Physical Training Increases Endothelial Progenitor Cells, Inhibits Neointima Formation, and Enhances Angiogenesis

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Background—The molecular mechanisms by which physical training improves peripheral and coronary artery disease are poorly understood. Bone marrow–derived endothelial progenitor cells (EPCs) are thought to exert beneficial effects on atherosclerosis, angiogenesis, and vascular repair.

Methods and Results—To study the effect of physical activity on the bone marrow, EPCs were quantified by fluorescence-activated cell sorter analysis in mice randomized to running wheels (5.1±0.8 km/d, n=12 to 16 per group) or no running wheel. Numbers of EPCs circulating in the peripheral blood of trained mice were enhanced to 267±19%, 289±22%, and 280±25% of control levels after 7, 14, and 28 days, respectively, accompanied by a similar increase of EPCs in the bone marrow and EPCs expanded from spleen-derived mononuclear cells. eNOS−/− mice and wild-type mice treated with N2-hydroxy-L-arginine methyl ester showed lower EPC numbers at baseline and a significantly attenuated increase of EPC in response to physical activity. Exercise NO dependently increased serum levels of vascular endothelial growth factor and reduced the rate of apoptosis in spleen-derived EPCs. Running inhibited neointima formation after carotid artery injury by 22±2%. Neoangiogenesis, as assessed in a subcutaneous disc model, was increased by 41±16% compared with controls. In patients with stable coronary artery disease (n=19), moderate exercise training for 28 days led to a significant increase in circulating EPCs and reduced EPC apoptosis.

Conclusions—Physical activity increases the production and circulating numbers of EPCs via a partially NO-dependent, antiapoptotic effect that could potentially underlie exercise-related beneficial effects on cardiovascular diseases. (Circulation. 2004;109:220-226.)

Key Words: exercise ■ cells ■ nitric oxide ■ angiogenesis ■ coronary disease

Regular physical activity is associated with a decrease in the incidence of cardiovascular events.1-2 Physical training improves endothelial function, exercise capacity, and collateralization in patients with coronary artery disease.3,4 Chronic heart failure,5,6 and peripheral artery disease.7,8 Physical activity is associated with improved mood, body weight, blood pressure, insulin sensitivity, and hemostatic and inflammatory variables.9,10 However, despite the wealth of evidence derived from epidemiological and interventional trials, there is limited understanding of the underlying molecular mechanisms. Notably, physical training reduces vascular oxidative stress at least in part via increased activity of endothelial nitric oxide synthase (eNOS) and extracellular superoxide dismutase, which in turn could exert beneficial vascular effects.11,12

Recent evidence has shown that vascular function not only depends on cells that reside within the vessel wall but also appears to be significantly modulated by circulating cells derived from the bone marrow.13 A specific subset of these stem cells has been shown to enhance angiogenesis, promote vascular repair, improve endothelial function, inhibit atherosclerosis, and increase ventricular function after myocardial infarction.14-19 This circulating bone marrow–derived cell population has been named endothelial progenitor cells (EPCs), characterized by coexpression of Sca-1 and vascular endothelial growth factor receptor 2 (VEGFR2).14,17,19,20 We refer to these cells as EPCs throughout this report. Numbers of EPCs are regulated. Although myocardial infarction and bypass surgery acutely increase the circulating numbers, accumulation of vascular risk factors appears to reduce these bone marrow–derived cells, which suggests that vascular health and repair processes after injury require increased numbers of this potentially beneficial population of cells.17,20-23 Therefore, we reasoned that physical activity may influence the numbers of EPCs and tested this hypothesis in mice subjected to a physical active lifestyle versus a
sedentary lifestyle and extended our observations to humans with coronary artery disease who were undergoing physical training.

Methods

Animals and Exercising

Animal experiments were conducted in accordance with institutional guidelines. Male C57Bl/6 (Charles River Laboratories, Sulzfeld, Germany), 129/SV (Bundesinstitut für Gesundheitsverbraucherschutz und Veterinärmedizin, Berlin, Germany), and eNOS−/− (B6129/Po-Nos3, Charles River) mice were kept under usual care at 1 to 6 mice per cage. Each exercising mouse was kept in an individual cage supplied with a running wheel (12.8-cm diameter) equipped with a tachometer (Sigma Sport BC-401) to record the daily running distance. Mice ran voluntarily. The mean running distance was 5100±800 m per 24 hours and did not differ in mice after carotid artery injury or disc implantation or in eNOS−/− mice. For comparison, treadmill training was performed (treadmill EXER-8, Columbus Instruments) for 3 weeks 5 times per week for 30 minutes at 12 m/min as described previously.11,12 Some C57Bl/6 mice were treated with rosuvastatin 2 mg/kg SC for 7 days. For indicated mice, Nα-nitro-l-arginine methyl ester (L-NAME; Sigma) was added to the drinking water (daily dose, ~50 mg/kg; concentration in drinking water, 1.5 mg/mL).13

Humans and Training

Patients with clinically stable coronary artery disease documented by angiography (n=19) underwent a 4-week controlled, standardized exercise program of bicycle ergometer training, moderate muscle strength training (lower-limb muscle training by shuttle device), and exercise program of bicycle ergometer training, moderate muscle strength training (lower-limb muscle training by shuttle device), and walking as described in detail previously.25 The maximum workload of ergometer training was defined to correspond to the heart rate measured at 60% to 80% of peak oxygen uptake. An initial warmup of 5 minutes at 15 W was followed by training units of 15 to 20 minutes. Patients with concomitant inflammatory disease, defined as clinical symptoms of infection or C-reactive protein >10 U/L, were excluded, as were patients unable to fully participate in the study period. Exercise capacity before and after the training program was assessed by peak oxygen uptake with a ramp protocol (initial level 25 W, 10-W increase every 10 minutes; Ergoline 900, Columbus Instruments) for 3 weeks 5 times per week for 30 minutes at 12 m/min as described previously.11,12 Some C57Bl/6 mice were treated with rosuvastatin 2 mg/kg SC for 7 days. For indicated mice, Nα-nitro-l-arginine methyl ester (L-NAME; Sigma) was added to the drinking water (daily dose, ~50 mg/kg; concentration in drinking water, 1.5 mg/mL).13

Fluorescence-Activated Cell Sorter Analysis

Mouse blood and bone marrow were analyzed as described previously.18,19,23 The viable lymphocyte population was analyzed for Sca-1/VEGFR2 (Flk-1; Pharmingen) and VEGFR-2 (Fik-1; Avas12e1, Pharmingen) conjugated with the corresponding phycoerythrin-labeled secondary antibody (Sigma). Isotype-specific antibodies served as controls in every experiment (Becton Dickinson). Isotype-identical antibodies served as controls in every experiment (Becton Dickinson). Isotype-specific antibodies were used for negative controls. For morphometric analyses, Lucia Measurement version 4.6 software was used to measure neointimal area of 25 sections per animal.

Carotid Injury Model

Carotid artery injury was induced as described in detail previously.18,19,23 Carotid arteries were harvested 14 days after surgery. Complete reendothelialization was confirmed by staining for von Willebrand factor (clone A 0082, Dako) and 4′,6-diamidino-2-phenylindole (Dapi, Linaris). Isotype-specific antibodies (Santa Cruz) were used for negative controls. For morphometric analyses, Lucia Measurement version 4.6 software was used to measure neointimal area of 25 sections per animal.

Disc Angiogenesis Model

A disc of polyvinyl alcohol sponge (Rippey), covered with nitrocellulose-cell-impermeable filters (Millipore), allowed capillaries to grow only through the rim of the disc.27 The discs were implanted subcutaneously. After 14 days, space-filling fluorescent microspheres (0.2 μm; Molecular Probes) were injected into the left ventricle to deliver them to the systemic microvasculature. The area of the disc invested by fibrovascular growth was assessed with Lucia Measurement version 4.6 software.

Statistical Analysis

Results are presented as mean±SEM. Paired and unpaired Student t tests and ANOVA for multiple comparisons were used where applicable. Post hoc comparisons were performed with the Neuman–Keuls test. Values of P<0.05 were considered significant.

Results

Physical Activity Increased EPCs in Mice

The time-dependent effect of voluntary running on the numbers of Sca-1/VEGFR2-positive cells is depicted in Figure 1. One day of running did not cause a significant increase in EPCs. After 7 days, numbers of EPCs were significantly increased in the peripheral blood, bone marrow, and spleen. This effect was sustained for up to 28 days of continuous activity.
Voluntary running of 129/Sv mice resulted in similar upregulation compared with C57/Bl6 mice. To exclude a potential unspecific effect of the voluntary running in wheels, mice were subjected to forced running on a treadmill (5 times per week for 30 minutes at 12 m/min). Treadmill training for 28 days increased EPC numbers to 247/H11006 23%, 160/H11006 14%, and 151/H11006 14% of baseline in blood, bone marrow, and spleen, respectively.

Regulation of EPCs by Endothelial Nitric Oxide
Exercise increases nitric oxide bioavailability. Figure 2A exhibits the time-dependent increase of eNOS mRNA expression in our experimental model. eNOS mRNA and protein expression and upregulation by exercise did not differ significantly between the aorta and the carotid arteries (data not shown). Voluntary exercise (28 days) increased NOS activity as assessed by [3 H]arginine to [ 3 H]citrulline conversion as assays to 329/H11006 78% of control levels in the aortas and to 385/H11006 89% in the carotid arteries (n=4, P<0.05). To explore the effect of endothelial NO on EPC numbers, running wheel experiments were repeated in eNOS knockout mice and wild-type mice treated with the NOS inhibitor L-NAME. Figures 2 B through 2D show that absolute EPC numbers were decreased after treatment with L-NAME for 28 days, as well as in eNOS−/− mice, in blood, bone marrow, and spleen. Running increased EPC numbers in eNOS−/− mice, but absolute numbers and the extent of increase were significantly smaller than with the wild-type animals. Mice treated with the NOS inhibitor showed no significant upregulation of EPCs after exercising. In addition, wild-type mice were treated with 2 mg/d of the HMG CoA reductase inhibitor rosuvastatin to increase NO availability independent of physical activity. Rosuvastatin increased Sca-1/VEGFR−/− positive cells in the circulation from 53.3 ±7.4 to 123.3 ±20.9 per 100 000 events (n=4, P<0.05). This induction of EPCs was abolished by concomitant treatment with L-NAME (58.3 ±7.6; n=4).
Exercise Increases VEGF and Inhibits EPC Apoptosis

VEGF and SDF-1 have been suggested as mediators of EPC regulation. Compared with sedentary mice, physical activity increased VEGF serum concentration (Figure 3A) after 7 and 28 days of physical activity. The increase in VEGF after day 7 was abolished by cotreatment with L-NAME. SDF-1 levels remained unchanged (Figure 3B). Circulating numbers of EPCs have been shown to depend at least in part on the rate of apoptosis. Therefore, the rate of apoptosis was quantified in EPCs expanded in vitro from wild-type mice. Figure 3C demonstrates that physical activity decreased EPC apoptosis to 54±11% of control levels.

Physical Activity Reduced Neointima Formation and Enhanced Neoangiogenesis

Neointima formation after carotid injury is dependent on the rate of reendothelialization, which is enhanced by circulating EPCs. Seven days after initiation of exercising, vascular injury was induced. Fourteen days after lesion induction, vessels were harvested and analyzed histologically. Figure 4 shows representative examples of neointima formation (A) and the quantitative histomorphometric measurement (C). Physical exercising markedly reduced the induction of neointima formation.

EPCs have been reported to significantly contribute to new blood vessel formation. Therefore, we determined whether exercise modulates the angiogenic response in vivo in a model of inflammation-induced neoangiogenesis in mice (Figures 4B and 4C). Subcutaneous implantation of a polyvinyl sponge for 14 days resulted in ingrowth of new vessels. Exercising, initiated after implantation of the disc, increased the area of neoangiogenesis by 41±16% compared with sedentary mice.

Exercise Training Increased EPC Levels in Humans

Patients with documented stable coronary artery disease (n=19) underwent a controlled, standardized exercise program of bicycle ergometer training, moderate muscle strength training, and walking for 28 days. Patient characteristics are summarized in the Table. Medications were not changed...
during the training period. The exercise program increased peak \( VO_2 \) from 9.58 ± 4.0 to 11.8 ± 5.80 kg/mL (\( P < 0.05 \)) and the 6-minute walking distance from 357 ± 98 to 422 ± 112 m (\( P < 0.05 \)). Patients showed no signs of myocardial ischemia during exercise testing before and after the training period.

EPC numbers in the peripheral blood were assessed via fluorescence-activated cell sorter analysis (CD34+/KDR+ cells) after 28 days. Figure 5A indicates a significant increase in circulating EPCs in response to training. In addition, EPCs were expanded from human blood in vitro before and after 28 days of training and identified by DiLDL uptake and lectin staining (Figure 5B). The rate of EPC apoptosis after the training program was reduced by 41 ± 11% compared with apoptosis before exercising.

**Discussion**

The present study produced several findings. (1) Physical exercise increases the numbers of EPCs in bone marrow, peripheral blood, and spleen in mice. (2) Upregulation of EPCs by exercise is dependent at least in part on endothelial NO and VEGF, and (3) exercise decreases the rate of EPC apoptosis. (4) Running diminished neointima formation after vascular injury and (5) enhanced neangiogenesis. Furthermore, (6) a 28-day exercise program upregulated circulating EPCs in patients with coronary artery disease.

Coronary heart disease evolves depending on the accumulation of risk factors that exert a wide array of molecular and cellular abnormalities within the vessel wall, which leads to the development of atherosclerotic lesions. However, the concept of local pathological processes within the vessel wall has recently been challenged by discoveries related to stem cell biology. In this context, EPCs, which resemble premature, circulating, bone marrow–derived cells with potential to transdifferentiate, depend on the occurrence of classic risk factors. Increasing numbers of risk factors lead to decreased numbers of circulating EPCs in patients with stable coronary heart disease. Given the fact that EPCs have been implicated in revascularization, vascular repair, and myocardial regeneration, it is presumable that EPC counts correlate inversely with the risk of cardiovascular diseases. However, it remains uncertain whether the Sca-1/VEGFR2-positive cell population named EPC represents a homogenous cell population. In addition, evidence is accumulating that EPC differentiation is not restricted to the endothelial lineage, but that these cells may develop into multiple cell types, eg, cardiomyocytes.

Intervention studies have demonstrated that physical training improves the outcome of patients with coronary heart disease and heart failure. The underlying mechanisms may
relate to increased shear stress on the endothelial monolayer, which in turn enhances the activity of enzymes such as eNOS and extracellular superoxide dismutase, shifting the reactive oxygen balance toward the beneficial NO.11,12 However, parallel or subsequent events are less clear. Importantly, the effect of physical exercising on EPCs has not been defined.

According to the present findings, physical activity leads to an increased number of circulating EPCs in mice and humans. This effect occurs rapidly and is sustained for at least 4 weeks. The increased circulating EPC numbers are associated with increased production within the bone marrow, because EPC numbers rise concomitantly in this compartment. Mice supplied with running wheels showed upregulation of VEGF serum levels. VEGF activates PI-3-kinase and increases EPC numbers14 and therefore may significantly contribute to the effects of exercise. Physical exercise increases NO bioavailability,12 and in concert with this fact, the effect of physical activity on EPCs is markedly reduced after inhibition or deletion of eNOS, which suggests an NO-dependent increase of EPCs in response to exercising. Statin treatment has been suggested to upregulate EPCs, potentially by an NO-mediated pathway.21 Supporting the importance of NO for EPC regulation, cotreatment with L-NAME completely inhibited the statin effect on EPCs. Concomitant treatment with an NO inhibitor abrogated the observed increase in VEGF plasma levels, which indicates that VEGF is regulated during exercise by NO. Because the effect on the bone marrow–derived cells was not completely omitted, additional mechanisms unrelated to NO are likely but remain unknown. Absolute numbers of EPCs in untrained eNOS−/− mice and mice treated with L-NAME were significantly reduced, which suggests an important role of eNOS for basal EPC regulation. In addition to an upregulation of EPC generation, physical exercise may increase EPC numbers by prolonging their lifespan. The data derived from cultured EPCs indicate that the observed EPC enhancement in the circulation and the bone marrow could be explained at least in part by antiapoptotic effects of physical activity on EPC and potentially their progenies.

EPCs are increased by ischemia, eg, in animal models of hindlimb ischemia.13 The here-in-used mouse models show an NO-dependent EPC increase that is probably unrelated to oxygen supply, because ischemia is unlikely to occur in this animal model of voluntary exercise. This is supported by epidemiological data showing that exercising not only prevents recurrent vascular events but is also effective in primary prevention.1,2

To test whether voluntary exercising versus a sedentary lifestyle improves vascular physiology in mice, we used a carotid artery injury model. Denuding of the endothelial monolayer results in neointima formation and stenosis. Accelerated reendothelialization after injury diminishes neointima formation. Here, we show that exercise reduces neointima formation. We and others have recently demonstrated that vascular repair and reendothelialization after injury is enhanced by circulating EPCs.18,20,22 EPCs are incorporated into sites of active angiogenesis and have been shown to augment collateral vessel growth and to contribute significantly to adult blood vessel formation.13,29 Another important benefi-


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