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ARTICLE *in* PFLÜGERS ARCHIV - EUROPEAN JOURNAL OF PHYSIOLOGY · MAY 1984

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Pflügers Archiv
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Exercise-induced fibre type transitions with regard to myosin, parvalbumin, and sarcoplasmic reticulum in muscles of the rat

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Abstract. Effects of a long-term, high intensity training program upon histochemically assessed myofibrillar actomyosin ATPase, myosin composition, peptide pattern of sarcoplasmic reticulum (SR), and parvalbumin content were analysed in muscles from the same rats which were used in a previous study (Green et al. 1983). Following 15 weeks of extreme training, an increase in type I and type IIA fibres and a decrease in type IIB fibres occurred both in plantaris and extensor digitorum longus (EDL) muscles. In the deep portion of vastus lateralis (VLD), there was a pronounced increase from $10 \pm 5\%$ to $27 \pm 11\%$ in type I fibres. No type I fibres were detected in the superficial portion of vastus lateralis (VLS) both in control and trained animals. An increase in slow type myosin light chains accompanied the histochemically observed fibre type transition in VLD. Changes in the peptide pattern of SR occurred both in VLS and VLD and suggested a complete transition from type IIB to IIA in VLS and from type IIA to I in VLD. A complete type IIA to I transition in the VLD was also suggested by the failure to detect parvalbumin in this muscle after 15 weeks of training. Changes in parvalbumin content and SR tended to precede the transitions in the myosin light chains. Obviously, high intensity endurance training is capable of transforming specific characteristics of muscle fibres beyond the commonly observed changes in the enzyme activity pattern of energy metabolism. The time courses of the various changes which are similar to those in chronic nerve stimulation experiments, indicate that various functional systems of the muscle fibre do not change simultaneously.

Key words: Exercise – Muscle fibre types – Myofibrillar actomyosin ATPase – Myosin light chains – Parvalbumins – Sarcoplasmic reticulum

Introduction

It is well established that increased contractile activity, as occurs in sustained exercise, elicits pronounced increases in mitochondrial enzymes related to aerobic substrate oxidation (for review see Holloszy and Booth 1976). In a recent study from this laboratory it was shown in rats that a high intensity, prolonged running program resulted in such changes in the enzyme activity pattern of energy metabolism which indicated fibre type transitions at the level of metabolic organization (Green et al. 1983). Specifically, increases in mitochondrial enzymes concomitant with decreases in glycolytic enzymes suggested a transition from fast-oxidative-glycolytic (FOG) to slow-oxidative (SO) in the deep portion of vastus lateralis. A fast-glycolytic (FG) to fast-oxidative-glycolytic transition was suggested for the superficial portion of this muscle by increases in mitochondrial enzymes at unaltered activity levels of the glycolytic enzymes.

In light of these results it was interesting to investigate whether a running program of this intensity would also produce changes in other type-specific properties which would support the suggested fibre type transitions. Fibre type transitions, as judged by histochemical staining for myofibrillar actomyosin ATPase (Andersen and Henriksson 1977; Jansson et al. 1978; Green et al. 1979; Ingjer 1979) as well as by immunohistochemistry for myosin (Schantz et al. 1982) have been suggested to occur as a result of endurance training in the human.

In light of these histochemical results, we decided to study the question of fibre transition by examining several fibre type-specific biochemical properties in addition to histochemical analyses. In this context, we also studied the myosin light chain complement. In addition measurements of parvalbumin contents and analyses of peptide patterns of isolated sarcoplasmic reticulum were included in the present study.

Methods

Animals and training

Experiments were performed with adult male Wistar rats which were fed rat chow and water ad libitum. These animals were the same rats used in our previous experiments. The two different treadmill training programs used have been described in detail (Green et al. 1983). Program I consisted of training for 12 weeks at a constant speed of 27 m/min with a progressive increase in grade and run duration. After 9 weeks the animals were capable of running 120 min at a 12.5 degree grade and after 11 weeks they ran 120 min at a 15 degree grade. Program II was the same as program I until the 7th week. From 7 to 15 weeks the animals exercised in the morning (8 a.m.), initially for a period of 15 min and then gradually progressing for 3 min per day, whereas in the afternoon (6 p.m.) the exercise duration was maintained at

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90 min. As in the first training program, modification to both grade and running duration was quickly made if it was thought that the animals were prematurely fatiguing. By the end of 15 weeks of training, the animals were running for 210 min per day at 27 m/min at 15 degree grade.

For program I, two experimental and two control animals were sacrificed at varying time points. For program II, experimental and control animals were sacrificed following the 15th week. Extensor digitorum longus, plantaris, and vastus lateralis muscles from both hind limbs were quickly removed, cleaned of adipose and connective tissue, frozen in melting isopentane (−160° C) and stored at −75° C until analysed. The vastus lateralis muscles were separated into a superficial, white portion (VLS) and a deep, red portion (VLD) on the basis of visual appearance. This method of isolation of VLS and VLD may introduce some uncertainty with regard to accurate separation of distinct fibre populations. VLS contains predominantly fast-glycolytic (FG) fibres whereas VLD is composed primarily of fast-oxidative-glycolytic (FOG) fibres with a small percentage of slow-oxidative (SO) fibres (Baldwin et al. 1972).

Since the muscles analysed were those used in the preceding study (Green et al. 1983), it was not possible, due to the limited amounts, to perform all analyses on all muscles. Therefore, sample sizes vary within this study and in comparison to the previous investigation (Green et al. 1983).

Biochemical analyses

Parvalbumin was purified from rat muscles by the method of Lehky et al. (1974). The amount of parvalbumin in control and experimental muscles was assessed electrophoretically by densitometry (LKB Ultrascan Laser Densitometer) using a modification of the method of Blum et al. (1977) as previously described (Klug et al. 1983a). Purified parvalbumin was used as standard.

Sarcoplasmic reticulum (SR) was isolated as previously described (Heilmann and Pette 1979). Electrophoresis of the SR was performed by the method of Laemmli (1970) as described (Heilmann and Pette 1979). After staining with Coomassie-blue, the peptide pattern was evaluated by densitometry.

Myosin light chains. Myosin was purified according to Ianuzzo et al. (1980). Electrophoresis was performed under denaturing conditions (Laemmli 1970). After staining with Coomassie-blue, amounts of myosin light chains were evaluated densitometrically. Molar concentrations were calculated after correcting for different staining intensities as recently described (Seedorf et al. 1983). For the purpose of evaluating molar ratios, the concentration of the DTNB light chains (LC2f + LC2s) was assumed to be 2 moles per mole holomyosin.

Histochemical analyses

Serial cross-sections (10 μm), were cut from whole muscles at −25° C on a cryostat microtome and stained for myofibrillar actomyosin ATPase according to Brooke and Kaiser (1970) as previously described (Reichmann and Pette 1982). Evaluation of percentage distribution of types I, IIA and IIB fibres was made on the entire cross-sectional areas. This method was chosen as fibre types are apparently classified on the basis of differences in myosin, a central point which we wanted to investigate. Fibre typing according to metabolic and myosin properties (Peter et al. 1972) was judged to be inappropriate for this study as fast fibres changed their metabolic properties with training (Green et al. 1983). Fast-glycolytic (FG) and fast-oxidative-glycolytic (FOG) fibres might therefore no longer be distinguishable in the trained muscles. While it is clear that the type I fibres are identical with the slow-oxidative (SO) fibres, only a gross correlation exists between type IIB and FG fibres and between type IIA and FOG fibres in rat leg muscles (Nemeth et al. 1979; Nemeth and Pette, 1980, 1981; Reichmann and Pette 1982). We point this out, because in our opinion, nomenclature of fibre types should only be used in relation with the methods from which they were derived.

Staining of myofibrillar actomyosin ATPase in the vastus lateralis according to Brooke and Kaiser (1970) gave results which were occasionally difficult to properly classify according to IIA and IIB fibre subgroups. It may be that the extremely small differences in pH lability that exist between these subgroups (Gollnick et al. 1983), were changed as result of the exercise. It is also possible that intermediate fibre types (Staron et al. 1983) existed which did not belong to either of the major fast type subgroups.

Results

Histochemical fibre transformation

The effect of endurance training on histochemically defined fibre types was studied in extensor digitorum longus (EDL), plantaris, and the superficial (VLS) and deep (VDL) portions of vastus lateralis. Pronounced fibre transitions, as judged by the histochemical staining for myofibrillar actomyosin ATPase, occurred in these muscles after 15 weeks training (program II). Figure 1 illustrates the decrease in type IIB fibres and the increase in type IIA and type I fibres in the plantaris muscle. The percentage distribution of fibre types in EDL and plantaris is given for training periods of 12 and 15 weeks in Table 1. Measurements at earlier time points were not performed.

Following 12 weeks of training (program I) there was a pronounced increase in the percentage of type IIA fibres in the plantaris. There was also a tendency for an increase in type I fibres. This transformation was sustained after 15 weeks (program II). Qualitatively similar, although less pronounced changes occurred in the EDL at both time periods. Program II evoked a more than twofold increase in type I fibres in VLD. However, no such increase was seen in VLS (Table 2). Since distinction of type IIA and IIB fibres was sometimes problematic in the vastus lateralis, no attempt was made to differentiate between these fast fibre subgroups in this muscle.

Myosin light chains

Since the greatest changes in the myosin light chain pattern would be expected in the muscle which demonstrated the greatest type II to type I fibre transformation, myosin light chains were analysed in the vastus lateralis. In the superficial portion of both 15 weeks trained and untrained animals only the light chain complement of fast myosin was detected (Table 3). In contrast, in the deep portion significant changes (Table 3) were observed. The light chain complement of the deep vastus lateralis was characterized by the coexistence of

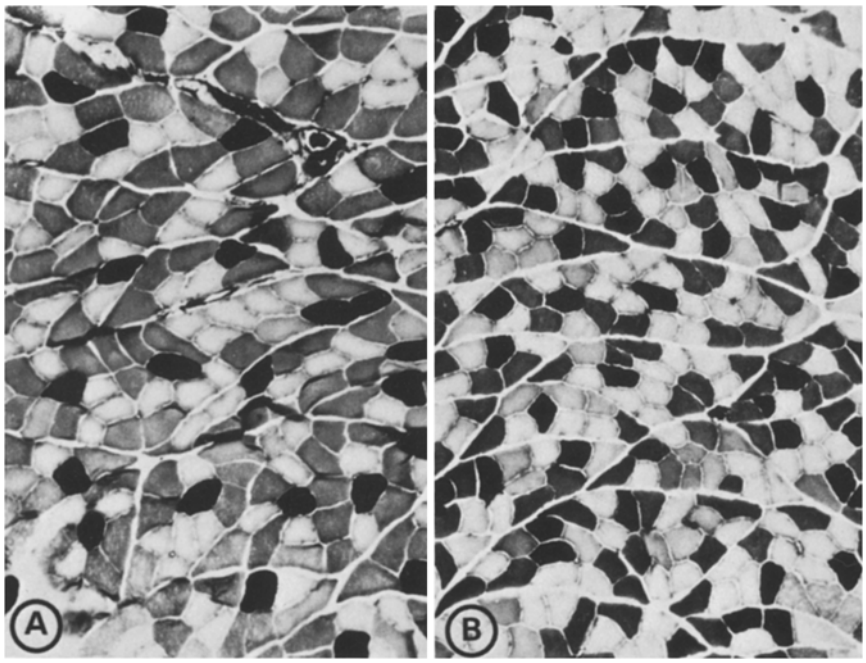

Fig. 1 A, B
Effects of endurance training upon fibre types according to Brooke and Kaiser (1970) in plantaris muscle of the rat, ×80. **A** Muscle from control rat; **B** muscle from 15 weeks trained rat (program II). Type I fibres stain dark, type IIB fibres intermediate and type IIA fibres light

Table 1
Effects of endurance training upon the percentage distribution of fibre types according to Brooke and Kaiser (1970) in hindlimb muscles of the rat

Muscle (*n*)	Program	Type I	Type IIA	Type IIB
		%		
Extensor dig. long.				
(1)	contr.	7.7	22.1	70.2
(1)	I (12 weeks)	8.9	26.3	64.8
(2)	contr.	3.1	16.2	80.7
(3)	II (15 weeks)	5.3 ± 1.3	21.3 ± 3.3	73.5 ± 4.6
Plantaris				
(1)	contr.	10.7	20.5	68.1
(1)	I (12 weeks)	12.3	32.0	53.4
(4)	contr.	12.7 ± 1.4	26.8 ± 2.2	60.5 ± 0.8
(5)	II (15 weeks)	16.7 ± 4.1	38.8 ± 4.2*	43.4 ± 6.0*

* $P < 0.005$

Table 2. Effects of endurance training upon the percentage distribution of type I and type II fibres in the superficial (VLS) and deep (VLD) portions of vastus lateralis muscle in the rat

Muscle (*n*)	Program	Type I	Type II
		%	
VLS (3)	contr.	0	100
(5)	II (15 weeks)	0	100
VLD (3)	contr.	10.1 ± 5.3	89.9 ± 5.3
(4)	II (15 weeks)	27.0 ± 10.8*	73.0 ± 10.8*

* $P < 0.05$

all 5 light chains found in fast and slow muscles of the rat. According to the low percentage of type I fibres, (10 ± 5%, Table 2), the slow myosin light chains represent a minor fraction in control muscles. However, after 15 weeks of training, the amount of the slow type myosin light chains increased considerably. This increase was accompanied by a decrease in fast myosin light chains. Thus, the sum of fast and slow alkali (LC1f + LC1s + LC3f) and DTNB (LC2f + LC2s) light chains remained constant. The increase was significant for light chains 1s. Although the mean values showed a pronounced increase also for light chain 2s, this increase was not significant statistically, presumably due to the large variation in the control value (Table 3). As is evident from Table 3, the variations (SD value) were much smaller in the 15 weeks trained than in the control animals. It is also obvious from Table 3 that no changes were evoked in the myosin light chain pattern by the 12 weeks training program I.

Parvalbumin

The parvalbumin content differs in various fibre types (Celio and Heizmann 1982). It has also been shown to be reduced in chronically stimulated fast muscle undergoing a type II to type I transformation (Klug et al. 1983a). Therefore, it was of interest to investigate possible changes in the content of this cytosolic, Ca^{2+}-binding protein. Results given in Table 4 indicate a marked decrease in the parvalbumin

Table 3. Effects of endurance training upon light chain composition of myosin from the superficial (VLS) and deep (VLD) portions of vastus lateralis muscle in the rat

Muscle (*n*)	Program	Myosin light chains				
		1s	1f	2s	2f	3f
		moles/mole myosin ± SD				
VLS (5)	contr.	0	1.34 ± 0.10	0	2.00 ± 0.09	0.65 ± 0.08
(5)	II (15 weeks)	0	1.30 ± 0.07	0	2.00 ± 0.17	0.72 ± 0.09
VLD (6)	contr.	0.25 ± 0.15	1.28 ± 0.11	0.16 ± 0.10	1.84 ± 0.17	0.47 ± 0.14
(3)	I (12 weeks)	0.28 ± 0.11	1.22 ± 0.01	0.19 ± 0.07	1.81 ± 0.17	0.45 ± 0.10
(4)	II (15 weeks)	0.61 ± 0.03*	1.13 ± 0.06*	0.26 ± 0.01	1.74 ± 0.11	0.26 ± 0.05*

* $P < 0.05$

Table 4. Effects of endurance training upon parvalbumin contents in superficial (VLS) and deep (VLD) portions of vastus lateralis and extensor digitorum longus (EDL) of the rat

Muscle (*n*)	Program	Parvalbumin	
		mg/g sol. protein	g/kg wet weight
VLS (4)	contr.	81.6 ± 10	5.00 ± 0.414
(2)	II (15 weeks)	66.5	3.74
VLD (4)	contr.	27.3 ± 6	1.64 ± 0.554
(2)	II (15 weeks	not detectable	
EDL (4)	contr.	126.7 ± 7	3.36 ± 0.258
(4)	II (15 weeks)	79.0 ± 18*	2.29 ± 0.335*

* $P < 0.005$

content of the deep portion of vastus lateralis as a result of training. After 15 weeks of training program II, parvalbumin was no longer detectable in VLD in either of the two animals studied. Due to the limited number of animals available for the different analyses, determination of parvalbumin was made in VLD and VLS of one animal after 4 and 10 weeks of program I. After 10 weeks parvalbumin tended to decrease in VLD (17.1 mg/g soluble protein) and VLS (51 mg/g soluble protein). There was only a 20% decrease in the parvalbumin content of VLS after 15 weeks of program II (Table 4). For comparison, parvalbumin contents were determined in another muscle having a similar fibre population as the VLS. As is seen in Table 4, 15 weeks training (program II) resulted in a reduction of parvalbumin in the EDL of a similar magnitude as in VLS.

Sarcoplasmic reticulum

In addition to the above described alterations in cytosolic, Ca^{2+}-binding capacity, training had a definite effect on the sarcoplasmic reticulum. These effects were manifest as changes in the peptide pattern of the isolated SR (Fig. 2). It has been shown that differences exist between the peptide patterns of SR isolated from normal VLS and VLD (Wiehrer and Pette 1983). The most prominent difference concerned the ratio between the 115,000-M_r Ca^{2+}-pumping protein and a 30,000-M_r peptide. The respective values from control VLS and VLD in Table 5 confirm this difference. The lower

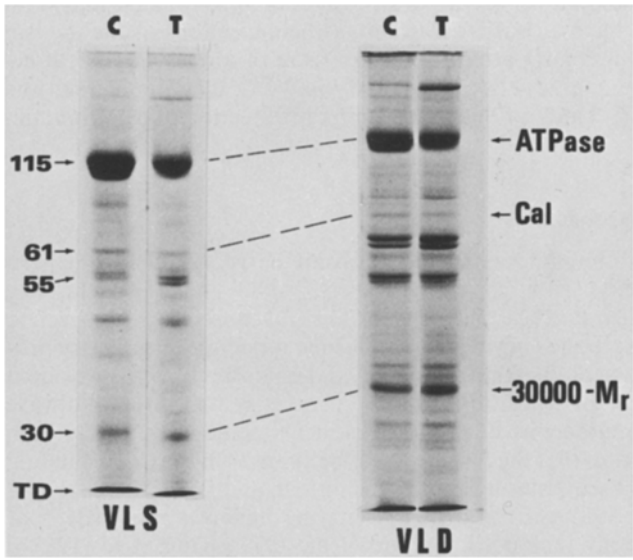

Fig. 2. Peptide patterns of sarcoplasmic reticulum from superficial (VLS) and deep (VLD) portions of vastus lateralis of control (*C*) and 15 weeks trained (*T*) rats (program II). Apparent molecular weights are given as daltons $\times 10^{-3}$. *Cal*, calsequestrin; *TD*, tracking dye

Table 5. Effects of endurance training upon the ratio of the 115,000-M_r Ca^{2+}-pumping ATPase protein and a 30,000-M_r peptide of sarcoplasmic reticulum from superficial (VLS) and deep (VLD) portions of vastus lateralis in the rat

Muscle (*n*)	Program	115,000-M_r-Peptide / 30,000-M_r-Peptide
VLS (6)	contr.	18.3 ± 3.0
VLS (1)	I (10 weeks)	17.6
VLS (1)	I (12 weeks)	6.9
VLS (3)	II (15 weeks)	3.9 ± 1.6*
VLD (6)	contr.	3.2 ± 1.1
VLD (1)	I (10 weeks)	4.1
VLD (1)	I (12 weeks)	1.0
VLD (3)	II (15 weeks)	1.2 ± 0.3*

* $P < 0.001$

value in VLD is due both to a lower content of the 115,000-M_r peptide and a higher content of the 30,000-M_r peptide.

As seen in Fig. 2, training produced a decrease in the 115,000-M_r Ca^{2+}-pumping protein and an increase in the 30,000-M_r peptide of both VLS and VLD. These changes result in significant reductions in the ratio of the two peptides after 12 weeks of training (Table 5). After 15 weeks of program II, this ratio in VLS attained a value similar to that found in the control VLD. However, in the VLD this ratio reached the value observed in normal soleus muscle (1.2). Based upon the numerical value of this ratio obtained from control VLS, VLD and soleus, which are each composed predominantly of a specific fibre type, the observed changes suggest that training induced some fibre type specific transitions in the SR. The magnitude of these changes is consistent with a type IIB to IIA transition of the SR in VLS and a type IIA to type I transition of the SR in VLD. These transitions are obviously more pronounced and seem to have an earlier onset than the alterations in the myosin light chain pattern. A comparison of Tables 4 and 5, however, shows that particularly in VLD they match well the extent and time course seen in the reduction of parvalbumin.

Discussion

Cross-reinnervation and chronic nerve stimulation experiments (for review see Pette 1980) have conclusively illustrated the plasticity of skeletal muscle with respect to metabolic enzymes, sarcoplasmic reticulum, regulatory proteins of the thin filament, and myosin. It is also evident that the transitions of these various systems are not always simultaneous but follow distinct time courses. It has been shown that the fast to slow type changes in the Ca^{2+}-binding and sequestering system (Heilmann and Pette 1979; Klug et al. 1983a, b) and in the enzyme and isozyme pattern of energy metabolism (Pette et al. 1973; Klug et al. 1983b) occur much earlier than the transition of the isoforms of myosin (Sréter et al. 1973; Pette et al. 1976; Seedorf et al. 1983). From these data, two conclusions can be drawn: 1) Different activity thresholds exist for different systems of the muscle fibre, 2) the notion of "fibre transition" must be considered at the level of specific systems as opposed to the fibre as a single entity.

With this in mind it is not surprising that increased muscular activity, as in endurance training, brings about a variety of metabolic adaptations (for review see Holloszy and Booth 1976). There still exists controversy concerning the question whether or not endurance training is capable of inducing more extensive changes, such as transforming the "fibre type" at the level of SR or myosin related properties. This uncertainty might be due to the failure to provide training programs which increase muscle activity to a level approaching that common to chronic nerve stimulation. Therefore, the present study utilized a more intense training protocol than those used in most preceding studies investigating this problem.

It is obvious from the present study that an extensive and prolonged training program can bring about fibre transitions as judged by conventional histochemical techniques. The decrease in type IIB fibres with concomitant increases in types IIA and I fibres in plantaris, EDL and vastus lateralis muscles (Fig. 1, Tables 1 and 2) confirm similar results obtained with high intensity training in the human (Andersen and Henriksson 1977; Jansson et al. 1978; Green et al. 1979; Ingjer 1979; Schantz et al. 1982). These results support the ordered type IIB to IIA to I transition proposed by Jansson et al. (1978) and Billeter et al. (1981).

The results of the myosin light chain analyses (Table 3) support the histochemically assessed fibre type transition. Since apparently no differences exist between the light chain patterns of types IIB and IIA fibres (Billeter et al. 1981), as well as between FG and FOG fibres (Pette and Schnez 1977a), no changes would be expected in the VLS. Conversely, changes in the light chain pattern would accompany the type IIA to I transition in the VLD. Examination of the data in Tables 2 and 3 suggests that the increase in type I fibres is correlated with the increase in slow type myosin light chains and a concomitant decrease in fast type light chains. These data do not exclude, of course, the possibility of fibres which display a coexistence of fast and slow myosin light chains as previously reported in chronic nerve stimulation experiments (Pette and Schnez 1977b).

The data on the changes in the peptide pattern of the SR (Fig. 2, Table 5) support the findings of Kim et al. (1981) who using a less intensive training program, found a decrease in the Ca^{2+}-uptake capacity of the SR in rat VLS. Furthermore, these results (Fig. 2, Table 5) indicate a type IIB to IIA and a type IIA and I transition in the VLS and VLD respectively. However, in contrast to the extent of the changes in histochemical staining and in the myosin light chain pattern, these changes would suggest a complete transformation of the fibre populations both in VLS and VLD. A complete type IIA to type I fibre transition would also be indicated by the failure to detect parvalbumin in the VLD after 15 weeks of training (Table 4). Evidently, parvalbumin content and fibre type specific properties of the SR appear to be altered in parallel in VLD as was shown recently in chronic nerve stimulation experiments (Klug et al. 1983b). The fact that only moderate reductions occurred in parvalbumin in the VLS (Table 4), indicate that such a strict correlation does not necessarily exist under all conditions.

Taken collectively, the results of this study show that increased contractile activity, as brought about in a physiological manner, is capable of inducing true fibre type transitions. While the changes are not as dramatic and rapid as in chronic nerve stimulation experiments, they concern various type-specific systems of the muscle fibre, i.e. energy metabolism (Green et al. 1983), parvalbumins, sarcoplasmic reticulum and myosin. As in chronic nerve stimulation, changes in the enzyme profile of energy metabolism, in parvalbumins and in SR occur in advance of those observed for myosin. Because these transitions follow an ordered pattern, it is too simplistic to speak of fibre transitions based solely on one paramenter. The time course of transformations might also suggest that late transitions, such as those in myosin isoforms, depend in some way on earlier changes as previously suggested with chronic stimulation (Klug et al. 1983b).

If the changes induced by increased contractile activity resemble qualitatively those evoked by chronic nerve stimulation, the question arises whether there is one common stimulus in both situations. It has been shown that altering running speed modifies the firing rates of motoneurons in freely walking cats (Hoffer et al. 1981). Therefore, motoneuron activity during increased contractile activity, as

in endurance training, may resemble the conditions created in chronic nerve stimulation. As has been recently shown, long-term stimulation of fast-twitch muscle in the rabbit with a phasic (40–60 Hz) pattern brings about similar transitions in metabolic and contractile properties as observed with continuous low frequency (10 Hz) stimulation (Hudlicka et al. 1980, 1982; Harris et al. 1982; Sréter et al. 1982; Pette and Tyler 1983). Thus, it appears to be the total activity over a period of time which induces in a graded fashion the observed transformations of the various functional systems of the muscle fibre. If this is true, it is understandable that a longterm, hight intensity training results in qualitatively similar transformation processes as chronic nerve stimulation.

Acknowledgements. This study was supported by the Deutsche Forschungsgemeinschaft, Sonderforschungsbereich 138, "Biologische Grenzflächen und Spezifität" and The Medical Research Council of Canada. G.A.K. was a fellow of the A. v. Humboldt-Stiftung. H.R. was a recipient of a postdoctoral stipend from the Fritz Thyssen Stiftung. Authors are grateful to Ms. Bärbel Gohlsch and Ms. Karin Tilch for expert technical assistance.

References

Andersen P, Henriksson J (1977) Training induced changes in the subgroups of human type II skeletal muscle fibres. Acta Physiol Scand 99:123–125

Baldwin KM, Klinkerfuss GH, Terjung RL, Molé PA, Holloszy JO (1972) Respiratory capacity of white, red and intermediate muscle: adaptive response to exercise. Am J Physiol 222:373–378

Billeter R, Heizmann CW, Howald H, Jenny E (1981) Analysis of myosin light and heavy chain types in single human skeletal muscle fibers. Eur J Biochem 116:389–395

Blum HE, Lehky P, Kohler L, Stein EA, Fischer EH (1977) Comparative properties of vertebrate parvalbumins. J Biol Chem 252:2834–2838

Brooke MH, Kaiser KK (1970) Three 'Myosin ATPase' systems: The nature of their pH lability and sulfhydryl dependence. J Histochem Cytochem 18:670–672

Celio MR, Heizmann CW (1982) Calcium-binding protein parvalbumin is associated with fast contracting muscle fibres. Nature (Lond) 297:504–506

Gollnick D, Parsons D, Oakley CR (1983) Differentiation of fiber types in skeletal muscle from the sequential inactivation of myofibrillar actomyosin ATPase during acid preincubation. Histochemistry 77:543–555

Green HJ, Thomson JA, Daub WD, Houston ME, Ranney DA (1979) Fiber composition, fiber size and enzyme activities in vastus lateralis of elite athletes involved in high intensity exercise. Eur J Appl Physiol 41:109–117

Green HJ, Reichmann H, Pette D (1983) Fibre type specific transformations in the enzyme activity pattern of rat vastus lateralis muscle by prolonged endurance training. Pflügers Arch 399:216–222

Harris B, Heilig A, Hudlická O, Leberer E, Pette D, Tyler K (1982) Changes in rabbit muscle enzyme activities in response to chronic stimulation with different frequency patterns. In: Semigonovský B, Tucêk S (eds) Metabolic and functional changes during exercise. Charles University, Prague, pp 27–31

Heilmann C, Pette D (1979) Molecular transformations in sarcoplasmic reticulum of fast twitch muscle by electrostimulation. Eur J Biochem 93:437–446

Hoffer JA, O'Donovan MJ, Pratt CA, Loeb GE (1981) Discharge patterns of hindlimb motoneurons during normal cat locomotion. Science 213:466–468

Holloszy JO, Booth FW (1976) Biochemical adaptations to endurance exercise in muscle. Ann Rev Physiol 38:273–291

Hudlická O, Tyler KR, Aitman T (1980) The effect of long-term electrical stimulation on fuel uptake and performance in fast skeletal muscles. In: Pette D (ed) Plasticity of muscle. Walter de Gruyter, Berlin New York, pp 401–408

Hudlická O, Tyler KR, Srihari T, Heilig A, Pette D (1982) The effect of different patterns of long-term stimulation on contractile properties and myosin light chains in rabbit fast muscles. Pflügers Arch 393:164–170

Ianuzzo CD, Patal P, Chen V, O'Brien P (1980) A possible thyroidal trophic influence on fast and slow skeletal muscle myosin. In: Pette D (ed) Plasticity of muscle. Walter de Gruyter, Berlin New York, pp 593–605

Ingjer F (1979) Effects of endurance training on muscle fibre ATPase activity, capillary supply and mitochondrial content in man. J Physiol (Lond) 294:419–432

Jansson E, Sjödin B, Thorstensson A, Hultén B, Frith K (1978) Changes in muscle fibre type distribution in man after exercise. A sign of fibre type transformation? Acta Physiol Scand 104:235–237

Kim DH, Wible GS, Witzmann FA, Fitts RH (1981) The effect of exercise training on sarcoplasmic reticulum function in fast and slow skeletal muscle. Life Sci 28:2671–2677

Klug G, Reichmann H, Pette D (1983a) Rapid reduction in parvalbumin concentration during chronic stimulation of rabbit fast twitch muscle. FEBS Lett 152:180–182

Klug G, Wiehrer W, Reichmann H, Leberer E, Pette D (1983b) Relationships between early alterations in parvalbumins, sarcoplasmic reticulum and metabolic enzymes in chronically stimulated fast twitch muscle. Pflügers Arch 399:280–284

Laemmli UK (1970) Cleavage of structural proteins during the assembly of the head of bacteriophage T_4. Nature (Lond) 227:680–685

Lehky P, Blum HE, Stein EA, Fischer EH (1974) Isolation and characterization of parvalbumins from skeletal muscle of higher vertebrates. J Biol Chem 249:4332–4334

Nemeth P, Hofer HW, Pette D (1979) Metabolic heterogeneity of muscle fibres classified by myosin ATPase. Histochemistry 63:191–201

Nemeth P, Pette D (1980) The interrelationship of two systems of fiber classification in rat EDL muscle. J Histochem Cytochem 28:193

Nemeth P, Pette D (1981) Succinate dehydrogenase activity in fibres classified by myosin ATPase in three hind limb muscles of rat. J Physiol (Lond) 320:73–81

Peter JB, Barnard RJ, Edgerton VR, Gillespie CA, Stempel KE (1972) Metabolic profiles of three fiber types of skeletal muscle in guinea pigs and rabbits. Biochemistry 11:2627–2633

Pette D (ed) Plasticity of muscle. Walter de Gruyter, Berlin New York, 1980

Pette D, Smith ME, Staudte HW, Vrbová G (1973) Effects of long-term electrical stimulation on some contractile and metabolic characteristics of fast rabbit muscles. Pflügers Arch 338:257–272

Pette D, Müller W, Leisner E, Vrbová G (1976) Time dependent effects on contractile properties, fibre population, myosin light chains and enzymes of energy metabolism in intermittently and continuously stimulated fast twitch muscles of the rabbit. Pflügers Arch 364:103–112

Pette D, Schnez U (1977a) Myosin light chain patterns of individual fast and slow-twitch fibres of rabbit muscles. Histochemistry 54:97–107

Pette D, Schnez U (1977b) Coexistence of fast and slow type myosin light chains in single muscle fibres during transformation as induced by long term stimulation. FEBS Lett 83:128–130

Pette D, Tyler KR (1983) Response of succinate dehydrogenase activity in fibres of rabbit tibialis anterior muscle to chronic nerve stimulation. J Physiol (Lond) 338:1–9

Reichmann H, Pette D (1982) A comparative microphotometric study of succinate dehydrogenase activity levels in Type I, II A

and IIB fibres of mammalian and human muscles. Histochemistry 74:27–41

Schantz P, Billeter R, Henriksson J, Jansson E (1982) Training-induced increase in myofibrillar ATPase intermediate fibers in human skeletal muscle. Muscle & Nerve 5:628–636

Seedorf K, Seedorf U, Pette D (1983) Coordinate expression of alkali and DTNB myosin light chains during transformation of rabbit fast muscle by chronic stimulation. FEBS Lett 158:321–324

Sréter FA, Gergely J, Salmons S, Romanul R (1973) Synthesis by fast muscle of myosin light chains characteristic of slow muscle in response to long-term stimulation. Nature New Biol (Lond) 241:17–19

Sréter FA, Pinter K, Jolesz F, Mabuchi K (1982) Fast to slow transformation of fast muscles in response to long-term phasic stimulation. Exptl Neurol 75:95–102

Staron RS, Hikida RS, Hagerman FC (1983) Reevaluation of human muscle fast-twitch subtypes: evidence for a continuum. Histochemistry 78:33–39

Wiehrer W, Pette D (1983) The ratio between intrinsic 115,000- and 30,000-M_r peptides as a marker of fibre type specific sarcoplasmic reticulum in mammalian muscle. FEBS Lett 158:317–320

Recieved August 11, 1983/Accepted January 3, 1984