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# THE EFFICIENCY COEFFICIENT OF THE RAT HEART AND MUSCULAR SYSTEM AFTER PHYSICAL TRAINING AND HYPOKINESIA

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Translation of "O Koeffitsiyente Poleznogo Deystviya Serdtsa Posle Fizicheskoy Trenirovki i Gipokinezii", Fiziologicheskiy Zhurnal SSSR im I. M. Sechenova, Vol. 66, No. 11, 1980, pp. 1660-1665.

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16. Abstract

The efficiency of an isolated heart did not change after prolonged physical training of rats for an extreme load. The increase in oxygen consumption by the entire organism in "uphill" running as compared to the resting level in the trained rats was 14% lower than in the control animals. Prolonged hypokinesia of the rats did not elicit a change in the efficiency of the isolated heart.

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# EFFICIENCY OF THE RAT HEART AND MUSCULAR SYSTEM AFTER PHYSICAL TRAINING AND HYPOKINESIA

Yu. S. Alyukhin and A. F. Davydov*

A number of works of our laboratory whose results have been generalized in a recently published survey [3] have shown that the efficiency of mechanical work of the heart, and probably also the diaphragm, experiences natural changes both during prolonged adaptation of the organism to cold, or (in the case of the heart), to hypokinesia, and during a number of other factors influencing the body or an isolated organ (thyrotoxicosis, effect of noradrenaline, 2,4-dinitrophenol, hypothermia, change in the oxygen supply to the organ). It is important to study such an important physiological factor from this viewpoint as the lengthy change in the level of physical work by the body both towards an increase (physical training) and a decrease (hypokinesia). /1660**

## Technique

Since it has been known that moderate physical swimming training of the object of our studies, albino rats, does not elicit changes in efficiency of the isolated heart [9,10], we gave ourselves the goal of studying the results of training for the maximum physical load which could be endured by the rats. This load was running at a speed of 33 m/min on a treadmill installed at a 15° angle to the horizontal plane (see figure).

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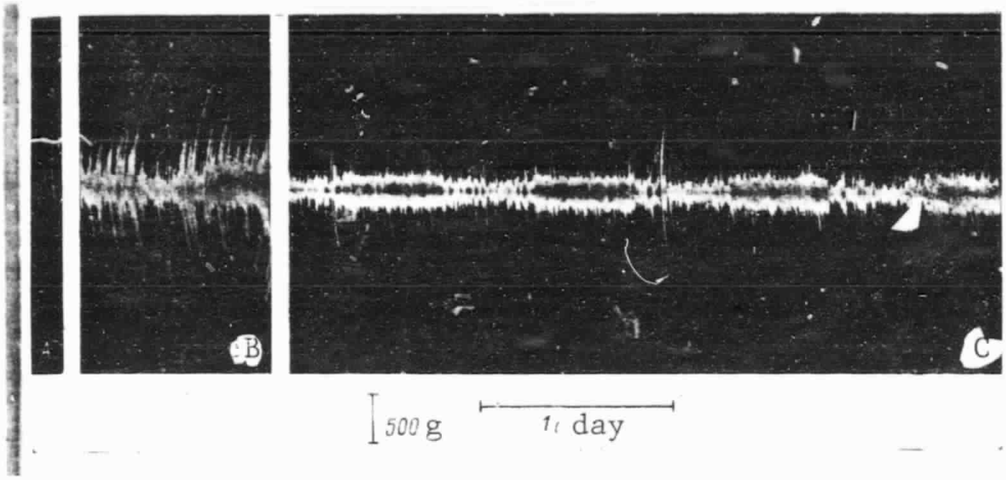
The design of the treadmill was mainly taken from the work of Gladfelter et al. [8]. An organic glass bubble divided into 6 running compartments was installed on the moving belt. This made it possible to train 6 animals at the same time. The rear wall of each compartment had an electric shock grid at 700 V of direct current engaged through constant resistance of 120 kOhm.

Both males and females were used for the training ith original age of 1.5-4 months (average 3 months) and original weight of 130-240 g (average 177 g). Some of the animals during the training systematically refused to run, "prefering" to be exposed to the electric shock, therefore a necessary condition for continuing the training was sorting of the animals who did not fulfill the set running pattern. A special series of experiments showed that differences in the original capacity of the rats to run were not associated with differences in heart efficiency, so that the sorting did not distort the results of studying the effect of physical training on the heart efficiency. A total of 64 out of 84 rats were rejected.

The training took place 5 days per week. In the beginning of /1661 training, the treadmill was installed horizontally and the duration of running was 10 min. During the training, the angle of inclination of the treadmill was gradually increased to 15°, and the duration of the running to 30 min. The speed of running was not altered. The total duration of training was 12-15 (average 14) weeks. During the last 4-7 weeks, the rats were trained in a constant regime (15°, 30 min. of running).

The experiments with hypokinesia used special individual small-sized (15 x 7 x 7 cm) cages which allowed the rats to adopt a natural position and change it, but excluded other movements. The cages were equipped with automatic feeders and automatic drinking bowls. A grid under the cage excluded the accumulation of excrement in it. Using a pneumatic actograph of original design where a block of cages with rats was installed on its elastic membranes, and a slowly rotating




Recording of Motor Activity (Actogram) of Rats in Control and during Hypokinetic Exposure

Key:

A. Response of actograph to three-fold application of force of 500 g
B. Daily actogram of 4 rats in standard cage
C. Four-day actogram of the same rats in block of hypokinetic cages
Diurnal rhythm of activity is visible

kymograph made a continuous recording of the motor activity of the animals. Before the beginning of hypokinetic exposure, an actogram was made of the rats in a standard cage. The obvious differences in the amplitude of the actogram of the rats in the standard cage and in the hypokinetic cages (see fig.) indicate that hypokinesia was actually reached. For 1.5 months of continuous recording, no significant changes were found in the level of motor activity of the animals. The total duration of hypokinetic exposure was 7-11 weeks (average 9 weeks). The experiments used males of the original age 2½-5 months (average 3 months) and original weight 210-265 g (average 236 g).

The heart efficiency was determined on a working isolated heart preparation according to the technique which was mainly described previously [1,2] but supplemented with the following changes. On the path of efflux of the perfusate from the left ventricle into the vertical tube in which hydrostatic pressure is created that is sufficient for effective perfusion of the coronary vessels, a chamber was installed which contained 2 ml of air. As a consequence of this, the resistance to efflux was elastic and the working conditions of the heart became closer to the normal. In addition, pressure of filling the left atrium in these experimentas was not constant, as before, but changed randomly in limits from 0 to 20 cm wat. col.

The efficiency of the mechanical operation of the muscular system of the animal was evaluated by measuring the oxygen consumption by the rat on a small treadmill placed in a pneumatic chamber of a modified Reno apparatus [4]. Initially the oxygen consumption of the rat at rest was measured, then while running at a speed of 27 m/min on a treadmill installed in the horizontal plane or at a 10° angle. The running continued for 20-30 min.

Before the rats were placed in the pneumatic chamber and immediately after the completion of running, their rectal temperature was taken.

## Study Results

Table 1 presents the average data for the energy parameters of the working isolated heart of rats who had passed physical training, and the control animals with the same pressure of filling of the left /1662 ventricle equal to 10 cm wat. col., as well as for the same preparations after stopping of the heart with potassium. The only energy parameter of those indicated in the table which revealed a statistically significant difference from the control after training was the absolute work of the heart which increased an average of 28%. In addition, an increase was observed by 13% in relation to the heart weight. There were no changes found in heart efficiency either with constant pressure of filling of the left ventricle or during regression analysis of the points obtained at different pressures of filling.

Table 2 generalizes the observation results of oxygen consumption by the entire organism, as well as the rectal temperature of the trained and control rats (males). In the trained rats, the oxygen

TABLE I. PARAMETERS OF ENERGY OF ISOLATED HEART, BODY WEIGHT AND HEART WEIGHT OF RATS IN CONTROL AND AFTER PHYSICAL TRAINING

| Parameter | Control | Training | $p$ |
|---|---|---|---|
| Working heart | | | |
| $P_{pr}$ = 10 cm wat. col. | | | |
| n | 13 | 18 | — |
| $V_c$ (ml/g x min) | 11.7±0.5 | 12.6±0.5 | 0.1—0.2 |
| $V_m$ (ml/g x min) | 22.1±1.9 | 27.1±1.8 | 0.05—0.1 |
| $pO_{2A}$ (mm Hg) | 645±2 | 651±4 | 0.1—0.2 |
| $pO_{2V}$ (mm Hg) | 184±6 | 203±9 | 0.1—0.2 |
| $MVO_2$ (μl $O_2$/g x min) | 168±7 | 176±6 | 0.2—0.5 |
| $E_\sigma$ (cal/g x min) | 0.806±0.032 | 0.845±0.030 | 0.2—0.5 |
| $P_{ex}-P_d$ (mm Hg) | 67.5±3.3 | 66.8±3.0 | 0.8—0.9 |
| $A_{abs}$ g x m/min) | 20.9±1.9 | 26.7±1.6 | 0.02—0.05 |
| A (g x m/g x min) | 20.3±1.8 | 24.1±1.6 | 0.1—0.2 |
| $E_A$ (cal/g x min) | 0.0475±0.0042 | 0.0564±0.0037 | 0.1—0.2 |
| η (%) | 5.85±0.51 | 6.67±0.37 | ≈0.2 |
| $\nu_c$ (contractions/s) | 4.18±0.16 | 4.04±0.14 | 0.5—0.8 |
| Stopped heart | | | |
| $V_c$ (ml/g x min) | 11.2±0.4 | 12.1±0.6 | 0.2—0.5 |
| $MVO_2$ (μl $O_2$/g x min) | 86.5±4.7 | 100±6 | 0.1—0.2 |
| $E_\sigma$ (cal/g x min) | 0.415±0.023 | 0.478±0.030 | 0.1—0.2 |
| Body weight (g) | 308±12 | 296±10 | 0.2—0.5 |
| Heart weight (g) | 1.036±0.042 | 1.125±0.035 | 0.1—0.2 |
| Heart weight, relative (mg/g) | 3.36±0.07 | 3.79±0.06 | <0.001 |
| | (n = 14) | (n = 20) | |

Note: (and for table 3). $P_{pr}$--Pressure in left ventricle; n--number of observations; $V_c$--coronary current; $V_m$--per-minute volume of heart; $pO_{2A}$--pressure of $O_2$ in perfusate flowing to heart; $pO_{2V}$--pressure of $O_2$ in perfusate flowing from coronary veins; $MVO_2$--$O_2$ consumption by heart; Eσ--total consumption of energy by heart; $P_{ex}$--average pressure of expulsion in left ventricle; $P_d$--final diastolic pressure in left ventricle; $A_{abs}$--absolute work of left ventricle; A--relative work of left ventricle; $E_A$--caloric equivalent of work of left ventricle; η--efficiency of heart; $\nu_c$--heartbeat rate; Average ± standard errors of averages are shown.

oxygen consumption at rest was higher than in the control (average by 28%). During running on a horizontal plane, the oxygen consumption of the trained rats, on the contrary, was somewhat lower than in the control (average by 10%).

While running "uphill" the oxygen consumption in the trained and control rats was practically not different. In this case, the consumption of oxygen during uphill running in the control rats averaged the same as during running on a horizontal plane, while in the trained rats it was 13% higher.

The table also presents the differences hetween the total oxygen consumption during running and at rest ("working increment" of oxygen consumption).

TABLE 2. OXYGEN CONSUMPTION BY ORGANISM, RECTAL TEMPERATURE AND BODY WEIGHT OF RATS IN CONTROL AND AFTER PHYSICAL TRAINING

| Parameter | Control | Training | p |
|---|---|---|---|
| $\dot{V}O_2$ ($\mu l\ O_2/g \times min$) | | | |
| At rest | 28.0±1.0 (9) | 35.7±1.2 (10) | <0.001 |
| Running: on horizontal plane | 72.0±1.0 (9) | 64.5±1.0 (6) | <0.001 |
| "uphill" (10°) | 71.9±2.0 (9) | 72.8±1.5 (9)* | 0.5—0.8 |
| ($\dot{V}O_2$ running-$\dot{V}O_2$ at rest)($\mu l O_2/g \times min$) For running: | | | |
| on horizontal plane | 44.0±1.0 (9) | 28.0±1.8 (6) | <0.001 |
| "uphill" (10°) | 43.9±2.5 (9) | 37.6±1.3 (9)* | 0.02—0.05 |
| Rt°(°C) | | | |
| At rest | 37.6±0.11 (9) | 37.6±0.12 (5) | >0.5 |
| Running: on horizontal plane | 39.6±0.23 (7) | 38.8±0.09 (4) | <0.05 |
| "uphill" (10°) | 39.8±0.17 (9) | 39.2±0.08 (7)** | <0.05 |
| (Rt° running-Rt° at rest)(°C) For running: | | | |
| on horizontal plane | 2.0±0.05 (7) | 1.1±0.13 (4) | <0.001 |
| "uphill" (10°) | 2.1±0.24 (9) | 1.5±0.17 (3) | 0.05—0.1 |
| Body weight (g) | 339±5 (9) | 327±4 (10) | 0.05—0.1 |

Note: $\dot{V}O_2$--oxygen consumption by organism; Rt°--rectal temperature. Average ± standard errors of averages. In parentheses--number of observations.*p for comparison with running on horizontal plane < 0.001. **p for comparison with running on a horizontal plane < 0.05.

The "working increment" of oxygen consumption in the trained rats was an average of 36% lower than in the controls when running on a horizontal plane, and 14% lower than in the controls when running "uphill." /1664

The "working increment" of oxygen consumption in the control when running on a horizontal plane and "uphill" did not differ. The "working increment" of oxygen consumption in the trained rats when running "uphill" averaged 34% more than running on a horizontal plane.

TABLE 3. ENERGY PARAMETERS OF ISOLATED HEART AND RELATIVE HEART WEIGHT OF RATS IN CONTROL AND AFTER PROLONGED HYPOKINESIA

| Parameter | Control | Hypokinesia | p |
|---|---|---|---|
| Working heart ($P_{pr}$ = 10 cm wat col.) | | | |
| n | 5 | 16 | — |
| $V_c$ (ml/g x min) | 12.1±1.1 | 12.4±0.5 | 0.8—0.9 |
| Vc (ml/g x min) | 25.5±1.9 | 30.1±1.8 | 0.05—0.1 |
| $pO_{2A}$ (mm Hg) | 649±3 | 659±4 | 0.05—0.1 |
| $pO_{2V}$ (mm Hg) | 197±24 | 200±14 | 0.90—0.95 |
| $MVO_2$ (µl $O_2$/g x min) | 173±13 | 177±5 | 0.5—0.8 |
| $E_\sigma$ (cal/g x min) | 0.830±0.062 | 0.850±0.025 | 0.5—0.8 |
| $P_{ex}-P_d$ (mm Hg) | 61.6±5.2 | 57.0±2.8 | 0.2—0.5 |
| A (g x m/g x min) | 21.2±2.1 | 23.0±1.5 | ≃0.5 |
| $E_A$ (cal/g x min) | 0.0496±0.0049 | 0.0538±0.0035 | ≃0.5 |
| η(%) | 6.02±0.24 | 6.31±0.41 | 0.5—0.8 |
| $\nu_c$ (contraction/s) | 3.92±0.12 | 4.20±0.10 | 0.05—0.1 |
| Stopped heart | | | |
| n | 10 | 15 | — |
| $V_c$ (ml/g x min) | 12.9±0.6 | 12.3±0.5 | 0.2—0.5 |
| $MVO_2$ (µl $O_2$/g x min) | 96.6±4.6 | 92.5±3.0 | 0.2—0.5 |
| $E_\sigma$ (cal/g x min) | 0.464±0.022 | 0.444±0.014 | 0.2—0.5 |
| Relative weight of heart (mg/g) | 3.30±0.09 (n = 10) | 3.48±0.10 (n = 15) | ≃0.2 |

Body temperature was increased in all the rats, but it was lower in the trained rats (average of 39°) than in the controls (average of 40°). When running on a horizontal plane, the body temperature of the control animals increased an average of 2.0°, and in the trained only 1.1°.

Table 3 presents the results of experiments with a heart after hypokinetic exposure of the rats. These experiments did not reveal any statistically significant changes in the energy parameters of the heart.

## Discussion of Results

Thus, neither physical training with an extreme load, nor lengthy hypokinesia had a significant effect on the efficient operation of an isolated rat heart. The results of the experiments with hypokinesia are not surprising since laboratory rats live a comparatively stationary lifestyle under normal conditions. The result of the experiments with training may be more unexpected. The training was apparently effective. This is indicated by the increase in performance capacity of the rats, decrease in the "working increment" of oxygen consumption, increase in relative heart weight and absolute working of the heart of the trained rats. The efficiency of the heart nevertheless did not change. It is appropriate to recall in this respect that in an even easier regime of training (swimming) in the experiments of Scheuer et al. [9, 10], no statistically significant changes were found in the rat heart under conditions of a sufficient oxygen supply to the heart preparation.

We have previously indicated that prolonged adaptation of rats to hypoxia causes an increased efficiency of the heart [2]. A high physical load apparently makes fewer requirements for efficient operation of the cardiac muscle of the rat than low oxygen content in the air. It is evident that the efficiency of the heart has greater difficulty in adapting to changes than the dimensions of the heart and its contractile capacity.

The increase we have shown in the oxygen consumption by the organism at rest as a result of physical training confirms similar observations of other authors [5-7]. A consequence of this increase was the fact that the total consumption of oxygen in the trained rats while running on a horizontal plane was only slightly less (average by 10%) than in the controls, and when running "uphill" almost did not differ. Training thus at best only slightly increased the "overall" efficiency of the muscle operation (ratio of work to total consumption of energy) when running on a horizontal plane. For running "uphill," the "overall" efficiency practically did not change.

There was a more pronounced decrease in the "working increment" of oxygen consumption as a result of the training (by 36% for running on a horizontal plane and by 14% for running "uphill"). This means that the "pure" efficiency of the muscle work (ratio of increase in work to increase in energy consumption) increased in both regimes.

In order to evaluate the actual degree of this increase, the data obtained during "uphill" running are apparently more adequate. The lack of differences in the "working increment" of oxygen consumption in the control rats during running in the two regimes indicates that the control rats while running on the horizontal plane actually did considerable "surplus" work, resisting the forced running, trying to stop or get out of the running chamber.

Comparison of the difference between the "working increment" of oxygen consumption in the trained rats when running "uphill" and when running on a horizontal plane with the work of rising on a vertical when running uphill made it possible to evaluate the absolute amount of "pure" efficiency of the work of elevation. It equalled 24%. /1665

Although oxygen consumption by the organism at rest in the trained rats was higher than in the controls, their rectal temperature did not differ before placement in the chamber. This can indicate both the intensification of the mechanisms for heat emission in the trained animals, and the fact that after they had been placed in the chamber, a conditioned reflex "prestart" intensification of gas exchange occurred. The differences in the rise in body temperature during running in the trained and control rats correspond to the differences in the "working increment" of oxygen consumption reflecting the different increase in heat production.

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