Attenuation of hypercapnic carbon dioxide chemosensitivity after postinfarction exercise training: possible contribution to the improvement in exercise hyperventilation

T Tomita, H Takaki, Y Hara, F Sakamaki, T Satoh, S Takagi, Y Yasumura, N Aihara, Y Goto, K Sunagawa

Objective: To elucidate the responsible mechanisms of increased slope of minute ventilation relative to carbon dioxide production (VE/VCO₂) during exercise after acute myocardial infarction without overt signs of heart failure, patients who had an acute myocardial infarction were examined after participating in a three month supervised exercise training programme.

Design: Exercise testing, hypercapnic CO₂ chemosensitivity measurement (rebreathing method), and pulmonary function test were repeated at entry and after three months in 50 acute myocardial infarction patients with neither symptoms nor signs of heart failure who completed the training programme. Ten patients who performed initial inhospital training served as controls.

Results: Age, peak oxygen uptake, left ventricular ejection fraction, CO₂ chemosensitivity, respiratory parameters (percentage of predicted normal vital capacity [%VC]), forced expiratory volume in one second (FEV₁), left ventricular ejection fraction, and because ergoreflex overactivation, probably caused by prolonged inactivity, does not appear to occur in these patients, we can postulate that these results may be associated with alteration in CO₂ chemosensitivity through unknown mechanisms such as excessive sympathetic tone, which has been observed in these patients and has been implicated as a factor of accelerated ventilation. We therefore measured exercise ventilation, hypercapnic CO₂ chemosensitivity, and respiratory function, including TICO, before and after a three month exercise training programme in patients with acute myocardial infarction. The purpose of the present study was twofold: firstly, to evaluate the determinants of an increased VE/VCO₂ slope in patients with acute myocardial infarction but with neither symptoms nor signs of heart failure; and, secondly, to examine the hypothesis that alteration in CO₂ chemosensitivity contributes to the attenuation of the VE/VCO₂ slope after exercise training.

Conclusion: After acute myocardial infarction, exercise hyperventilation is seen in association with aging, enhanced hypercapnic CO₂ chemosensitivity, and reduced TICO, even in the absence of overt heart failure. The correlation of VE/VCO₂ attenuation after training with the reduction in CO₂ chemosensitivity suggests that exercise training may reduce increased VE/VCO₂ slope, at least partially by reducing CO₂ chemosensitivity.

Abbreviations: FEV₁, forced expiratory volume in one second; LVEF, left ventricular ejection fraction; TICO, carbon monoxide transfer factor; VC, vital capacity; VE/VCO₂, minute ventilation relative to carbon dioxide production; V₀₂, oxygen uptake
Symptom limited exercise testing, pulmonary function testing, and measurement of CO₂ chemosensitivity were repeated at entry into the training programme and three months later in all 60 subjects. The three tests were performed on the same day: exercise testing was followed by pulmonary function testing and measurement of CO₂ chemosensitivity after at least 30 minutes of rest. The first and second examinations were conducted 19 (14) days (median 17 days) and 111 (23) days (median 108 days) after the onset of myocardial infarction, respectively. All subjects gave written informed consent for the study.

**Exercise test with gas analysis**

Symptom limited exercise testing with simultaneous gas analysis (AE-280, Minato Medical Science, Osaka, Japan) was performed on an electronically braked ergometer (Examiner 400, Lode, Groningen, The Netherlands) in the upright position. After unloaded bicycling (0 W) for one minute, exercise intensity was increased in a ramp fashion (15 W/min) until exhaustion in terms of dyspnoea or fatigue. Subjects were constantly encouraged to make their maximal efforts. ECGs were continuously monitored throughout the test. Arterial blood pressure was measured by cuff sphygmomanometer every minute during exercise and 1–2 minutes during recovery. Peak VO₂ was determined as the averaged VO₂ over 18 seconds before the termination of exercise. The slope of the linear regression relating minute ventilation to CO₂ output between the beginning of the exercise and the respiratory compensation point was used as the index of the ventilatory response to exercise (VE/VO₂ slope).

**Pulmonary function test**

Standard measurements of forced expiratory volume in one second (FEV₁) and vital capacity (VC) were made with PUDAC-70 (Fukuda Denshi Co Ltd, Tokyo, Japan). Pulmonary carbon monoxide diffusion (TlCO) was measured using a single breath technique. These data were expressed as a percentage of predicted normal values (%FEV₁, %VC, and %TlCO) on the basis of standard nomograms incorporating age, sex, height, and weight.

**CO₂ chemosensitivity measurement**

According to the CO₂ rebreathing method reported by Read,¹ we measured CO₂ chemosensitivity as follows. Breath by breath minute ventilation and end tidal CO₂ concentration were measured by the gas analyser system (AE-280, Minato Medical Science), and the data were stored in the computer hard disk for later analysis. We used custom made equipment consisting of a mouthpiece, an airway tube with a one way valve, and a 6 l bag, which initially contained a gas mixture of 7% CO₂ in 93% O₂. The test was terminated earlier if subjects had too strong a sensation of dyspnoea to continue the rebreathing or if end tidal CO₂ concentration exceeded 10%. CO₂ chemosensitivity was defined as the slope of the increase in minute ventilation relative to the increase in end tidal CO₂ concentration and was expressed in terms of l/min/mm Hg. Because CO₂ chemosensitivity reported by others varies considerably,¹⁰ ¹⁷ ¹⁸ ¹⁹ we examined age matched healthy subjects (n = 9, 62 (8) years old) without any cardiovascular disease.

**Exercise training programme**

Initial early sessions of the exercise training programme were conducted individually under close supervision for approximately the first two weeks during hospitalisation. Patients

### METHODS

#### Study population

Among patients who were admitted to the coronary care unit of our hospital for the diagnosis of acute myocardial infarction, 60 consecutive patients were enrolled into this study. They subsequently (during hospitalisation) participated in the supervised exercise training programme at our rehabilitation institute and consented to take part in the study (table 1). The mean (SD) interval between the onset of myocardial infarction and entry into the programme was 13 (4) days (median 13 days). Forty three of the 60 patients (72%) received revascularisation in the acute phase of infarction. In the acute phase, eight patients had transient haemodynamic impairment defined as a grade of subset II or greater according to the Forrester classification. At entry, no patients had previous myocardial infarction and entry into the programme was 13 (4) days post myocardial infarction, respectively. All subjects gave written informed consent for the study.

#### Table 1 Patient characteristics

<table>
<thead>
<tr>
<th></th>
<th>Group C (n=10)</th>
<th>Group T_low (n=27)</th>
<th>Group T_high (n=23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>57 (13)</td>
<td>58 (11)</td>
<td>63 (7)</td>
</tr>
<tr>
<td>Men/women</td>
<td>7/3</td>
<td>22/5</td>
<td>22/1</td>
</tr>
<tr>
<td>Ejection fraction (%)</td>
<td>46 (9)</td>
<td>45 (8)</td>
<td>41 (10)</td>
</tr>
<tr>
<td>Forrester’s subset II or greater</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Drug administration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACE inhibitors</td>
<td>8 (80%)</td>
<td>16 (59%)</td>
<td>14 (61%)</td>
</tr>
<tr>
<td>β Blockers</td>
<td>4 (40%)</td>
<td>2 (7%)</td>
<td>7 (30%)</td>
</tr>
<tr>
<td>Digoxin</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>3 (13%)</td>
</tr>
<tr>
<td>Spirometry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VC (%predicted)</td>
<td>105 (13)</td>
<td>102 (12)</td>
<td>97 (13)</td>
</tr>
<tr>
<td>FEV₁ (%predicted)</td>
<td>82 (6)</td>
<td>86 (11)</td>
<td>80 (11)</td>
</tr>
<tr>
<td>TlCO (%predicted)</td>
<td>102 (17)</td>
<td>105 (17)</td>
<td>96 (26)</td>
</tr>
<tr>
<td>Peak VO₂ (ml/kg/min)</td>
<td>24 (5)</td>
<td>23 (5)</td>
<td>19 (4)†</td>
</tr>
<tr>
<td>VE/VO₂ slope</td>
<td>30 (10)</td>
<td>25 (3)</td>
<td>35 (9)†</td>
</tr>
</tbody>
</table>

Data are mean (SD) or number of patients. *p<0.05 v control; †p<0.05 v T_low (pretraining slope of minute ventilation relative to carbon dioxide production [VE/VO₂] <30). ACE, angiotensin converting enzyme; Group C, control group; FEV₁, forced expiratory volume in one second; Peak VO₂, peak oxygen uptake; T_low, pretraining VE/VO₂ slope 30 (10) 25 (3)* 35(5)*†

¹ ² ³ ⁴ ⁵ ⁶ ⁷ ⁸ ⁹ ¹⁰ ¹¹ ¹² ¹³ ¹⁴ ¹⁵ ¹⁶ ¹⁷ ¹⁸ ¹⁹ ²⁰ ²¹ ²² ²³ ²⁴ ²⁵ ²⁶ ²⁷ ²⁸ ²⁹
performed brisk walking on an indoor track and light bicycling at a heart rate of 20–30 beats/min above the resting rate. Subsequent standard training programme for 50–90 minutes consisted of bicycling and aerobic exercise (calisthenics, stretching, dancing) under the guidance of an exercise trainer. In this late phase, the exercise intensity was maintained at a heart rate of 50–60% of heart rate reserve, calculated from the resting and peak heart rate during the symptom limited exercise test. During each session, we continuously monitored the ECG to maintain each patient’s individual training heart rate.

Statistical analysis
Data are expressed as mean (SD). We conducted linear univariate regression analysis to assess the significance of association between VE/V\text{CO}_2 and its possible correlates. To determine which of these factors were significant independent determinants of the VE/V\text{CO}_2 slope, we used multivariate regression analysis. Between group analysis was done by one way analysis of variance with Scheffé’s test for multiple comparisons. The paired \( t \) test was used for comparisons within a group. Data were considered to be significantly different if \( p < 0.05 \) was observed.

RESULTS
At baseline, there was no significant difference between the training group (groups T\text{High} and T\text{Low}) and group C with respect to age, male to female ratio, LVEF, incidence of Forrester’s subset II or greater, or use of drugs (angiotensin converting enzyme inhibitors, \( \beta \) blockers, and digoxin), spirometric parameters, or peak \( V_0 \) (table 1). However, when the three groups were compared separately (groups T\text{High}, T\text{Low}, and C), peak \( V_0 \) in group T\text{High} was significantly lower than that in group T\text{Low} or group C (both \( p < 0.05 \)). Trends towards higher age, greater male to female ratio, lower LVEF, and more frequent use of digoxin were also observed in group T\text{High} but these differences did not reach significance.

In nine age matched normal healthy subjects, hypercapnic CO\text{2} chemosensitivity was estimated to be 1.4 (0.4) l/min/mm Hg. This value was quite similar to that of group C (1.3 (1.0) l/min/mm Hg) and group T\text{Low} (1.3 (0.5) l/min/mm Hg) under baseline conditions (at entry into the exercise training programme). Only group T\text{High} (2.0 (0.7) l/min/mm Hg) had higher than normal values of CO\text{2} chemosensitivity (\( p < 0.05 \)).

Baseline relation of variables of pulmonary function and CO\text{2} chemosensitivity to VE/V\text{CO}_2 slope
In the 60 patients under the baseline conditions, three pulmonary function variables were all weakly but significantly correlated with the VE/V\text{CO}_2 slope during exercise (percentage of predicted normal carbon monoxide transfer factor [%T\text{CO}_2], \( r = -0.33, p = 0.01 \); percentage of predicted normal vital capacity [%VC], \( r = -0.28, p = 0.03 \); and percentage of predicted forced expiratory volume in one second [%FEV\text{1}], \( r = -0.30, p = 0.02 \)). CO\text{2} chemosensitivity was relatively strongly correlated with the VE/V\text{CO}_2 slope (\( r = 0.62, p < 0.001 \)).
phase haemodynamic impairment (subset II or greater of Forrester class). The multivariate regression model including the above six significant variables with p < 0.05 showed that age, %TLCO, and CO2 chemosensitivity were significant independent variables; however, the association was most evident for CO2 chemosensitivity (β = 0.49, p < 0.0001) compared with age (β = 0.29, p = 0.007) and %TLCO (β = −0.27, p = 0.008). These results suggest that CO2 chemosensitivity has an important role in determining the V̇E/ V̇CO2 slope early after acute myocardial infarction, although multiple factors seem to be involved in the pathogenesis.

Changes in peak V̇O2 and V̇E/ V̇CO2 slope

Peak V̇O2 and V̇E/ V̇CO2 slope did not change significantly in group C at the exercise testing after three months (table 2). In 50 patients who completed the exercise training programme, peak V̇O2 increased significantly from 21 (5) to 23 (5) ml/min/kg after the three month training programme (p < 0.001). This improvement was similar in both subgroups (p < 0.01 for group Tlow, p < 0.001 for group THigh). The V̇E/ V̇CO2 slope was significantly attenuated in group THigh (p < 0.001) but not in group Tlow after three months compared with the baseline value. The changes in V̇E/ V̇CO2 slope for the whole group (30 (6.4) to 29 (6.0)) did not reach significance (p = 0.11).

Changes in CO2 chemosensitivity and pulmonary function parameters

After three months, CO2 chemosensitivity in group C remained unchanged (1.3 (1.0) to 1.4 (1.3) l/min/mm Hg, NS), while that in the training group was significantly attenuated from 1.6 (0.7) to 1.3 (0.6) l/min/mm Hg (p < 0.001) in the whole

| Table 2 | Changes in exercise parameters, CO2 chemosensitivity and spirometric variables before and after a three month exercise training programme |
|---------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
|         | Group C                                        | Group Tlow                                     | Group THigh                                    |
|         | Before After                                   | Before After                                   | Before After                                   |
| Exercise testing | | | | |
| Peak V̇O2 (ml/kg/min) | 24 (5) | 25 (6) | 23 (5) | 25 (6)** | 19 (4) | 21 (3)***** |
| V̇E/ V̇CO2 slope | 30 (10) | 29 (8) | 25 (3) | 26 (4) | 35 (5) | 33 (6)* |
| CO2 chemosensitivity (l/min/mm Hg) | 1.3 (1.0) | 1.4 (1.3) | 1.3 (0.5) | 1.0 (0.4)***** | 2.0 (0.7) | 1.6 (0.7)***** |
| Spirometry | | | | | |
| VC (%predicted) | 105 (13) | 107 (18) | 102 (12) | 104 (12) | 97 (13) | 101 (13)* |
| FEV1 (%predicted) | 82 (6) | 81 (7) | 86 (11) | 86 (14) | 80 (11) | 81 (12) |
| TLC (%predicted) | 102 (17) | 108 (17) | 105 (17) | 115 (21)***** | 96 (26) | 100 (29) |

*p<0.05; **p<0.01; ***p<0.001 v baseline.

Figure 2. Relation between changes (Δ) in the V̇E/ V̇CO2 slope and in CO2 chemosensitivity, and between changes in the V̇E/ V̇CO2 slope and in spirometric parameters in the training group (n = 50). Changes in the V̇E/ V̇CO2 slope after three months were significantly correlated with changes in CO2 sensitivity (r = 0.50, p < 0.001) but not with changes in spirometric parameters.
group. This attenuation was significant in both subgroups (p < 0.001 for group T\textsubscript{sw}, p < 0.001 for group T\textsubscript{sh}).

Among the three pulmonary function parameters, in the training group %VC and %TLCO increased significantly (both p < 0.05), while %FEV\textsubscript{1} remained unchanged. When analysed separately within each subgroup, significant changes were observed in %VC only in group T\textsubscript{sh} (p < 0.05) and in %TLCO only in group T\textsubscript{sw} (p < 0.001). None of these three parameters was significantly different in group C.

**Changes in VE/V\textsubscript{CO\textsubscript{2}} slope versus changes in CO\textsubscript{2} chemosensitivity and pulmonary function parameters**

In the 50 patients in the training group, the changes from baseline in the VE/V\textsubscript{CO\textsubscript{2}} slope after three months were significantly correlated with changes in CO\textsubscript{2} sensitivity (r = 0.50, p < 0.001). No such significant correlation was found for any of these pulmonary function variables (fig 2). When analysed separately within each subgroup, significant changes were observed in VE/V\textsubscript{CO\textsubscript{2}} slope only in group T\textsubscript{sh} (p < 0.05) and in %TLCO only in group T\textsubscript{sw} (p < 0.001). None of these three parameters was significantly different in group C.

**DISCUSSION**

Our previous study showed that an increased VE/V\textsubscript{CO\textsubscript{2}} slope (≥ 30) during exercise is seen in a substantial proportion (over 40%) of patients with acute myocardial infarction, in whom the increased slope was attenuated after three months’ exercise training. The present study has confirmed these results in a separate population. We aimed at exploring the mechanisms responsible for the above hitherto unknown issues and obtained the following results. (1) Among the three subgroups, only group T\textsubscript{sh} with increased VE/V\textsubscript{CO\textsubscript{2}} relative to baseline had higher than normal CO\textsubscript{2} chemosensitivity. (2) Age, TLCO, and CO\textsubscript{2} chemosensitivity were independently related to the baseline VE/V\textsubscript{CO\textsubscript{2}} slope. (3) Regardless of the baseline level, CO\textsubscript{2} chemosensitivity was significantly attenuated after exercise training. Changes in the VE/V\textsubscript{CO\textsubscript{2}} slope after exercise training were significantly correlated only with changes in CO\textsubscript{2} chemosensitivity, with no effect on the other parameters. These results suggest that, even in the absence of overt heart failure, VE/V\textsubscript{CO\textsubscript{2}} slope is increased in a significant proportion of postinfarct patients in association with aging, reduced TLCO, and enhanced CO\textsubscript{2} chemosensitivity, and that the increased VE/V\textsubscript{CO\textsubscript{2}} slope may be reduced by exercise training, at least partially, through the attenuation of CO\textsubscript{2} chemosensitivity. To our knowledge, in patients with heart disease, the possible role of CO\textsubscript{2} chemosensitivity in the improvement in increased VE/V\textsubscript{CO\textsubscript{2}} slope after exercise training has not been shown elsewhere.

**Mechanisms for increased VE/V\textsubscript{CO\textsubscript{2}} slope**

Although the detailed mechanisms underlying the increased VE/V\textsubscript{CO\textsubscript{2}} slope during exercise are still debated, multiple factors appear to be related to this phenomenon. Traditionally, these include a ventilation–perfusion mismatch underlying a limited increase in cardiac output and an increase in pulmonary dead space caused by rapid and shallow exercise breathing caused by decreased lung compliance. However, a normal or near normal VE/V\textsubscript{CO\textsubscript{2}} slope is not uncommon in patients with the most severe left ventricular dysfunction, such as candidates for cardiac transplantation. Conversely, the VE/V\textsubscript{CO\textsubscript{2}} slope is often greatly increased in some patients with relatively preserved left ventricular function and no pulmonary disease. This notion is compatible with the wide ranges of VE/V\textsubscript{CO\textsubscript{2}} slope in previous studies examining patients with severe heart failure.

These findings suggest that exercise hyperventilation may be caused not only by severely depressed left ventricular function and inefficient ventilation (rapid–shallow respiratory pattern caused by decreased lung compliance) but also by other mechanisms such as changes in exaggerated ergoreflex activity or alterations in the control of ventilation during exercise. Our results suggest that in cardiac patients the presence of chronic heart failure is not necessarily a prerequisite for increased VE/V\textsubscript{CO\textsubscript{2}} slope.

The present study has shown that, in patients after acute myocardial infarction, the VE/V\textsubscript{CO\textsubscript{2}} slope increases in association with aging, decreased TLCO, and enhanced CO\textsubscript{2} chemosensitivity. Among these three factors, enhanced CO\textsubscript{2} chemosensitivity seems to be the most potent determinant. The increase in VE/V\textsubscript{CO\textsubscript{2}} slope with aging was reported in healthy subjects.

Reduction of TLCO is well known in chronic heart failure. In the study by Guazzi and colleagues in which enalapril improved reduced TLCO in patients with chronic heart failure, changes in the ratio of dead space to tidal volume (a major determinant of the VE/V\textsubscript{CO\textsubscript{2}} slope) with enalapril were closely related to changes in TLCO. This may be in keeping with our finding that reduction of TLCO is a weak but significant independent determinant of the VE/V\textsubscript{CO\textsubscript{2}} slope in our patients; however, changes in TLCO after three months were not associated with changes in the VE/V\textsubscript{CO\textsubscript{2}} slope.
In our patients, the $\dot{V}E/\dot{V}CO_2$ slope was relatively strongly correlated with peak $V_O_2$, similar to reports from studies in patients with heart failure. A weak but significant correlation between $\dot{V}E/\dot{V}CO_2$ slope and LVEF, which is not necessarily seen in chronic heart failure, may be explained by the wider distribution of LVEF (19–59%) in our population.

$\dot{V}E/\dot{V}CO_2$ slope in patients with acute myocardial infarction

Although, as described above, several factors should contribute to the increased $\dot{V}E/\dot{V}CO_2$ slope in patients after myocardial infarction but without chronic heart failure, enhanced CO2 chemosensitivity seems to be the most plausible mechanism. If this is the case, which mechanism can explain the enhanced CO2 chemosensitivity in these patients? Although our study cannot explain it, it is conceivable that activation of the sympathetic nervous system after acute myocardial infarction enhances CO2 chemosensitivity, which in turn increases the $\dot{V}E/\dot{V}CO_2$ slope. These patients are known to have heightened sympathetic tone, which is reported to increase ventilation, possibly by activation of the chemoreceptor. Another possible explanation is that an exaggerated muscle ergoreflex occurring with chronic physical deconditioning may be related to chemosensitivity activation. Further studies are necessary to confirm these issues.

Effects of exercise training

Given the importance of the contribution of enhanced CO2 chemosensitivity to the increased $\dot{V}E/\dot{V}CO_2$ slope, one can suppose that some manipulations to reduce CO2 chemosensitivity would improve the $\dot{V}E/\dot{V}CO_2$ slope, leading to an amelioration of breathlessness during exercise. A study by Chua and colleagues examined this possibility with short-term administration of dihydrocodeine. Of interest, the suppression of chemosensitivity with this agent was associated with a reduction of the $\dot{V}E/\dot{V}CO_2$ slope and an improvement in exercise tolerance (peak $V_O_2$) and sensation of dyspnoea at a given work rate. On the other hand, it is well established that chronic physical training attenuates increased $\dot{V}E/\dot{V}CO_2$ slope in patients with chronic heart failure, whereas the $\dot{V}E/\dot{V}CO_2$ slope is shown to remain unchanged in normal subjects, suggesting that the $\dot{V}E/\dot{V}CO_2$ slope may be altered only when the baseline level is increased. These findings are in agreement with our results—that is, the $\dot{V}E/\dot{V}CO_2$ slope was attenuated only in group $T_{bas}$ with the increased baseline level of $\dot{V}E/\dot{V}CO_2$ slope.

Our finding that changes in the $\dot{V}E/\dot{V}CO_2$ slope after exercise training were correlated only with changes in CO2 chemosensitivity supports the notion that attenuation of CO2 chemosensitivity may have an important role in improving exercise hyperventilation. However, the causality of this relation remains to be solved. Unknown beneficial effects produced by chronic exercise, such as improvement of the activated neurohumoral systems, may directly influence both of these two changes. In the literature, there are few data showing exercise training induced attenuation of CO2 chemosensitivity in cardiac patients. Although this issue has not yet been fully established even in the normal subjects, the prevailing thought is that endurance training may attenuate CO2 chemosensitivity. Despite the presence of acute myocardial infarction, the mean values of CO2 chemosensitivity in group C and group $T_{bas}$ were comparable with the mean value measured in healthy subjects. Only group $T_{bas}$ had increased CO2 chemosensitivity. The CO2 chemosensitivity values in healthy subjects were established even in the normal subjects, cardiac patients. Although this issue has not yet been fully established even in the normal subjects, the prevalence is that endurance training may attenuate CO2 chemosensitivity.

$\dot{V}E/\dot{V}CO_2$ chemosensitivity after exercise training

In our patients, the $\dot{V}E/\dot{V}CO_2$ slope was relatively strongly correlated with peak $V_O_2$, similar to reports from studies in patients with heart failure. A weak but significant correlation between $\dot{V}E/\dot{V}CO_2$ slope and LVEF, which is not necessarily seen in chronic heart failure, may be explained by the wider distribution of LVEF (19–59%) in our population.

Clinical implications

Exercise training induced improvement of exercise hyperventilation may alleviate patient’s dyspnoea during daily activities, as well as of exercise performance in patients with heart failure. The well established benefits of exercise training on exercise performance and quality of life in coronary artery disease may be partly brought about by the improvement in exercise hyperventilation. Exercise training has various benefits not only in the functional status of the peripheral organs but also in the regulation of the cardiocirculatory system, such as that seen by an improvement in autonomic imbalance (enhanced sympathetic drive and attenuated parasympathetic tone). It is possible that a similar central alteration of the control system of ventilation improves exercise hyperventilation, leading to amelioration of symptoms.

Study limitations

Several potential limitations of the present study should be considered. First, the present study was not designed as a randomised, controlled trial; the patients assigned to the control group (group C) underwent initial low grade exercise training during hospitalisation. The well established various benefits of a postinfarct exercise training programme could not ethically allow us to design the study in such a fashion. Although the training group and group C were well matched for all of the baseline parameters and none of the parameters changed significantly in group C after three months, this potential selection bias should be noted. The small number of patients in this group C should be recognised as one limitation of the study. Although we defined the cut off value of 30 as an increased $\dot{V}E/\dot{V}CO_2$ slope according to our previous study, there is no consensus regarding this issue. Because multiple factors including aging, sex, and physical conditioning are likely to affect this value, its validity needs to be confirmed by further investigation.

To measure hypercapnic CO2 chemosensitivity, we used the rebreathing method, which estimates both central and peripheral CO2 chemosensitivity. Although both may have clinically important implications, we almost exclusively estimated the former because the peripheral hypercapnic chemosensitivity is known to be very small and negligible under the high oxygen concentration.

Although our patients generally had preserved LVEF, several patients had a low LVEF: five patients had LVEF < 30%, for example. Thus, we cannot completely exclude the possibility that our population may have included a number of patients with no overt but latent heart failure, especially in group C. This would be particularly true if the decrease in LVEF was due to an increase in ventricular mass. Nevertheless, in the present study we reanalysed the data after excluding these five patients, and the statistical results were exactly the same as those presented, supporting the idea that inclusion of patients with latent heart failure did not distort our results.

Conclusion

The present study indicated that, in patients with acute myocardial infarction, exercise hyperventilation as indicated by increased $\dot{V}E/\dot{V}CO_2$ slope during exercise occurs in association with aging, reduced $T_{bas}$, and hypercapnic CO2 chemosensitivity. Among these three factors, chemosensitivity seems to be the most potent determinant of the abnormality. A subsequent three month supervised exercise training programme attenuates the increased $\dot{V}E/\dot{V}CO_2$ slope, at least partially, through the reduction of hypercapnic CO2 chemosensitivity. We studied patients with acute myocardial infarction and no overt heart failure and thus cannot extrapolate these results to
patients with chronic heart failure. However, our results may provide insight into the understanding of the responsible mechanism for exercise hyperventilation and exercise training induced beneficial effects in cardiac patients.

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