Aerobic Fitness Is Associated With Cardiomyocyte Contractile Capacity and Endothelial Function in Exercise Training and Detraining

Ole Johan Kemi, MSc*; Per Magnus Haram, BSc*; Ulrik Wisløff, PhD; Øyvind Ellingsen, MD, PhD

**Background**—Physical fitness and level of regular exercise are closely related to cardiovascular health. A regimen of regular intensity-controlled treadmill exercise was implemented and withdrawn to identify cellular mechanisms associated with exercise capacity and maximal oxygen uptake (V$\text{O}_2$ max).

**Methods and Results**—Time-dependent associations between cardiomyocyte dimensions, contractile capacity, and V$\text{O}_2$ max were assessed in adult rats after high-level intensity-controlled treadmill running for 2, 4, 8, and 13 weeks and detraining for 2 and 4 weeks. With training, cardiomyocyte length, relaxation, shortening, Ca$^{2+}$ decay, and estimated cell volume correlated with increased V$\text{O}_2$ max ($r=0.92, -0.92, 0.88, -0.84, 0.73, P<0.01$). Multiple regression analysis identified cell length, relaxation, and Ca$^{2+}$ decay as the main explanatory variables for V$\text{O}_2$ max ($R^2=0.87, P<0.02$). When training stopped, exercise-gained V$\text{O}_2$ max decreased 50% within 2 weeks and stabilized at 5% above sedentary controls after 4 weeks. Cardiomyocyte size regressed in parallel with V$\text{O}_2$ max and remained (9%) above sedentary after 4 weeks, whereas cardiomyocyte shortening, contraction/relaxation- and Ca$^{2+}$-transient time courses, and endothelium-dependent vasorelaxation regressed completely within 2 to 4 weeks of detraining. Cardiomyocyte length, estimated cell volume, width, shortening, and Ca$^{2+}$ decay and endothelium-dependent arterial relaxation all correlated with V$\text{O}_2$ max ($r=0.85, 0.84, 0.75, 0.63, -0.54, -0.37, P<0.01$). Multiple regression identified cardiomyocyte length and vasorelaxation as the main determinants for regressed V$\text{O}_2$ max during detraining ($R^2=0.76, P=0.02$).

**Conclusions**—Cardiovascular adaptation to regular exercise is highly dynamic. On detraining, most of the exercise-gained aerobic fitness acquired over 2 to 3 months is lost within 2 to 4 weeks. The close association between cardiomyocyte dimensions, contractile capacity, arterial relaxation, and aerobic fitness suggests cellular mechanisms underlying these changes. (*Circulation*. 2004;109:2897-2904.)

**Key Words:** exercise ■ myocytes ■ hypertrophy ■ contractility ■ endothelium

Several lines of evidence suggest that regular physical exercise not only improves fitness and aerobic capacity but also reduces morbidity and mortality. Maximal oxygen uptake (V$\text{O}_2$ max) has emerged as an important clinical refer-

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enced cell volume is the main explanatory variable for V$\text{O}_2$ max. However, cell volume is also inversely correlated with myocardial and arterial effects remain unclear. Reported regression of training-induced hypertrophy ranges from none to 20% over a period of 3 weeks. Experimental data suggest hypertrophy regression at varying time courses with no account on cardiomyocyte or arterial function. Thus, the aim of the present study was to assess the cardiomyocyte contractile capacity and endothelium-dependent arterial relaxation changes in animals undergoing a controlled program of exercise training and detraining. We report V$\text{O}_2$ max and associated changes in cardiomyocyte contractile capacity and endothelial function during detraining after 10 weeks of regular exercise and analyze correlations derived from previous 2- to 13-week training experiments in our laboratory.
Vascular Function
L-shaped holders were inserted into the lumen of 2- to 4-mm segments of the common carotid arteries; one holder was connected to a force-displacement transducer and the other to a micrometer in organ baths containing Krebs buffer and indomethacin. After gradually increasing tension to 1000 mg and exposure to 60 mmol/L K⁺, 3 × 10⁻³ mol/L phenylephrine, and 10⁻³ mol/L acetylcholine to ensure reactivity, segments were equilibrated 30 minutes before experiments started. Four segments from each animal were precontracted with phenylephrine (3 × 10⁻³ mol/L) and relaxed with cumulative doses of acetylcholine (2 segments) and Na⁺ nitroprusside (1 segment), whereas 1 segment was also pretreated with 10⁻⁴ mol/L N⁵-nitro-L-arginine methyl ester (L-NAME) before exposure to acetylcholine.

Allometric Scaling
In addition to exercise, differences in cardiac muscle weight and VO₂ may result from altered body mass. According to dimensional analysis and empirical studies, VO₂ should be expressed with the scaling exponent 0.78, which empirically is the best approximation when lean body mass is unavailable.

Statistics
Data are expressed as mean±SD. EC₅₀ values were obtained as previously described. The Friedman test, Wilcoxon paired samples t test, and appropriate procedures for multiple comparisons determined changes in VO₂max, whereas the Mann-Whitney test determined different cellular data, cardiac weights, and arterial function; a univariate repeated-measures ANOVA including Scheffé post hoc tests verified the differences. Relationships were assessed by Pearson’s correlation coefficient and complementary univariate, forward and backward linear regression analyses. VO₂max was modeled using cardiomyocyte volume, length, width, fractional shortening, time to half contraction and relaxation, and time to half Ca²⁺ peak and decay, and vasorelaxation EC₅₀ for detraining as explanatory variables, with P > 0.05 as exclusion criterion.

Results
Both exercise training and detraining led to substantial increase and regression of aerobic fitness and VO₂max, which closely corresponded to changes in cardiomyocyte contractile capacity, Ca²⁺ handling, and arterial endothelium function.

VO₂max During Training and Detraining
As previously reported, regular high-intensity interval running increased VO₂max substantially. After 8 to 10 weeks...
of training, VO\(_2\)max stabilized 37% above baseline and 26% above sedentary. During detraining, exercise-gained VO\(_2\)max decreased 50% within 2 weeks and stabilized 5% above sedentary after 4 weeks (Figure 1). In trained animals, univariate analysis of the data revealed that cardiomyocyte length, relaxation, shortening, Ca\(^{2+}\) decay, and volume correlated strongly with VO\(_2\)max (Figure 2). Backward multiple regression identified cell length, diastolic relaxation, and Ca\(^{2+}\) decay as the main factors for VO\(_2\)max; unstandardized coefficients \(b = 0.95 \pm 0.06, P < 0.01; -0.71 \pm 0.54, P < 0.01; \) and \(-1.02 \pm 0.42, P < 0.02, \) respectively; residual SD = 4.84, adjusted \(R^2 = 0.87\). In detraining, cell hypertrophy regression correlated closely with VO\(_2\)max. Strong correlation also occurred for myocyte relaxation (Figure 3). Acetylcholine-induced relaxation correlated less markedly with VO\(_2\)max \((r = -0.37, P < 0.05)\) than cardiomyocyte variables. Backward multiple regression identified cardiomyocyte length and endothelium-dependent arterial relaxation as the main determinants for changes in VO\(_2\)max during detraining with unstandardized coefficients \(b = 0.80 \pm 0.09, P < 0.01; -4.67 \pm 1.85, P < 0.02, \) respectively; residual SD = 4.63, adjusted \(R^2 = 0.76\).

**Cardiomyocyte Morphology and Function**

Training increased ventricular weights and cardiomyocyte dimensions and improved contractility and Ca\(^{2+}\) handling in the heart\(^6\) (Figure 1). Animals randomized for detraining also increased cardiomyocyte width and length by 20% to 22% and estimated volume by 46% (Figure 4). During
detraining, the responses varied slightly; cell width regressed completely within 2 weeks, whereas length (7% to 5%) and volume (15% to 9%) remained enlarged after 2 and 4 weeks, respectively, ie, similar to \( \dot{V}O_2 \) max. Parallel changes occurred in cardiac weights, which regressed toward sedentary within 4 weeks of detraining (Table).

Cardiomyocyte Ca\(^{2+}\)/H\(\text{11001}\) handling and intrinsic contractility were assessed at physiological cell stimulation frequencies (Figure 5). Within 2 weeks of detraining, the \( \approx \)30% increase in cardiomyocyte fractional shortening regressed almost completely. Diastolic and systolic fura 2 Ca\(^{2+}\) ratios and amplitude of Ca\(^{2+}\) transient were largely unaffected by training/detraining. The increase in cardiomyocyte contractility seemed to be associated with higher myofilament Ca\(^{2+}\) sensitivity. The Ca\(^{2+}\) sensitivity index (cell shortening/Ca\(^{2+}\) ratio amplitude) was elevated at 7 to 10 Hz electrical stimulation after 10 weeks of training and reversed to sedentary values during detraining. As shown in Figure 6, rates of both contraction and relaxation were increased, with parallel changes in Ca\(^{2+}\) handling. These changes prevailed to some extent after 2 weeks of detraining but not by week 4.

### Endothelium-Dependent Arterial Relaxation

Endothelium-dependent arterial relaxation increased significantly after regular exercise training. After 10 weeks, the magnitude of acetylcholine-induced relaxation increased by 13% and EC\(_{50}\) for agonist decreased 4-fold, whereas maximal absolute relaxation (R\(_{\text{max}}\)) leveled off 24% above sedentary (Figure 7). With detraining, all effects reversed within 2 weeks. The 7% and 2-fold larger EC\(_{50}\) and 11% increased R\(_{\text{max}}\) after cumulative Na\(^+\) nitroprusside addition in trained animals indicate a transient enhanced sensitivity to nitric oxide (NO), because it vanished within 2 weeks of detraining.

### Discussion

The present training-detraining experiments identified 2 distinctive cellular factors associated with changes in aerobic fitness, one closely correlated with cardiac myocyte size and function and another related to endothelium-dependent arterial relaxation. Although both may be important for the salutary health effects of exercise, the myocardial mechanisms seem to be more closely correlated to \( \dot{V}O_2 \) max.

### Cardiomyocyte Contractile Capacity

During long-term adaptation to regular exercise, the heart meets increased needs of peripheral tissues by matching pump capacity to afford sufficient cardiac output to transport oxygen corresponding to \( \dot{V}O_2 \) max. \(^{25}\) Both physiological hypertrophy and changes in myocardial function may account for the required increase in stroke volume. In the present study, changes in \( \dot{V}O_2 \) max closely paralleled cardiomyocyte length and width, providing a cellular basis for increase and regression of right and left ventricle stroke volumes. In addition, long-term changes in myocardial function may contribute significantly by altering diastolic filling and systolic emptying,\(^{12,14,26}\) as indicated by higher
Several aspects of cardiomyocyte contractile function were investigated in the study. Ejection fraction and fraction of shortening after training were significantly different between the training and detraining groups. The data are mean ± SD. TR/DETR vs sedentary: *P<0.01, †P<0.05. TR10 vs DETR2: ‡P<0.01, §P<0.05, and DETR4: ||P<0.01.

**Body Mass and Cardiac Weights**

<table>
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<th></th>
<th>Sedentary</th>
<th>TR10</th>
<th>DETR2</th>
<th>DETR4</th>
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<tr>
<td>Body mass, g</td>
<td></td>
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<tr>
<td>Before</td>
<td>239.4±11.0</td>
<td>232.8±12.5*</td>
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<tr>
<td>After</td>
<td>303.9±15.3</td>
<td>288.0±27.1†</td>
<td>325.5±19.3</td>
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<td>In mg</td>
<td>1422.8±140.3</td>
<td>1569.2±150.6</td>
<td>1697.2±55.3§</td>
<td>1482.7±186.3</td>
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<tr>
<td>In mg/g</td>
<td>4.7±0.4</td>
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<td>In mg/g²⁻⁷⁸</td>
<td>16.5±1.4</td>
<td>18.9±1.1†</td>
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<td>In mg</td>
<td>1051.3±109.7</td>
<td>1162.5±126.6</td>
<td>1263.1±80.6†</td>
<td>1111.9±172.5</td>
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<td>In mg/g</td>
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<td>4.0±0.2*</td>
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<td>3.6±0.7</td>
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<tr>
<td>In mg/g²⁻⁷⁸</td>
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<td>13.9±1.4</td>
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<tr>
<td>In mg</td>
<td>371.5±52.6</td>
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<td>434.1±81.0</td>
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<td>In mg/g</td>
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</tr>
<tr>
<td>In mg/g²⁻⁷⁸</td>
<td>4.3±0.6</td>
<td>4.9±0.8</td>
<td>4.7±0.7</td>
<td>4.3±0.6</td>
</tr>
</tbody>
</table>

**Figure 4.** Cardiomyocyte length (A), width (B), and estimated volume (C) in detrained and sedentary rats (SED10, SED2, SED4) in 4800 cells, 150 from each rat. Training lasted 10 weeks (TR10) and detraining 2 (DETR2) and 4 (DETR4) weeks, respectively. Data are mean ± SD. TR/DETR vs sedentary: *P<0.01, †P<0.05. TR10 vs DETR2: ‡P<0.01, §P<0.05, and DETR4: ||P<0.01.

Ejection fraction and fraction of shortening after training were significantly different between the training and detraining groups. Several aspects of cardiomyocyte contractile function corresponded to training- and detraining-induced changes in VO2 max, including cardiomyocyte shortening and relaxation representing systolic and diastolic contractile properties, respectively. Although stroke volume is acutely regulated by extracardiac factors such as venous return, neurohormonal regulation, and afterload, previous studies identified significant correlation between contractile function of isolated myocytes and integrated in vivo function, indicating a contribution of intrinsic myocardial properties as well at both the molecular and cellular levels. Both statistical correlation and parallel time courses indicate that changes in cardiomyocyte size and function are likely to account for the changes in VO2 max. Because of the high internal correlations between different measures of cardiomyocyte size and function, it is to be expected that only 1 or 2 prove to be significant in multivariate regression analysis. However, this statistical interdependence does not preclude the possibility that myocyte size, contractility, and relaxation contribute cumulatively to the total contractile capacity in vivo.

**Endothelium-Dependent Arterial Relaxation**

The training-detraining experiment demonstrated substantial changes in acetylcholine-induced arterial relaxation, which were highly sensitive to inhibition of the endothelial nitric oxide synthase (eNOS) inhibitor L-NAME. These observations indicate induction and regression of endothelial function, which were significantly correlated with VO2 max in both univariate and multivariate analysis. However, the marked difference in time course of EC50 for acetylcholine indicates that endothelium-dependent vasodilation may not be as directly related to VO2 max as cardiomyocyte size and function. Whereas training-induced myocardial effects gradually regress over 3 to 4 weeks, exercise-gained endothelium-dependent relaxation is completely abolished within 2 weeks. The time course of the onset of endothelium-dependent changes could not be
determined because the previous studies did not include arterial function. On the basis of pilot experiments and exercise-induced resistance to decompression, we hypothesize that endothelial function changes much more quickly than myocardial. A more rapid time course does not preclude salutary health effects. Hambrecht et al recently demonstrated training-induced improvement in myocardial oxygen supply associated with increased endothelium-dependent relaxation and upregulation of the eNOS signaling pathway.

Figure 5. Cardiomyocyte contractility and Ca\(^{2+}\) handling in detrained and sedentary rats determined in 4 to 10 cells per rat. Training lasted 10 weeks (TR10) and detraining 2 (DETR2) and 4 (DETR4) weeks, respectively. A, Cell shortening; B, Ca\(^{2+}\) ratio amplitude; C, Ca\(^{2+}\) ratio sensitivity index (cardiomyocyte relative shortening/Ca\(^{2+}\) ratio amplitude); and D, diastolic and systolic Ca\(^{2+}\) ratios. Data are mean±SD. TR10 vs sedentary: *P<0.05; TR10 vs DETR2: †P<0.05; and DETR4: ‡P<0.01, §P<0.05.

Figure 6. Time course of contraction/relaxation and Ca\(^{2+}\) transient in detrained and sedentary cardiomyocytes stimulated at increasing frequencies. Training lasted 10 weeks (TR10) and detraining 2 (DETR2) and 4 (DETR4) weeks, respectively. A and B, Time to peak contraction and peak Ca\(^{2+}\) ratio, respectively; C and D, half-time to peak contraction and peak Ca\(^{2+}\) ratio, respectively; E and F, half-time to relaxation and Ca\(^{2+}\) ratio decay, respectively. Data are mean±SD. TR10 vs sedentary: *P<0.01, †P<0.05. DETR2 vs sedentary: ‡P<0.05. TR10 vs DETR2: §P<0.01, ‡P<0.05, and DETR4: #P<0.01.
detraining and suggests an even more rapid time course for endothelium-dependent arterial relaxation. Although both myocardial and endothelium-dependent factors correlate significantly with $\dot{V}O_2\text{max}$, the parallel temporal relationship of cardiomyocyte hypertrophy and contractile function indicate that myocardial cellular mechanisms may be more important for increased aerobic capacity. Studies in progress will more accurately define the time course of exercise-induced changes in endothelial function and determine whether training intensity affects magnitude of myocardial and endothelial responses differently and how these findings apply in heart failure.

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