Aerospace Science and Technology 34 (2014) 20–23

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Effects of microgravity on blood flow in the upper and lower limbs

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ARTICLE INFO

Article history:
Received 26 November 2013
Accepted 21 January 2014
Available online 12 February 2014

Keywords:
Blood flow
Microgravity
Parabolic flight
Upper limbs
Lower limbs

ABSTRACT

Fluid shifts toward the upper body may cause differences in the blood flow of the upper and lower limbs under microgravity compared to that under gravity conditions. Blood flow was compared between the upper and lower limbs in a sitting position under different gravity levels generated by parabolic flight of an airplane. The blood flow of both the upper and lower limbs increased immediately after 0 G. Thereafter, the blood flow of both the upper and lower limbs returned to the normal level observed under 1 G. The blood flow of the upper limbs remained at the normal level during 0 G and after 1.5 G, whereas the blood flow of the lower limbs decreased during 0 G. The decreased blood flow of the lower limbs recovered to the normal level after 1.5 G. We concluded that decreased blood flow, under microgravity conditions, is observed in the lower limbs, but not in the upper limbs.

1. Introduction

Downregulation of the mRNA expression of heat shock proteins (HSPs), e.g., HSP27, HSP70, and HSP84, and atrophy and type shift of fibers in skeletal muscles of rats occur in response to exposure to microgravity [5,7,22]. These changes in skeletal muscles are observed after hindlimb suspension-induced unloading on Earth [9,12,16]. The atrophy and type shift of fibers in skeletal muscles following exposure to microgravity and unloading are more marked in slow muscles such as the soleus muscle, than in fast muscles such as the extensor digitorum longus and plantaris muscles; the weight of the soleus muscle of male rats decreased by 23% after 7 days of exposure to microgravity, whereas the weight of the extensor digitorum longus muscle decreased by 11% [4]. Additionally, greater weight loss was observed in the hindlimb muscles than in the forelimb muscles. The weight of the soleus muscle in the hindlimbs of male rats decreases by 23–40% after 5–19 days of exposure to microgravity, whereas those of the biceps and triceps brachii muscles in the forelimbs decreased by 12–24% [25].

Adequate blood flow, which continuously delivers nutrients and oxygen to individual cells, is necessary to maintain the function and metabolism of skeletal muscles and their fibers, particularly antigravity slow muscles and high-oxidative fibers, in the hindlimbs. The soleus, plantaris, and extensor digitorum longus muscles in the hindlimbs of rats have smaller fiber sizes and higher oxidative enzyme activities than the biceps brachii and triceps brachii muscles in the forelimbs [8,15,17–19], indicating that skeletal muscles and their fibers in the hindlimbs require more nutrients and oxygen from the capillaries to maintain their function and metabolism than those in the forelimbs. Therefore, there is a possibility that decreased blood flow, which may be more pronounced in the lower limbs of humans under microgravity conditions because of fluid shifts toward the upper body [14,27], is associated with muscle atrophy in the lower limbs. However, there are no data available on the comparison of blood flow between the upper and lower limbs under microgravity conditions. In this study, we examined the differences in blood flow between the upper and lower limbs of humans in a sitting position under microgravity compared to that under gravity conditions.

2. Materials and methods

This study was approved by the Institutional Committee of Human Experimentation of Kyoto University (Kyoto, Japan). Healthy man (22 years of age, subject A) and woman (36 years of age, subject B) were enrolled in this study. The subjects underwent a special physical examination and gave written informed consent for participation in this study. They were not on any medication before and during parabolic flight.

The blood flow of the upper and lower limbs in a sitting position was measured by a laser-Doppler flow meter (FLO-N1; NeuroScience Inc., Tokyo, Japan). Probes for flowmetry were attached to the back of the hand and the instep before parabolic flight. The data were transferred to a personal computer via an interface

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http://dx.doi.org/10.1016/j.ast.2014.01.009
1270-9638/

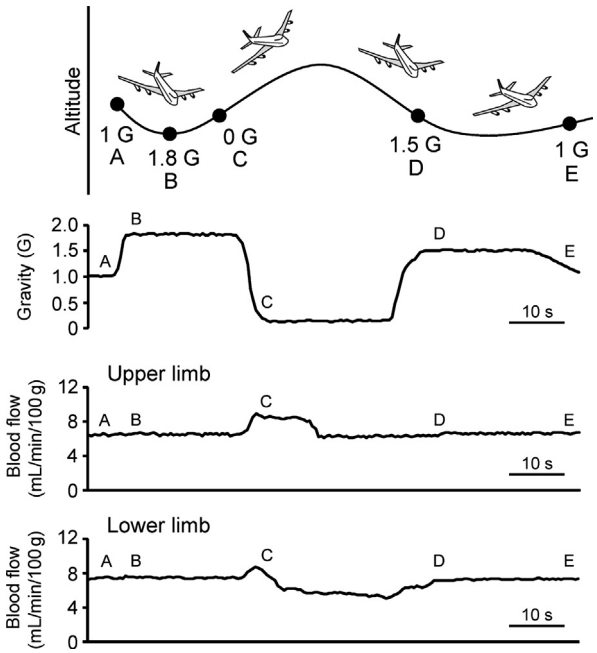

Fig. 1. Schematic drawing of the parabolic trajectory in combination with traces in gravity and blood flow of the upper and lower limbs of 1 subject under different gravity levels generated by the parabolic flight of an airplane.

(EFA/400; Distributed Design Concept, Dover, NH) from the flow meter. Blood flow was continuously measured during parabolic flight, and the subjects checked their blood flow using a monitor on the computer with real-time. The data were stored using a data recording software, LogWorx, Ver. 1.804 (Distributed Design Concept).

Hyper- and microgravity conditions were generated via the parabolic flight of an airplane (Gulfstream II; Diamond Air Service Inc., Nagoya, Japan). The subjects fastened a seat belt, maintained a sitting position, and fixed their upper and lower limbs during parabolic flight. Gravity levels were altered from 1 to 1.8 G. Thereafter, gravity was set at 0 G for 22 s. The gravity levels were increased from 0 to 1.5 G followed by a new steady state at 1 G. Parabolic flights were conducted with an interval of approximately 10 min of 1 G between each parabolic flight. The blood flow of the upper and lower limbs was determined during 5 parabolic flights (3 for subject A and 2 for subject B).

One-way analysis of variance (ANOVA) was used to evaluate significant differences in the time-dependent changes in blood flow of the upper and lower limbs under different gravity levels. When the differences seemed significant as per ANOVA, further comparisons were made using post-hoc tests.

3. Results

Representative time-dependent changes in gravity and the blood flow of the upper and lower limbs of 1 subject are shown in Fig. 1. Gravity levels were altered from 1 to 1.8 G and maintained at 1.8 G for 18–20 s. Thereafter, the gravity level was set at 0 G for 22 s. The gravity levels were increased from 0 to 1.5 G and maintained at 1.5 G for 18–22 s, followed by a new steady state at 1 G. There was a difference in blood flow between the upper and lower limbs during parabolic flight.

Individual data of blood flow from 5 parabolic flights (3 for subject A and 2 for subject B) are shown in Fig. 2. The blood flow of 5 parabolic flights displayed similar changes, and therefore, we combined these 5 datasets and compared the time-dependent changes in blood flow of the upper and lower limbs under different gravity levels.

The blood flow of both the upper and lower limbs did not change under 1.8 G. The blood flow of both the upper and lower limbs increased immediately after 0 G. The increased blood flow of the upper limbs was maintained for 6 s, after which it returned to the normal level observed under 1 G. Thereafter, the blood flow of the upper limbs remained at the normal level during 0 G and after 1.5 G conditions.

In contrast, the blood flow of the lower limbs decreased after 10 s at 0 G, and the decreased blood flow was maintained under 0 G. The decreased blood flow of the lower limbs recovered to the normal level after 6 s at 1.5 G.

4. Discussion

In this study, we collected the data of blood flow in 3 parabolic flights for 1 male subject and 2 parabolic flights for 1 female subject of different ages. We pooled these 5 datasets and compared the time-dependent changes in blood flow of the upper and lower limbs during parabolic flight because we observed no differences in blood flow according to gender and age during parabolic flight (Fig. 2). We will collect further data concerning blood flow of the upper and lower limbs of different subjects of different genders and ages to confirm the present results.

Bailliart et al. [2] measured instantaneous thigh and calf girths of standing subjects at 1, 1.7, and 0 G during parabolic flight, by using strain-gauge plethysmography. Leg segment volumes during 1.7 G increased by 0.9% for the thigh and by 0.5% for the calf relative to 1 G. In contrast, leg segment volumes during 0 G following hypergravity were reduced by 3.5% for the thigh and by 2.5% for the calf relative to 1.7 G. An increased volume at the end of hypergravity conditions and a subsequent decrease in volume during microgravity conditions were due to fluid shifts, most probably corresponding to venous blood shifts, which were induced by hemodynamic alterations. However, it is difficult to determine the fluid shifts by using only limb volumes because skeletal muscles in the standing position contract and relax under hypergravity and microgravity, respectively, and therefore, changes in muscle volume depend on the gravity levels.

There are no previous studies available concerning differences in blood flow between the upper and lower limbs in response to microgravity conditions. In this study, the blood flow of both the upper and lower limbs increased immediately after 0 G. Acute weightlessness during parabolic flight increased the seated cardiac output by 29% without increasing the mean arterial pressure [20]. Similarly, cardiac output is increased and the vasculature dilated and relaxed from the very onset of weightlessness compared to upright standing or sitting on the ground [24,26], whereas arterial pressure and heart rate are unaffected [20,21]. This is in accordance with observations that acute weightlessness during parabolic flight leads to a decrease in systematic vascular resistance [20]. Therefore, a suggested cause of the increased blood flow of both the upper and lower limbs immediately after 0 G is that cardiac distension is promptly counteracted by an increase in cardiac output, which leads to baroreflex-mediated systemic vasodilatation, from the very onset of weightlessness generated by parabolic flight [20,21,23].

We found that exposure to microgravity decreases the oxidative enzyme activity of medium-sized motoneurons in the spinal cord innervating the skeletal muscles of rats [10,11]. In addition, we observed that the oxidative enzyme activity of spinal motoneurons innervating the hindlimb muscles, but not the forelimb muscles, of rats decreased after exposure to microgravity [13]. Finally, these results suggest that the decreased oxidative enzyme activity of spinal motoneurons is linked to atrophy and/or a type shift of oxidative fibers in the hindlimb muscles under microgravity conditions.