Eccentric Exercise in Coronary Patients: Central Hemodynamic and Metabolic Responses

[CLINICAL SCIENCES: Clinical Investigations]

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Submitted for publication July 2002. Accepted for publication February 2003.

ABSTRACT


Purpose: With lengthening (eccentric) muscle contractions, the magnitude of locomotor-muscle mass and strength increase has been demonstrated to be greater compared with shortening (concentric) muscle contractions. In healthy subjects, energy demand and heart rate responses with eccentric exercise are small relative to the amount of muscle force produced. Thus, eccentric exercise may be an attractive alternative to resistance exercise for patients with limited cardiovascular exercise tolerance.

Methods: We tested the cardiovascular tolerance of eccentric exercise in 13 coronary patients (ages 40–66) with preserved and/or mild reduced left ventricular function. Patients were randomly assigned to either an eccentric (ECC; \(N = 7\)) or a concentric (CON; \(N = 6\)) training group and trained for 8 wk. Training workload was increased progressively (from week 1 to 5) to an intensity equivalent to 60% \([\text{O}_2\text{peak}]\).

Results: On average, maximum power output achieved with ECC was fourfold compared with CON (357 ± 96 W vs 97 ± 21 W; \(P < 0.005\)), whereas measures of oxygen uptake and blood lactate were significantly lower (\(P < 0.05\) each), and ratings of perceived exertion were similar for ECC and CON. During a 20-min session of ECC and CON, central hemodynamics was measured by means of right heart catheterization. During ECC, responses of mean arterial blood pressure, systemic vascular resistance, pulmonary capillary pressure, cardiac index, and stroke work of the left ventricle on average were in the normal range of values and similar to those observed during CON. Compared with baseline, after 8 wk of training, echocardiographic left ventricular function was unchanged.

Conclusion: The results indicate uncoupling of skeletal muscle load and cardiovascular stress during ECC. For low-risk patients with coronary heart disease without angina, inducible ischemia, or left ventricular dysfunction, ECC can be recommended as a safe new approach to perform high-load muscular exercise training with minimal cardiovascular stress.

To improve muscle mass and strength in patients with cardiovascular disease, a training method would be desirable which would allow high intense muscular load with resulting low cardiovascular stress. Fifty years ago, it was demonstrated that eccentric muscle work (i.e., lengthening of muscle while producing force (2)) has certain advantages over concentric work (i.e., shortening of muscle while producing force). When muscles produce tension eccentrically, greater torque is developed than in concentric contractions, particularly at high angular velocities (8,9,11). Furthermore, eccentric contractions not only produce greater torque but also do so at a greatly reduced oxygen requirement (1,3). During submaximal cycling, the eccentric oxygen demand has been reported
to be only one sixth to one seventh of that of cycling concentrically at the same workload (3). Previously, it was demonstrated in healthy subjects that 8 wk of eccentric cycle ergometer training (ECC) resulted in a 40% increase in both muscle strength and apparent cross-sectional area of biopsied muscle fibers, whereas cardiovascular stress and metabolic demand were kept at a low level (10,13). Thus, in principle, ECC could be an attractive alternative to resistance exercise for patients with limited cardiovascular exercise tolerance. Currently, there are no data on central hemodynamic variables obtained during ECC. To train coronary patients safely, this information is needed. This study was designed as a pilot project in patients with coronary heart disease to assess central hemodynamic and metabolic responses during ECC as compared with traditional conventional concentric cycle ergometer training (CON).

METHODS

Patients.

The local ethic committee approved the study protocol. All patients gave informed written consent before participation.

Thirteen male patients with coronary artery disease were randomized to either ECC (N = 7) or CON training group (N = 6). Before randomization, all patients were familiarized with both the ECC and CON exercise methods. In each group, five patients had prior documented myocardial infarction. N = 6/3 (ECC/CON) underwent percutaneous transluminal coronary angioplasty, and N = 1/2 (ECC/CON) underwent coronary bypass surgery. For the ECC and CON groups, age (53 ± 8 vs 56 ± 9 yr) and body mass index (27.1 ± 3 vs 27.1 ± 5) did not differ significantly. Patients had either preserved or mildly reduced left ventricular function. All were in sinus rhythm and exhibited neuromuscular capability to cope with ECC. Exclusion criteria were angina and/or electrocardiographic evidence of exertional ischemia, atrial fibrillation, significant ventricular arrhythmia, obstructive or restrictive lung problems, significant peripheral vascular disease, and orthopedic/neurologic disorders that limit exercise. Cardiovascular medication was not changed during the study period. The medication included beta-blockers (ECC/CON; N = 4/4), ACE inhibitors (N = 3/2), and calcium channel blockers (N = 1/0), ASS (N = 6/6), and statins (N = 5/4). Before inclusion, patients were physically active and participated regularly in leisure activities (e.g., hiking, tennis, cycling, and/or swimming) for 4 ± 2 h·wk⁻¹ (ECC) and 3 ± 1 h·wk⁻¹ (CON).

Eccentric ergometer.

A lower-extremity eccentric ergometer for cycling in the sitting position was constructed locally. The ergometer is driven by a 5-horsepower direct current (DC) motor, equipped with a flywheel (Simoreg, Siemens). All components are mounted to a steel frame. A DC motor controller regulates motor speed and thus, pedal rpm and torque. Under software control, the voltage and amperage outputs from the controller are monitored through an analog-to-digital board in a dedicated computer. The ergometer was calibrated by using a friction band and applying known loads (via weights) as the motor moved the flywheel. The amperage/voltage of the motor were noted for different cadences, and loads and power in both directions of rotation were calculated. Both cadences and torque were displayed to the patient during training sessions. In addition, the calibration of the ECC ergometer was checked physiologically.

During eccentric cycle ergometry patients had to resist the turning pedals. In other words, they had to brake the electrically generated torque transmitted to the pedals. Concentric exercise was performed in a sitting position on a standard cycle ergometer (Ergoline, er-900 L).

Training regimes.

Both training sessions with ECC and CON were performed three times weekly for 30 min each over an 8-wk period. The training intensity for both groups, ECC and CON, was set to a fixed and similar target of approximately 60% oxygen uptake peak (\(\text{[latin capital V with dot above]}\)\(\text{O}_{2\text{peak}}\)) and/or 85% peak heart rate, determined at baseline exercise testing. This training intensity was reached at the end of week 5 by a progressive increase of training workload in an identical fashion for both methods (Fig. 1). The rate of increase in exercise intensity of ECC was determined by avoidance of muscle soreness. Patients could choose cadence individually; cadence was 55-min⁻¹ on average (range 51–60) during ECC and 80-min⁻¹ (range 74–82) during CON.

http://gateway.ut.ovid.com/gw1/ovidweb.cgi
Central hemodynamic measurements.

During a 20-min training session of ECC and/or CON, at training workloads achieved at the end of week 5, central hemodynamics were measured by means of right heart catheterization. A 7.5F double luminal Swan Ganz catheter (Baxter Company) was inserted via the left cubital vein. Right atrial pressure (mm Hg), pulmonary capillary pressure (mm Hg), and pulmonary artery oxygen saturation (%) were measured at rest, and at exercise minutes 5, 10, 15, and 20. Arterial oxygen saturation (%) (capillary blood, earlobe; Oximetric system, Baxter), systemic arterial blood pressure (cuff method; mm Hg), and heart rate (electrocardiogram; beats·min⁻¹) were also measured at these time intervals.

Hemodynamic calculations.

From measured data, arteriovenous oxygen difference (Vol %), and stroke volume index (mL·m⁻²·beat⁻¹) were calculated with computer assistance. For calculation of cardiac output (L·min⁻¹) via the Fick formula \[\text{cardiac output} = \frac{\text{O}_2 \text{ (mL·min}^{-1})}{\text{arteriovenous oxygen difference (Vol %)}},\] \[\text{O}_2 \text{ (mL·min}^{-1})\] was measured in a separate session of ECC and CON. Cardiac index (L·m⁻²·min⁻¹) was determined by dividing cardiac output by body surface. Calculation of systemic vascular resistance (dyn·s⁻¹·cm⁻⁵) was performed by the formula: \[(\text{mean arterial blood pressure - mean right arterial pressure})/\text{cardiac output} \times 80.\] Stroke work of the left ventricle (g·m⁻¹) was calculated as follows: \[(\text{systolic blood pressure - pulmonary capillary pressure}) \times \text{stroke volume} \times 0.0136.\]

Blood lactate and rating of perceived exertion.

At rest and at exercise minutes 5, 10, 15, and 20, blood lactate concentrations (mmol·L⁻¹) (enzymatic method; Biosen 5030 L) were determined from capillary blood (earlobe). At the same exercise minutes, rating of perceived exertion was recorded by means of Borg scale, rating 6–20 (17).

Echocardiography.

At baseline and at week 8, echocardiography was performed in supine patients. Systolic function (ejection fraction [%]) and diastolic function (transmitral Doppler flow indexes e-deceleration time [m·s⁻¹]; E/A ratio; and isovolumetric relaxation time [m·s⁻¹]) were determined by means of transthoracic echocardiography to assess left ventricular function of ECC and CON.
Cardiopulmonary exercise testing (CPX).

To study changes in cardiopulmonary exercise capacity CPX was performed at baseline and at week 8 using a cycle ergometer (Ergoline, er-900 L). Individualized ramp testing protocol was chosen (21). Along with maximum power output (W), oxygen uptake ([\(\text{VO}_2\) mL·kg\(^{-1}\)·min\(^{-1}\)]) was assessed breath by breath (Oxycon sigma; Jaeger Company).

Statistics.

Statistical analyses were performed using the StatView program (SAS Company, Berkeley, CA). Data are presented as mean ± SD. A nonparametric Mann-Whitney test was used to compare baseline measures for ECC versus CON. With the same test, hemodynamic parameters measured during ECC and CON were analyzed for differences at baseline and compared for the magnitude of change between rest and exercise minute 5, and between exercise minutes 5 and 20. Using the nonparametric U-test, the magnitude of change in a single parameter obtained by echocardiography and CPX was analyzed for statistical differences between ECC and CON (baseline vs week 8). A \(P\) value < 0.05 was considered significant.

RESULTS

Training and testing procedures were well tolerated. No patient demonstrated signs or symptoms of myocardial ischemia and/or rhythm disorders.

During training, maximum power output (W) was markedly greater for ECC than for CON (357 ± 96 W vs 97 ± 21 W; \(P < 0.005\)), whereas training heart rate percent peak heart rate was similar for both ECC and CON (64% in first week, and 75% in eighth week) (Fig. 1). In either group, patients experienced no significant muscle soreness and discomfort. During week 1–5 (and week 6–8), average rating of perceived exertion was 10.0 ± 1.7 (9.5 ± 1.7) for ECC and 9.2 ± 1.6 (9.3 ± 1.5) for CON. The difference was not statistically significant. The following results were recorded at the maximum power output achieved at the end of training week 5.

Hemodynamic responses to eccentric and concentric exercise.

At rest, mean values of central hemodynamic parameters were in the normal range of values, and there was no significant difference for measures between ECC and CON (Figs. 2 and 3). Between rest and exercise minute 5, for both ECC and CON, there was a significant increase in [\(\text{VO}_2\)] and heart rate (Fig. 2, a and b), mean pulmonary capillary pressure, cardiac index, stroke work of the left ventricle, and arteriovenous \(\text{O}_2\) difference (Fig. 3, c, e, f, and g). Starting from a slightly increased level at rest, systemic vascular resistance decreased significantly within the first 5 min of exercise (Fig. 3b). Between exercise minutes 5 and 20, none of the parameters demonstrated a further significant change. When comparing ECC and CON between rest and minute 5 for the magnitude of change of parameters, [\(\text{VO}_2\)], heart rate (Fig. 2, a and b), arteriovenous \(\text{O}_2\) difference, and blood lactate (Fig. 3, g and h) differed significantly.
FIGURE 2— a and b. Oxygen uptake, and heart rate at rest and during a 20 min eccentric (---) and concentric (- - - -) exercise session at week 5. Results are presented as mean and standard deviation. *P* values are presented for change in parameters during eccentric and concentric exercise (rest -> minute 5, and minute 5 -> minute 20), and for differences in the magnitude of change in parameters between eccentric and concentric exercise.
FIGURE 3— a–h. Central hemodynamics and blood lactate concentrations at rest and during a 20-min eccentric ( - - - ) and concentric (——) exercise session at week 5. Results are presented as mean and standard deviation. P values are presented for change in parameters during eccentric and concentric exercise (rest -> minute 5, and minute 5 -> minute 20), and for differences in the magnitude of change in parameters between eccentric and concentric exercise.
Left ventricular function during course of training.

Before starting with the training program, mean left ventricular ejection fraction was in the normal range of values (ECC/CON; 57 ± 7% vs 65 ± 8%; NS). After 8 wk of training, there was a significant increase in the ECC group (62 ± 6%; *P* < 0.05), and no significant change in the CON group (63 ± 2%). At baseline, parameters of diastolic function did not differ significantly for either ECC or CON, and were in normal range of values (ECC vs CON: E/A ratio 1.3 ± 0.7 vs 1.2 ± 0.4; isovolumetric relaxation time 83 ± 12 vs 82 ± 22 m·s⁻¹; e-deceleration time 168 ± 23 vs 174 ± 42 m·s⁻¹). During the course of training, none of these parameters changed significantly.

Cardiopulmonary exercise capacity during course of training.

At baseline, peak power output and [left capital V with dot above]O₂peak did not differ significantly for ECC and CON. From baseline to week 8, peak power output improved significantly in both ECC and CON, whereas peak [left capital V with dot above]O₂ only did in ECC (Fig. 4).

![FIGURE 4— Peak power output (W) and peak oxygen uptake (mL·kg⁻¹·min⁻¹) measured by means of cardiopulmonary exercise testing at baseline and week 8 in eccentric (filled bars) and concentric training group (open bars). *P* values are presented for intra-group change and intergroup difference from baseline to week 8.](http://gateway.ut.ovid.com/gw1/ovidweb.cgi)

DISCUSSION

In our study, at similar relative training heart rates in ECC and CON (Fig. 1), the patients generated almost fourfold greater power output with ECC compared with CON, whereas oxygen consumption was significantly lower during ECC (Fig. 2a). Despite this greater muscle load during ECC, the rating of perceived exertion corresponded to "fairly light" for the entire period of both ECC and CON. The observed functional and cardiovascular responses in cardiac patients are similar to results reported previously in healthy subjects (13). During ECC, a fourfold greater work rate was observed compared with CON, despite exercising at identical heart rates (13) and at a somewhat lower oxygen consumption (14).

Central hemodynamic responses during eccentric and concentric exercise.

Despite markedly greater torque generated by muscles with ECC, there was a similar response in mean arterial blood pressure in both ECC and CON. No significant increase was observed during exercise (Fig. 3a). During ECC, systemic vascular resistance decreased significantly in the first 5 min of exercise, with no further decrease between minutes 5 and 20 (Fig. 3b). This is in contrast to high-force isometric muscle contractions with resistance exercise (7). In healthy subjects who exercised at intensities corresponding to an oxygen requirement of >1300 mL·min⁻¹, similar responses of arterial blood pressure and peripheral resistance were demonstrated for ECC and CON (19). These pressure responses suggest that the fourfold greater muscle workload during ECC does not seem to be associated with a greater left ventricular afterload.
During the first 5 min of ECC, the mean pulmonary capillary pressure as a marker of left ventricular preload increased significantly to the upper range of normal values. Afterward, however, the average wedge pressure tended to return to a physiologic range (Fig. 3c). Heart rate and cardiac index increased initially, before achieving a steady state similar to that seen in CON (Figs. 2b and 3e). These cardiovascular responses suggest that during eccentric muscle work, venous return is maintained as it is during concentric aerobic exercise. This indicates that even at high skeletal muscle tensions with eccentric exercise the muscle pump does not seem to inhibit peripheral circulation (18). Conversely, with isometric resistance exercise, high skeletal muscle tension occludes vascular channels and impedes inflow of blood, resulting in a reduced venous return (7). This is potentially hazardous for coronary patients.

The stroke work, which integrates pre- and afterload as well as contractility, also demonstrated a short-term adaptation of the left ventricle to ECC. After an initial increase, there was a plateau of stroke work during both ECC and CON (Fig. 3f). Again, despite a fourfold greater torque generated by peripheral muscles during ECC, no greater stress on the left ventricle was observed. These results imply that there is an uncoupling of skeletal muscle load and cardiovascular stress during ECC. Furthermore, taking into consideration a fourfold greater torque generated at a lower oxygen consumption during ECC (Fig. 2a), the significantly smaller arteriovenous O2 difference (Fig. 3g) and lower blood lactate concentration (Fig. 3h) also implicate an uncoupling of skeletal muscle mechanical loading and systemic metabolic demand. This phenomenon is explained by the specific conditions for muscle work in an eccentric mode. At all times, the forces acting on the muscle exceed the force produced by the muscle. Thus, muscle lengthens while producing force, thereby absorbing mechanical energy. In repetitive ECC contractions, in principle, a large portion of the energy is absorbed as elastic recoil potential energy and can be returned during the concentric shortening phase of the stretch-shorten cycle (4,15). However, the eccentric resistance exercise as described here reflects eccentric lengthening contractions, with no recovery of the elastic recoil energy. As during ECC work, the muscles are acting as a brake to decelerate the pedals, and there is a small metabolic energy requirement. This has also been demonstrated by a markedly lower amount of ATP breakdown (12) and lower blood lactate level during eccentric versus concentric muscle work (19). Our measures of [\text{O}_2] (Fig. 2a), arteriovenous O2 difference (Fig. 3g) and blood lactate concentration (Fig. 3h) further substantiate these previous findings. Thus, the characteristics of eccentric muscle work are completely different from those of concentric contractions. However, muscle blood flow during eccentric exercise appears to be similar to that during shortening (concentric) muscle contractions performed at the same metabolic demand (19).

Systolic and diastolic left ventricular function during the course of training.

In our patients, neither systolic nor diastolic left ventricular function demonstrated an abnormal physiologic adaptation. The concerns about negative left ventricular adaptation related to resistive muscle work in strength training (5) therefore do not apply to ECC.

Cardiopulmonary exercise capacity during course of training.

The absence of muscle soreness and the improvement of peak power output (W) and [\text{O}_2] by ECC (Fig. 4) indicates that significant ultrastructural muscle damage and loss of function as a consequence of a too rapid increase of eccentric training workload (6,16) could be avoided in our patients. Within an 8-wk ECC training program, LaStayo et al. (13) increased workload slowly but progressively over 7 wk up to 489 W on average in previously sedentary subjects. No subjects experienced muscle injury (i.e., loss of muscle strength) or soreness. Moreover, one session of high-intensity eccentric exercise did not compromise muscle oxidative function (20). From these experiences, ECC workload might have been increased somewhat harder in our patients between weeks 1 and 5, and thus slightly higher workloads could have been achieved.

Clinical implications.

Despite an approximate fourfold greater muscular stress with ECC, the central hemodynamic and metabolic responses of coronary patients did not exceed values measured in patients of the CON group. All parameters stayed within normal range of values. ECC allows for greater muscle torque in exercise training, hence, a greater overload to the locomotor muscles. This is possible without overstrressing the cardiovascular system. In conclusion, cardiovascular and metabolic responses during ECC were similar to those observed during CON. Aerobic exercise training using CON mode has been applied safely and successfully in coronary patients for more than three decades. ECC can thus be recommended as a new approach that may maximize the improvement of muscle mass and strength in coronary patients.

Eccentric cycle training has been demonstrated to be: a) highly effective in improving both muscle strength and apparent cross-sectional area of biopsied muscle fibers (13), b) not overly time consuming, and c) easy to run. Until the time when specific equipment such as eccentric bikes are commercially available, eccentric muscle training can be performed, e.g., by eccentric weight training or more conventionally, for example, by walking downhill or downstairs.
Potential study limitations.

This was the very first study on application of ECC in cardiovascular rehabilitation. Because of the lack of knowledge on central hemodynamic response to ECC in coronary patients, only patients with minimal left ventricular dysfunction and no exertional ischemia were involved. Additionally, workload was increased very carefully, and a further increase of training load was stopped arbitrarily for safety reasons at training week 5. This was also a safety requirement suggested by the ethical committee. At week 5, central hemodynamics were measured to verify cardiovascular tolerability of ECC. Between weeks 6 and 8, ECC workload was not further increased. In the future, further increase in training load should be undertaken in order to maximize the growth stimulus for muscle tissue. We would then expect muscle fiber size and muscle strength to increase significantly by as much as 30%, as indicated by previous studies in untrained healthy subjects (13).

Although all cardiovascular responses with ECC corresponded uniformly to responses obtained with CON, results allow conclusions to be drawn only with regard to ECC in patients as assessed. The impact of ECC on left ventricular function and size when including patients with more severe left ventricular dysfunction, or even heart failure, or when using long-term training with greater workloads, needs to be addressed in further studies.

We thank Klaus Schnellbacher, Bad Krozingen, Germany, and Carl Foster, La Crosse, Wisconsin, for worthwhile discussions.

REFERENCES


Key Words: EXERCISE TRAINING; LEFT VENTRICULAR FUNCTION; SKELETAL MUSCLE LOAD; RESISTIVE EXERCISE; TRAINING METHOD; MUSCLE STRENGTH

Accession Number: 00005768-200307000-00002

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Version: rel10.1.0, SourceID 1.11080.2.37