data acquisition, data analysis, and manuscript revisions. And, KT and CM contributed to developing the study concept and design and manuscript revisions. All authors read and approved the final manuscript.

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