Physiological aspects of training in rowing

Article *in* International Journal of Sports Medicine · October 1993

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Physiological Aspects of Training in Rowing

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Abstract

J. M. Steinacker, Physiological Aspects of Training in Rowing. Int J Sports Med, Vol 14, Suppl 1, pp S3–S10, 1993.

At the start of a rowing race, the boat is accelerated and the force on the oars reaches between 1000 and 1500 N. During the race, the speed is maintained at a lower level with a peak rowing force of 500–700 N for 210–230 strokes for about 6.5 min. Rowers are adapted to this effort by a large muscle mass and high metabolic capacities.

The muscles of successful rowers demonstrate 70 %–85 % slow-twitch fibers. Both slow- and fast-twitch fibers have increased oxidative enzyme activities reflecting elevated number and density of mitochondria. Rowing force and boat velocity correlate to maximal oxygen uptake ($\dot{V}O_2$) which reaches $6.0–6.6\,l \cdot min^{-1}$ ($65–70\,ml \cdot min^{-1} \cdot kg^{-1}$) and to the $\dot{V}O_2$ during a race. In turn, the $\dot{V}O_2$ during a race is related to slow-twitch fibers content of the muscles, also to the aerobic-anaerobic threshold (AAT) and inversely related to the maximal blood lactate level. The AAT is 80 %–85 % of maximal performance in highly trained rowers.

In successful rowers training intensity is 70 %–90 % of the training time below the AAT. Training eliciting a blood lactate above 4.0 mmol/l, sprint training and athletics training complete the training schedule, which may reach 1000 h, or 5000–7000 km per year.

Key words

Maximal oxygen consumption, biomechanics, work efficiency, aerobic-anaerobic threshold, lactate

Introduction

The typical rowing competition takes place on a 2000-m course and lasts 6–7 min. During the competition, anaerobic alactic and lactic as well as aerobic capacities are stressed to their maximum. A large body muscle mass is involved in rowing and the maximum oxygen uptake ($\dot{V}O_2max$) of oarsmen is among the largest values recorded (7,10,16,18, 26,28,52,61,63,71).

Rowers are large and heavy because their body weight is supported while seated in the boat. Rowing involves approximately 70 % of the muscle mass because all extremities and the trunk participate in the propulsion of the boat. Rowing is a cyclic movement, where both legs and arms work synchronized. The body is moved on a sliding seat by the propulsion of the legs during the stroke, while pulling on one (sweep rowing) or two oars (sculling).

During training 15–40 strokes/min are used and from 32 to 38 strokes/min during a race in the single scull corresponding to a stroke duration of 0.6–2.2 s. In the coxed weight, the stroke rate may reach 48 strokes/min at the start. In the starting phase, the peak force is 1000–1500 N and the force levels off at 500–700 N during the middle part of the race (Table **1**). Between 210 and 230 strokes are performed during

Table 1 Stroke rate, peak force, peak power, work and power per stroke and average power for stroke and recovery during a typical rowing race in the single scull. Results are compiled from biomechanical measurements and evaluations in the former department of biomechanics of the Humboldt-Universität at East Berlin and the center of rowing research of the former East Germany (courtesy of P. Schwanitz and W. Roth).

	Time (min, s)	Stroke rate (l/min)	Peak force (N)	Peak velocity (m/s)	Peak power (W)	Work per stroke (Nm)	Power per stroke (W)	Average power (W)
Start spurt	0–10 s	36–42	1000–1500	3.0–4.0	2500–3000	900–1100	800–1200	600–700
Start phase	10–60 s	34–38	600– 800	2.2–3.5	1400–2800	800– 950	700–1000	450–600
Race	1– 5 min	30–36	500– 700	2.0–2.2	1000–1600	650– 800	600– 900	350–450
Final spurt	5– 6 min	34–38	600– 700	2.2–2.8	1300–1800	700– 800	750–1000	400–500

Int. J. Sports Med. 14 (1993) S3–S10

the race. Mainstays of the rowing technique are the turning points at the start (chats) and the end of the stroke and its force-time characteristic. Also, the balance is important and may be a challenge especially in the smaller racing shells. The coordination with team members is another prerequisite (4,46, 47,57,60,62).

Evaluation of rowers in the laboratory does not allow prediction of performance in actual rowing. Psychological characteristics such as self-awareness, self-motivation, mental strength and team membership are necessary to withstand training and to be successful in the competition.

Training has been evaluated with respect to the skeletal muscle structure, metabolic capacity and performance in rowing ergometers as well as in the boat. Physiological and metabolic data are helpful for evaluation of training and competition results. In this paper studies on successful rowers and their training are reviewed.

Muscle Capacity

For the muscles engaged in rowing the percentage of slow-twitch (ST) muscle fibers is approximately 70 % (3, 18,25,36,61). Furthermore, differences are found between the structure of muscles in highly and less able rowers, although they trained similarly with respect to time and volume. The more successful rowers have a higher percentage of ST fibers (76 %) and significantly lower percentages of fast-twitch (FT) muscle fibers with oxidative metabolism (FTO, type IIa, 4 %) than the less successful (12 %) (Table **2**) (55). In internationally successful competitive rowers ST fiber content has been reported as high as 85 %, with few glycolytic FT (type IIb) and many intermediate IIc fibers (26,36).

Muscle fiber hypertrophy is evident in rowers. Hypertrophy is found not only for FT fibers, but also for ST fibers (25). The hypertrophy of ST fibers is more evident in internationally successful athletes (36,54,56).

Enzyme activities determined either histochemically or in muscle homogenates demonstrate high oxidative metabolic capacity (succinate dehydrogenase [SDH], citrate synthase [CS]) in well-trained oarsmen. In contrast, the glycolytic capacity evaluated as the activity of lactate dehydrogenase (LDH) is not different between groups of oarsmen, but the better oarsmen have a higher percentage of subtypes LDH_{1-3} (94 %) which is characteristic also for the heart (Table **2**; 21,52,55).

Table 2 Histochemical and morphometrical characteristics of highly performing rowers (n = 24, 100 samples) and nonperforming rowers (n = 28, 210 samples) of the former German Democratic Republic (from Roth et al. 1983, with permission).

		Performers	Nonperformers	Sign.
ST	%	76.2 ± 5.8	66.1 ± 9.5	*
FT	%	23.8 ± 5.8	33.9 ± 9.5	*
FTO	%	3.8 ± 0.7	11.8 ± 3.0	*
FTG	%	20.0 ± 5.7	24.5 ± 6.0	*
SDH	μmmol/s/g	40.8 ± 11.2	14.5 ± 7.0	*
CS	μmmol/s/g	0.39 ± 0.08	0.24 ± 0.07	*
LDH	μmmol/s/g	1.17 ± 0.32	1.22 ± 0.39	–
LDH_1	% of total LDH	32 ± 7	14 ± 7	*
LDH_5	% of total LDH	2 ± 2	32 ± 15	*

ST = slow-twitch muscle fibers, FT = fast-twitch muscle fibers, FTO = fast-twitch muscle fibers with oxidative metabolism, FTG = fast-twitch muscle fibers with mainly glycolytic metabolism, SDH = succinate dehydrogenase, CS = citrate synthase, LDH = lactate dehydrogenase, given relative to g from wet muscle weight; $^*p < 0.05$.

In trained rowers, the density of mitochondria is high. The elevated absolute number of mitochondria, expressed also as the ratio of mitochondria to fiber areas, is evident for ST and FT fibers. The mitochondria are clustered under the sarcolemma (26,52,73). It is remarkable that the oxidative capacity of FT fibers increases with intensive rowing training which is consistent with the morphological and histochemical data (24,26,52,72).

Muscle hypertrophy as a result of training is primarily caused by volume expansion of single fibers (39,52). The muscle structure may be "plastic" in that the genetically preformed muscle type, due to high training loads, changes from FT fibers through intermediates (IIc) to ST fibers (1,2,25, 30,36). This is exemplified by the finding in rowers that the muscle structure depends on the biomechanical requirements of different boat seats (Roth et al., this supplement).

The number of capillaries increases with fibers area. Although the ratio of capillaries to fibers is elevated for rowers, it does not differ in rowers according to the level of competition (26,36,56).

Maximal Aerobic Capcity

During competition a rower depends mainly on his aerobic metabolism because energy stores and glycolysis are limited to cover the energy demand only for approximately 1.5–2 min. The $\dot{V}O_2max$ is an important predictor of competitional success, although its predictive influence varies in different analyses (Fig. **1**; 18,63,76).

Intensive endurance training increases not only mitochondrial volume in ST fibers but also in FT fibers (27).

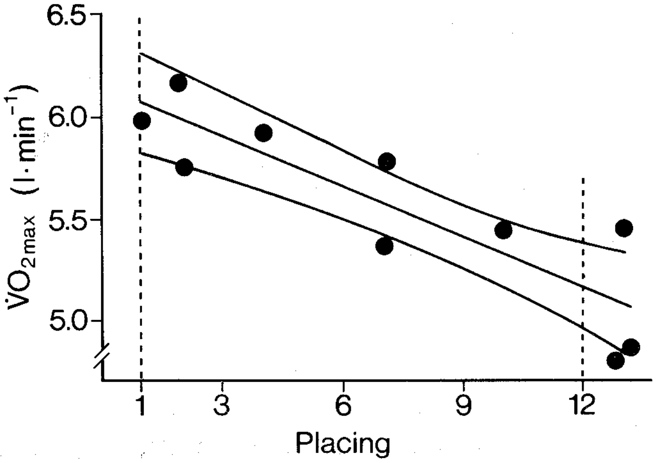

Fig. 1 Maximal oxygen consumption ($\dot{V}O_2max$) of a crew and its placing in an international championship regatta. Regression line: y = 6.15–0.08 x, r = 0.87, n = 10 (from Secher et al. 1982, with permission).

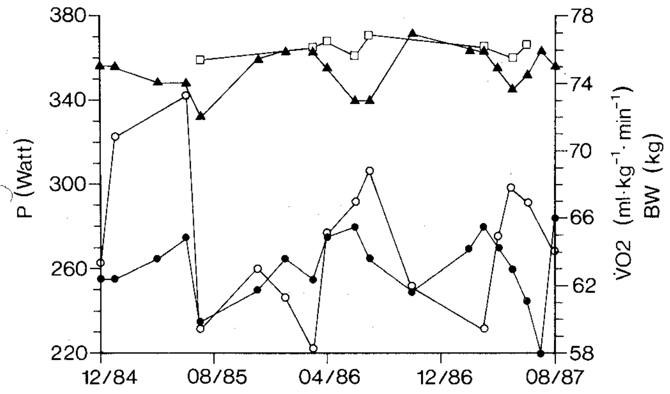

Fig. 2 Power in a 6-min maximal ergometer test (P 6 min, □), power at the aerobic-anaerobic threshold (P_{AAT}, ●) and relative maximum oxygen consumption ($\dot{V}O_2max$/kg, ○) in an exhausting incremental ergometer test and body weight (BW, □) during 2½ years in 19 tests on an internationally successful lightweight rower (from Steinacker 1988).

There is a strong relation between $\dot{V}O_2max$ and whole body mitochondrial volume because $\dot{V}O_2max$ is limited to 4–5 ml/min per ml mitochondria (24).

As rowing training increases the oxidative capacity of both ST fibers and also in FT fibers, the $\dot{V}O_2max$ of highly trained rowers with different ST fiber content may not differ (26,52), despite a general relation found between $\dot{V}O_2max$ and ST fiber content (34). With higher ST fiber content rowers perform better during a ergometer rowing test over the race distance (52).

In world class oarsmen, $\dot{V}O_2max$ reaches 6.0–6.6 l·min^{-1} (65–70 ml·min^{-1}·kg^{-1}). The relative $\dot{V}O_2max$ is low in oarsmen compared to other endurance athletes because their body weight is high (16,18,28,52,53,61,63,67,71). Only in some, mainly light weight oarsmen, relative $\dot{V}O_2max$ reaches 75 ml·min^{-1}·kg^{-1} (26,45,65).

The $\dot{V}O_2max$ increases with training distance per year, but levels off at training volumes of approximately 5000–6000 km per year (52). Seasonal changes have been described in $\dot{V}O_2max$. Maximal $\dot{V}O_2$ increases 5 and 15 ml/min·kg during the competition season (Fig. **2**; 48,65) or by 22 % (18). Pronounced changes in $\dot{V}O_2max$ of highly trained athletes take place if during the off-season the distance rowed is reduced to below approximately 100 km/week (45,65).

Rowers of equal $\dot{V}O_2max$ may have different competition results depending on physiological (52,55,67) and biomechanic efficiency (50,58,60). With increasing stroke rate the mechanical efficiency in actual rowing may increase (10). It should be considered that with increasing stroke rate the work for moving the body on the seat on the ergometer increases as well; otherwise, during actual rowing the body is hardly moved and the boat is pushed in contrast to ergometer rowing (46,52, 61).

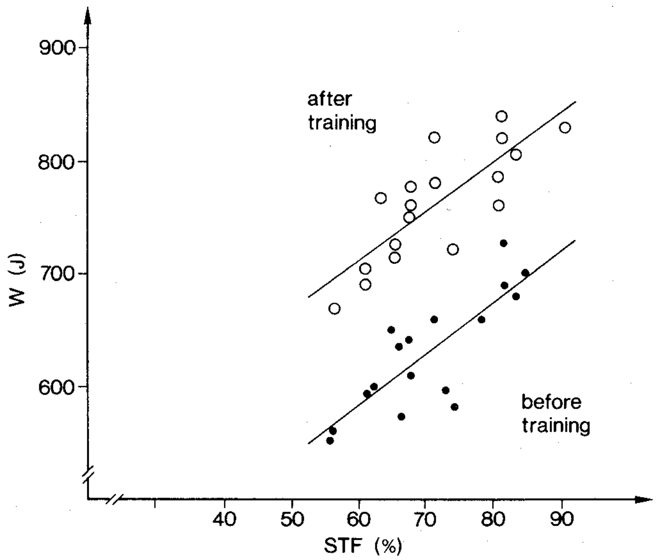

Fig. 3 Work (J) in simulated rowing at a lactate of 4.0 mmol/l in dependence on the slow-twitch fiber (STF) content in m. deltoideus before (●, regression line: y = 301.1 + 4.75 x, r = 0.81, n = 17) and after (○, regression line: y = 452.4 + 4.42 x, r = 0.80, n = 18) intensive endurance training (redrawn from Roth 1979, with permission).

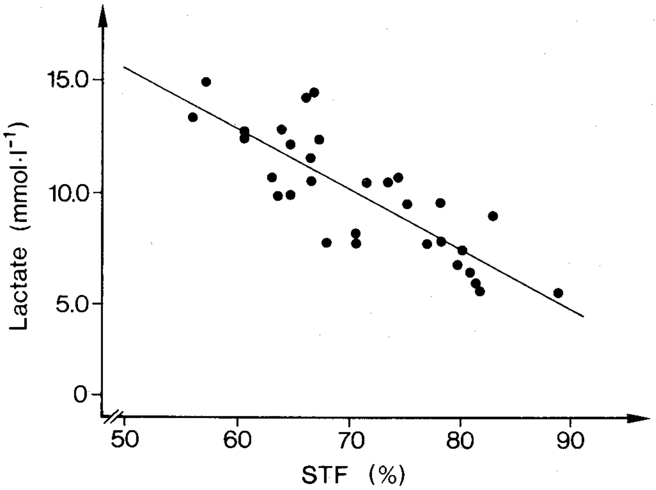

Fig. 4 Maximal lactate in dependence on the slow-twitch fiber (STF) content in m. deltoideus in the incremental rowing test. Regression line: y = 28.98–0.27 x, r = 0.83, n = 31 (redrawn from Roth 1979, with permission).

Endurance Capacity

The muscular structure is also reflected in submaximal performance. With a higher percentage of ST fibers, rowers are able to perform with more power per stroke at a blood lactate concentration of 4 mmol/l. However, specific endurance training increases the work per stroke at a given lactate level, without changing the ST fiber content (52) (Fig. **3**), mainly due to higher oxidative capacities of FT fibers (or increase in type IIc fibers) (26). The maximal blood lactate concentration after exhausting rowing decreases with higher ST fiber content due to lower glycolytic capacities (Fig. **4**).

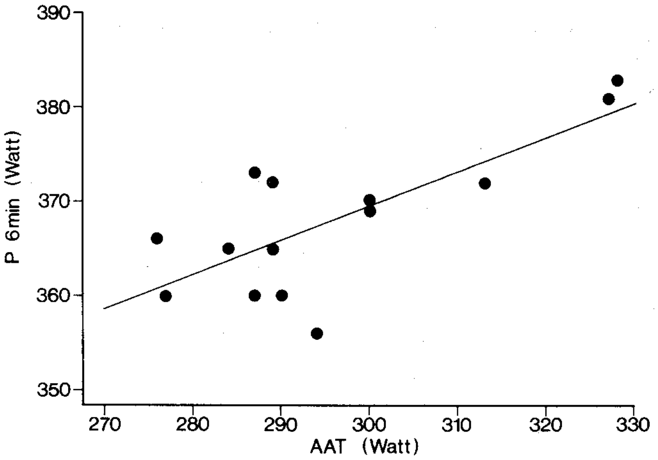

Fig. 5 Power in the 6-min maximal rowing test (P 6 min) on the Gjessing rowing ergometer in dependence on the power at the aerobic-anaerobic threshold (AAT) in 14 rowers of the German lightweight rowing team. Regression: P 6 min = 0.37 AAT + 260 (r = 0.76) (from Steinacker 1988).

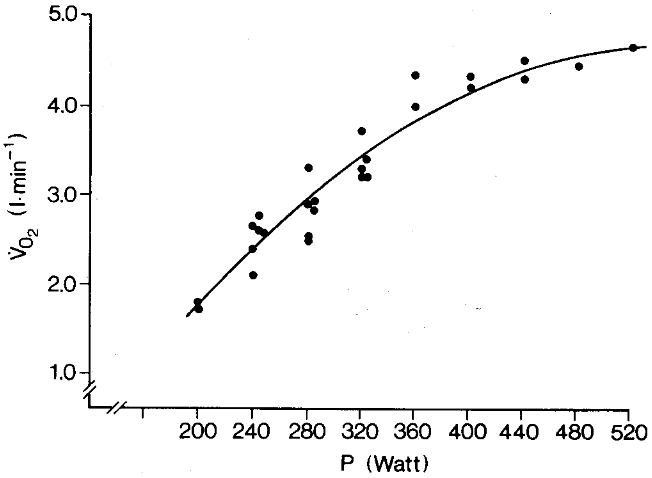

Fig. 6 Oxygen consumption ($\dot{V}O_2$) at 4 mmol/l blood lactate ($\dot{V}O_2$) in an incremental rowing ergometer test versus the maximal power in 7 min simulated rowing race in the rowing tank (P). Tests in 819 rowers were grouped in classes of 40 W increment and the average values are demonstrated. Regression line: $\dot{V}O_2$ = 2.54 + 0.03 Pmax – 0.00002 Pmax (redrawn from Roth 1979, with permission).

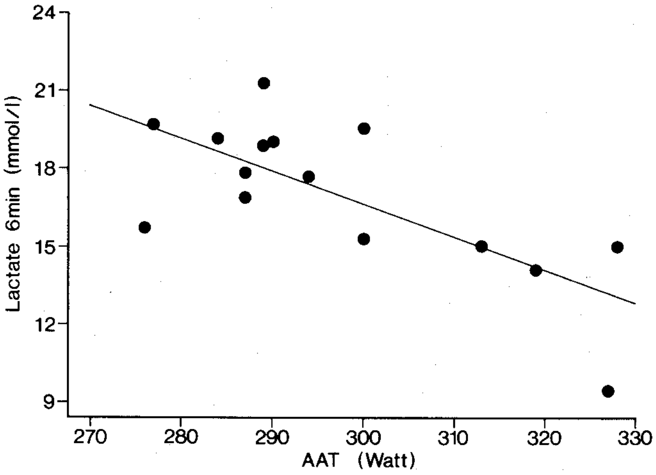

Fig. 7 Maximal lactate in the 6-min maximal rowing test (lactate 6 min) on the Gjessing rowing ergometer in dependence on the power at the aerobic-anaerobic threshold (Paas) in 14 rowers of the German lightweight rowing team. regression line: Lactate 6 min = –0.13 AAT + 54.56, r = –0.72, n = 15 (from Steinacker 1988).

Ergometer rowing at submaximal and maximal work rates is an important indicator of the metabolic adaptation. Fiber composition and metabolic capacities are reflected in the relation of blood lactate formation to performance during exercise (lactate performance curve; 51,56,66). Rowing ergometer tests with increasing work rates to exhaustion have been developed for determination of the lactate increase with work rate (56,66,69) or for ventilatory determination of aerobic-anaerobic threshold (AAT) (44,49).

The lactate performance curve offers information on anaerobic energy formation if carbohydrates are the dominant substrate (43,52,56). The curve is influenced by lactate production in the working muscles but also by its elimination in other organs such as the liver, the heart, and other muscles (14,15,40).

The AAT should be the power which can be sustained for 30 and 60 min without further increase in the blood lactate concentration. The AAT was determined for rowing at an average blood lactate of 4.0 mmol/l (15,42,43,52, 56). In rowers a lactate steady state can occur at higher or lower levels depending on the intensity of training (26). For that reason determinations of an "individual lactate threshold" (74) or of an "individual heart rate threshold" (12,26) have been proposed.

The endurance capacity measured as the power which elicits a blood lactate level of 4.0 mmol/l is the most predictive parameter for competition performance in trained rowers, especially in small boats such as singles and doubles (76). In highly trained rowers, AAT corresponds to approximately 80 %–85 % of maximum performance (Fig. 5). The AAT is approximately 60 W lower than the power of a maximal 6-min "all-out" test (42,48,56,65,76). The $\dot{V}O_2$ at the 4 mmol/l lactate AAT is also approximately 85 % of $\dot{V}O_2$max. Also, the $\dot{V}O$ at the AAT reflects well the average $\dot{V}O_2$ of the 3rd–5th min of a maximal a6-min ergometer test, where $\dot{V}O_2$ is in a relative maximal steady state (45). This is reasonable because $\dot{V}O_2$ at the AAT and ST fiber content are related (56) and mainly ST fibers are stressed during a rowing race (55). Rowing performance is related to this maximal steady state of $\dot{V}O_2$ in a simulated rowing race (17,45). Therefore, with higher $\dot{V}O_2$ at the AAT rowers demonstrate improved performance in the maximal 6- or 7-min test (Fig. **6**; 45,52). Maximum lactate decreases with higher AAT due to higher oxidative metabolic capacity (Fig. **7**).

The lactate performance curve and the AAT are sensitive to changes in endurance training. Maximal rowing of 6-min duration has a lower sensitivity for training control (Fig. **7**; 48,74,76).

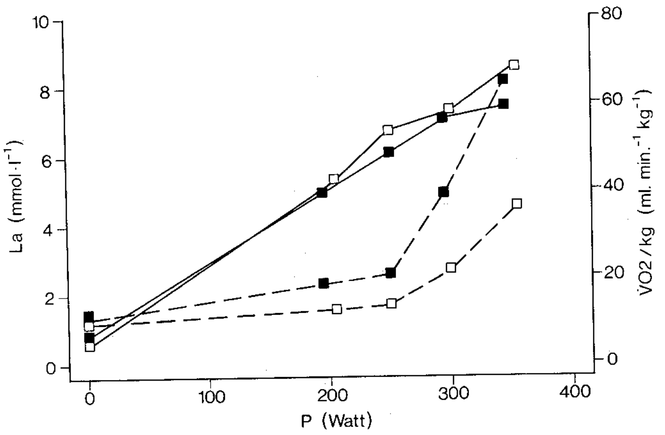

Fig. 8 Lactate concentration (La) and relative oxygen consumption ($\dot{V}O_2$/kg) in an incremental ergometer test in 2 rowers of a successful coxed lightweight eight.
Rower 1 (□): AAT 280 W;
6-min test: max. power 365 W, lactate 19.2 mmol/l.
Rower 2 (x): AAT 335 W;
6-min test: max. power 370 W, lactate 13.2 mmol/l.
(from Steinacker 1988)

Despite the importance of the lactate performance curve and the AAT, this concept has limitations. In successful rowers of comparable competitional level, the AAT, maximum lactate and $\dot{V}O_2max$ may be very different, which is illustrated in Fig. **8**. A lower AAT may be compensated to some degree by higher strength, by higher lactate formation, by increased lactate tolerance (26,65), and also by higher work efficiency (52). Also, competitional rowing means not only maximal oxidative, but also maximal anaerobic metabolic effort.

Strength and Anaerobic Capacity

Roth et al. (55) calculated from metabolic and bioptic measurements in tank rowing that the energy for the work of 18,760 kpm of a simulated rowing race of 7 min was provided 67 % aerobically and 33 % anaerobically, 21 % alactic and 12 % lactic. However, anaerobic capacity explains only 10 %–20 % of the performance in competition in trained rowers (26,76). One reason could be that all trained rowers have a highly developed strength due to hypertrophy of ST and FT fibers as well as increased muscle mass.

Trained rowers develop more force and power than other endurance trained athletes at relatively low contraction velocities (19,38,61). However, in world class oarsmen with a power of 420 W during a 6-min row on the Gjessing ergometer, for five maximal strokes the average power varies between 650 and 990 W and the time needed for these five strokes varied from 5.0 to 6.5 s. The power in a 40-s test varied from 550 to 780 W.

Anaerobic tests have not been sensitive enough to detect changes with training (38). Although, strength and anaerobic capacity are important for rowing, they need not be increased above a "critical" value (26,38,76).

Training Control

Effects of training on endurance are evaluated by testing the relation of lactate and performance during exercise tests. The AAT is an indicator of this relation. Measurements of $\dot{V}O_2max$ and maximal lactate are necessary for a complete analysis of aerobic and anaerobic capacities (51,56, 65).

The $\dot{V}O_2max$ and the lactate performance curve are valid only for the recovered athlete. If substrate availability is restricted, in particular muscle glycogen is decreased by diet or high training loads, blood lactate during exercise is lower because muscle glycogen is the primary substrate for lactate formation. This effect can be obtained also if blood lactate is measured during prolonged endurance training because glycogen stores are depleted (8,14,29,40).

When the importance of the aerobic-anaerobic threshold was acknowledged, endurance training was often prescribed at the AAT. This practice often led to overstrain mainly due to substrate depletion and incomplete recovery. With extended training schedules, sometimes reaching more than 1000 h per year (52) the training intensity has to be reduced (20,43). Therefore, the importance of training intensities below the AAT has gained increased attention and the AAT is used more as a diagnostic tool than for training control.

During low-intensity training, fat utilization is the main substrate for the Krebs cycle. Lipolysis is increased in endurance trained athletes compared to normals (32,35). Therefore, the ratio of free fatty acids to glucose rises in the blood during long-lasting, low-intensity exercise (13,33). As a consequence, blood lactate decreases during low-intensity exercise due to increased lipolysis, and the increase of lactate even in incremental exercise tests is postponed.

During endurance training, blood lactate will give information on the relationship of glycolysis to lipolysis, if substrate availability is not restricted. A blood lactate level lower than 2.0 mmol/l indicates lipolysis as the main source of aerobic energy formation (9).

Training Schedules and Rowing Success

The knowledge about physiological effects of exercise in trained athletes has grown in the last decades. But up to now, there are only a few studies on the effects of specific training programs in highly trained athletes. One reason may be that such studies were not allowed to be published in the Eastern countries. However, it is more likely that scientists have not been successful in carrying out controlled studies in such athletes, which may allow conclusions to be drawn about effects of certain training programs in certain parts of the training season.

Another problem of studying training effects is the complexity of training. Rowing training can be divided into extensive and regenerative (below 2 mmol/l blood lactate), intense (2–4 mmol/l blood lactate), highly intense (4–8 mmol/l blood lactate) endurance training and speed or tempo training. Running and other types of exercise such as gymnastics or ball games are regularly part of the training.

Endurance training is the mainstay of success in rowing (26,43,45,52,61,62,65). Training of successful athletes is characterized by extensive as well as intense endurance training with approximately 70%–80% of the time spent on the water (31,45,65). During the season, highly intense endurance training is emphasized and also tempo training becomes of importance. However, high percentages of tempo training (>30%) do not improve performance and $\dot{V}O_2max$ compared to training with only 5%–10% tempo training (31, 48,65). Intense endurance training above the AAT may be important for improvement of $\dot{V}O_2max$ during the competition season, but should not amount to more than 10% of the training volume (48,65). In a retrospective study, Mader et al. (41) found that 86%–94% of training during winter and 70%–77% during summer was extensive (<2 mmol/l blood lactate) so that 93%–99% of the time was reported to involve exercise with a blood lactate level below 4 mmol/l. Consequently, they questioned the importance of intense training for success in rowing. Unfortunately, the amount of athletic and power endurance training was not reported, making this question less reasonable.

With low intensity training energy turnover decreases which affects mitochondrial density and $\dot{V}O_2max$ as well as lactate tolerance (26,65). Furthermore, the stroke structure and the recruitment of fibers depends on stroke rates and rowing force. These facts may have the rower less prepared for the performance required in competition (54,60). Therefore, the extremely high training volumes, e.g., more than 10,000 km and 1200 h/year applied in some Eastern countries between 1965 and 1980 are no longer recommended.

Highly altitude training is commonly used by national rowing teams despite a lack of controlled studies. Mader et al. (41) could only demonstrate an improvement of performance at altitude, but did not report the values for sea level rowing. Improvement of performance at sea level after altitude training is questionable (37) because the metabolic rate is limited at high altitude. This may decrease the total number and density of mitochondria and consecutively lower performance at sea level (23). Accordingly, a controlled study involving rowers found no differences in $\dot{V}O_2max$ and performance when training at sea level and at altitude (1822 m) were compared (31).

Conclusions

Rowers need large muscular strength for the acceleration of the boat at the start and a high oxidative capacity to maintain the speed during the race. Morphological and metabolic data indicate the importance of specific and maximal endurance for competition success. Therefore, endurance training forms the main part of the training schedule. Further studies are needed for the evaluation of the interaction between the rowing stroke, biomechanical influences, muscle structure and metabolism during training and competition.

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