脊髄損傷者の運動時循環応答*

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Cardiovascular response during exercise in individuals with spinal cord injury

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要　旨

In individuals with spinal cord injury (ISCI), the cardiovascular responses during arm exercise differ from those in able-bodied subjects (ABS). Because in ISCI the loss of the sympathetic vasomotor response and the inactivity of the skeletal muscle pump below the lesion interfere with the effective redistribution of the blood to the active muscles. This leads to diminished venous return from the paralyzed area, which results in reduced stroke volume (SV) at a given cardiac output ($\dot{Q}$) and oxygen uptake ($\dot{V}O_2$) during arm exercise, compared to those in ABS.

Several investigators have interpreted the diminished venous return as mainly due to the increased venous blood pooling in the paralyzed lower limbs with exercise in ISCI. On the other hand, Hopman (1994) objected to this explanation, and suggested two new hypotheses to account for the blood redistribution incapacity below the lesion. One hypothesis posits that persistent venous blood pooling arises due to the lack of sympathetic vasoconstriction below the lesion. The venous blood pooling below the lesion at rest also persists even during arm exercise. The other hypothesis is diminished vascular bed in the legs of ISCI due to the marked muscle atrophy. The diminished vascular bed in the legs is conceived as precluding blood flow from this area during arm exercise. Thus, the circulatory characteristics in the paralyzed lower limbs during exercise in ISCI clearly need to be clarified.

The purpose of my dissertation research is, therefore, to clarify the effect on the circulation in the paralyzed area on the cardiovascular responses during arm exercise in ISCI. For this purpose, I investigated the cardiovascular responses during arm-cranking exercise (ACE) at various work loads and durations in ISCI with lesions at different levels, and especially focused on the blood flow in the paralyzed lower limbs. Furthermore, their circulatory responses were studied during passive leg

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exercise which can be considered as an effective method for promoting the circulation of the paralyzed lower limbs. If the blood pooling exists in the paralyzed area, the cardiovascular responses would be effected by passive leg exercise.

The purpose of the delineated in Chapter 2 was to clarify the effect of the level of SCI and of daily exercise on the relationship between $\dot{V}O_2$ and heart rate (HR) during submaximal ACE in ISCI. Twenty-nine male ISCI with lesions at various levels and eleven ABS performed an ACE at three submaximal exercise intensities. The relationship between $\dot{V}O_2$ and HR indicated that the HR at a given $\dot{V}O_2$ increased with the level of spinal cord injury (SCI) during ACE. Furthermore, the HR at a given $\dot{V}O_2$ during the exercise was significantly higher in ISCI than CS. These results suggested that greater paralyzed area led to greater decrease in venous return and consequently to an increase in HR during exercise. In addition, the HR in active ISCI was lower in comparison with those in inactive ISCI. These results clearly showed that the $\dot{V}O_2$ - HR relationship in ISCI is markedly influenced by both the level of SCI and habitual exercise.

The purpose of the investigation described in Chapter 3 was to examine whether an increase in $\dot{Q}$ during submaximal ACE produces changes in the blood flow in the paralyzed lower limbs in ISCI. Ten ISCI with lesions at various levels (T5 - L5) and six ABS performed ACE at different submaximal exercise intensities (10, 30 and 50 W) for 6 min. Throughout the exercise, the skin blood flow (SBF) at the thigh (SBFT) was monitored using laser-Doppler flowmeter. The response of SBFT depended on the level of SCI. In ISCI with lesions above T12, the SBFT was unchanged during ACE, irrespective of exercise intensity. On the other hand, in ISCI with lesions below L1, the SBFT increased significantly with an increase in $\dot{V}O_2$ and HR, although the SBFT at a given $\dot{V}O_2$ and HR was lower than that in the ABS. These results suggest that the circulation below the lesion was unaffected by the increase in $\dot{Q}$ during submaximal arm exercise.

Chapter 4 reports the response of SBF in the paralyzed lower limbs in ISCI during prolonged ACE sufficient to produce an elevation in core temperature (T_c). Moreover, the relationship between the SBF and T_c in ISCI was compared with that in ABS. Eight ISCI with lesions from T6 to L5 and six ABS performed ACE at 20 W for 30 min at an ambient temperature of 25℃. Similar to in the study presented in Chapter 3, the increase in the SBFT depended on the level of SCI. The SBFT in the four ISCI with higher lesions (T6 to T12) remained unchanged during exercise. The SBFT in the other four ISCI with lower lesions (T12 to L5, ΔSBFT+) began to elevate markedly when the tympanic membrane temperature (T_{ty}) exceeded a threshold temperature of 36.69℃. In those with ΔSBFT +, however, the peak of SBFT during exercise was significantly lower in comparison with that in ABS. This lower peak in the ISCI with ΔSBFT+ was considered to be related to the additional time required to reach the threshold T_{ty} in this group, because the T_{ty} at rest was much lower than threshold.

Chapter 5 presents the response of blood circulation in the paralyzed lower limbs evaluated during maximal ACE (MACE) in ISCI. MACE elicits greater $\dot{Q}$, which may induce changes in blood flow in the paralyzed lower limbs. The SBFT and SBF at the calf (SBFC) in eight ISCI with lesions from T3 to L1 were monitored at rest and for 15 s immediately after the graded MACE test. In all ISCI, neither SBFT nor SBFC was changed immediately after MACE, compared with the values at rest. These results suggest that in ISCI with higher lesions, the circulation below the lesion is unaffected by the relative increase in $\dot{Q}$ during MACE. On the other hand, in ISCI with lower lesions, it is considered that the circulation in the inactive lower limbs is inhibited, supplying more blood to the active upper limbs.

The results presented in Chapter 3, 4, and 5 oppose the concept of increased venous blood pooling in the paralyzed lower limbs with arm exercise in ISCI. Therefore, it is necessary to examine the two hypotheses as to the cardiovascular characteristic of persistent venous blood pooling and venous atrophy in the paralyzed lower limbs as suggested by Hopman (1994). Chapter 6 presents the cardiovascular responses to passive leg cycle exercise (PLE) of the paralyzed lower limbs in ISCI. It is possible that the PLE produces promotion of circulation in the paralyzed lower limbs, and consequently increases venous return from the lower limbs to the heart, if there is venous blood pooling at rest. Eight ISCI at lesions from T8 to L1 and five ABS performed PLE at 20 and 40 rpm for 7 min with the lower limbs using a modified recumbent ergometer with pedals driven by a motor. During PLE, the ISCI showed significant increase in $\dot{Q}$ and SV without a rise of HR. These results suggest the promotion of venous return from the paralyzed lower limbs and support the hypothesis of persistent venous blood pooling.

In conclusion, the cardiovascular responses during arm exercise in ISCI are markedly influenced by the level of the SCI and the corresponding size of the paralyzed area. The HR during exercise increases with the size of the paralyzed area. This increase in HR is considered to be due to the reduction of venous return from the paralyzed area. In ISCI with lesions at or above T12, the blood flow in the lower limbs remains unchanged, regardless of the exercise intensity or exercise duration. This suggests that the circulation in the paralyzed lower limbs is unaffected by arm exercise. On the other hand, in ISCI with lesions at or below T12, the SBF in the lower limbs depends in part on the change in T_c. The SBFT begins to markedly increase once the T_{ty} exceeds a critical temperature. Because the sympathetic vasomotor responses in the lower limbs are preserved in ISCI with lesions at or below T12, the blood flow in the lower limbs seems fundamentally dependent on the level of the SCI. There are two hypotheses to account for the altered cardiovascular response in ISCI; persistent venous blood pooling and venous atrophy. To test these hypotheses, the cardiovascular responses in ISCI were examined during PLE, which can be considered to promote circulation in the paralyzed lower limbs. During the PLE, increases in $\dot{Q}$ and SV were observed in ISCI. These results suggest an increase in venous return from the paralyzed lower limbs during PLE and imply the existence of venous blood pooling in the paralyzed lower limbs.

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Chapter 2

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Chapter 6

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