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AUTHOR Spinks, W. L.
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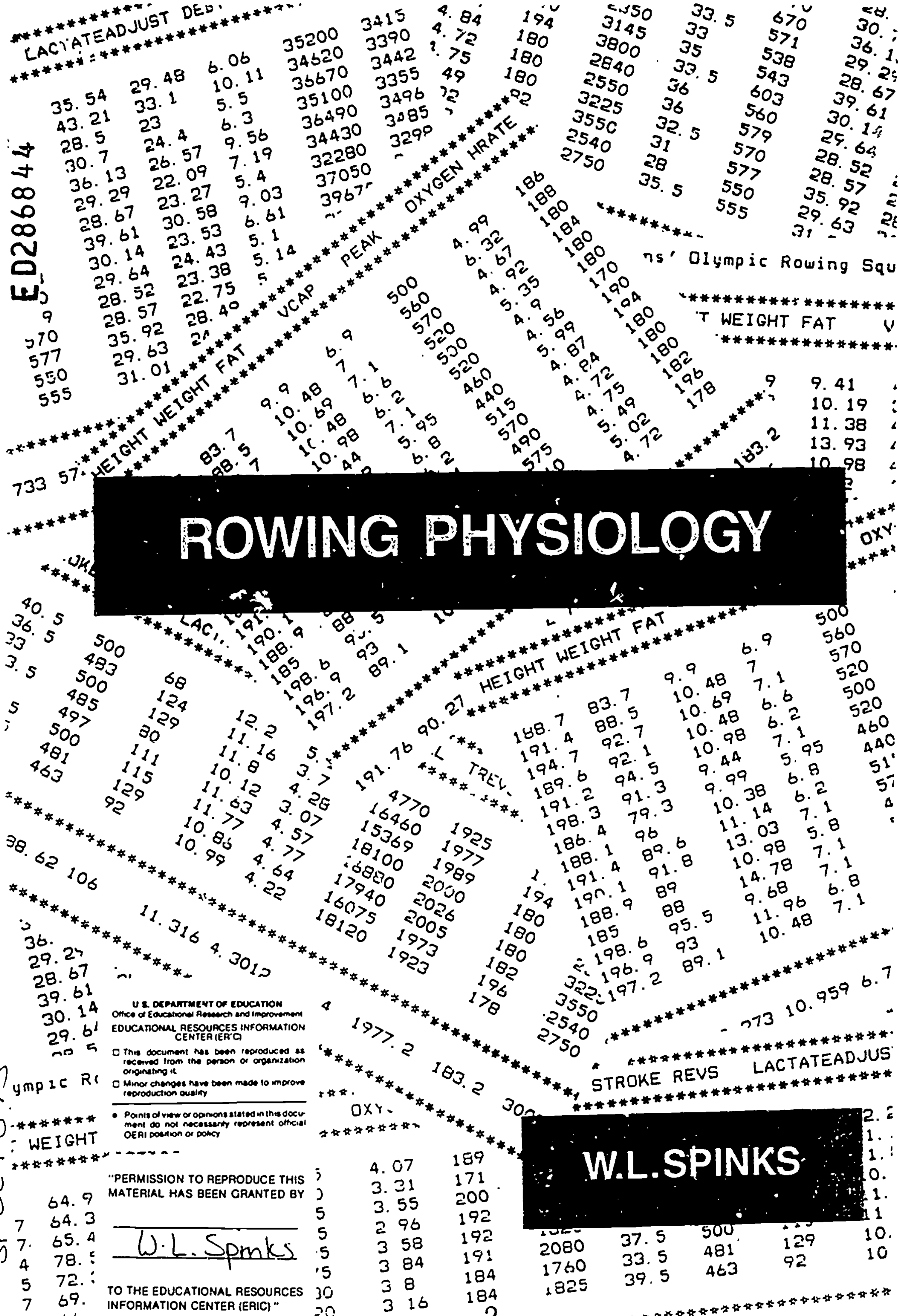
ABSTRACT

This review of the literature discusses and examines the methods used in physiological assessment of rowers, results of such assessments, and future directions emanating from research in the physiology of rowing. The first section discusses the energy demands of rowing, including the contribution of the energy system, anaerobic metabolism, and the "alactacid" component. Methods of research addressed in the second section include work test instrumentation and work test characteristics. The third section covers measured physiological capacities, including pulmonary ventilation, ventilatory efficiency, oxygen pulse, maximum oxygen uptake, maximum heart rate, and ventilatory threshold characteristics. The fourth part discusses future research directions. A 69-citation bibliography is included. (CB)



ROWING PHYSIOLOGY

W.L.SPINKS

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LIST OF SYMBOLS AND ABBREVIATIONS

ATP	adenosine triphosphate
cap	capillary
CO_2	carbon dioxide
f	frequency
fr	breathing frequency
FT	fast-twitch muscle fibres (glycolytic)
hr	hour
$\geqslant$	greater than or equal to
H_2O	water
IS	in season
kcal	kilocalorie
$kcal.min^{-1}$	kilocalories per minute
kg	kilogram
$kpm.min^{-1}$	kilopond metres per minute
LA	lactic acid
$l.l^{-1}$	litres per litre
$l.min^{-1}$	litres per minute
m	metre
min	minute
ml	millilitre
mm	millimetre
mmol	millimole
mg%	milligrams per 100ml of blood
n	number (usually number of subjects)
O_2	oxygen
PO_2	partial pressure of oxygen
OS	off season
r	correlation coefficient
$revs.min^{-1}$	revolutions per minute
s	second
ST	slow-twitch muscle fibres (oxidative)
$st.min^{-1}$	strokes per minute

SV	stroke volume
t	time
um	micrometer
VEmax	maximal minute pulmonary ventilation
VE	minute pulmonary ventilation
VE/VO_2	ventilatory equivalent - volume of air required to support volume of oxygen consumed
VO_2	volume of oxygen consumed per minute
VO_2max	maximal volume of oxygen consumed per minute during exercise
VT	ventilatory threshold
W	watt

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W.S.

INTRODUCTION

Competitive rowing is considered to be one of the most demanding continuous endurance sports (Di Prampero et al., 1971; Larsson & Forsberg, 1980; McKenzie & Rhodes, 1982). Elite level rowers are invariably large individuals with very high aerobic work capacities (Hagerman et al., 1972; 1975; 1978; 1979; Szogy & Cherebetiu 1974; Cunningham et al., 1975; Wright et al., 1976).

Rowing is different from other forms of human exercise in that the body is supported by a seat and both the arms and legs are involved with the two legs working in the same phase. This contrasts with running for example, during which one leg is predominantly performing work at a time (Secher, 1983:24).

The development of the concept of national rowing teams in the 1960's led to an upsurge of interest in the elite rower, the aim being to determine the characteristics of rowers who are successful in the international rowing arena. This information is seen as providing a better understanding of the demands of the sport, allowing one to learn more about the elite rower in general, revealing deficiencies in a rower's physiological profile and acting as a useful adjunct to the training programme (Mickelson & Hagerman, 1982:440).

Lilejestrand & Lindhard (1920) initiated examination of the physiology of rowing by measuring oxygen uptake, heart rate and cardiac output during the rowing of an "ordinary" boat. Henderson & Haggard (1925) examined energy expenditure in rowing an eight-oared racing shell by determining the magnitude of pull against a tow boat, the work performed during machine rowing and the indirect analysis of oxygen uptake from respiratory frequency. Most subsequent research has focused on the maximal oxygen uptake characteristics of oarsmen.

This presentation sets out to examine the methods used in the physiological assessment of rowers, the results of such assessments and the future directions emanating from research in the physiology of rowing.

THE ENERGY DEMANDS OF ROWING

Unlike athletes in other continuous endurance sports, rowers begin a race with a maximal effort that may extend for 45 s (McKenzie & Rhodes, 1982:21). This (unique) initial effort is followed by a 5-6 min (for male rowers) period of continuous high intensity work during which the rower reportedly recruits some 220-280 high tension muscle contractions (Larsson & Forsberg, 1980:239). When this effort is added to a final sprint to the finish, it is apparent that a "unique and very high demand is placed on the contractile mechanisms as well as on the oxygen utilizing capacity of the working muscles" (Larsson & Forsberg, 1980:239).

In the early stages of a race, elite eight oared male crews sprint through the first 30-40 s rating between 40-50 strokes per min ($st.min^{-1}$) covering the first 150 m. During this stage considerable circulatory adjustment is necessary. The "start" phase is followed by the "middle" phase of the race where crews normally stroke at between 34-38 $st.min^{-1}$ this increment being held for between 30 s and 1 min. This constitutes "high order" work or "short, heavy" exercise (Gollnick, 1982:14) and is particularly taxing on the anaerobic energy system with the rower operating at or near maximal "oxygen debt" capacity (Hagerman et al., 1978:91).

Tactical manoeuvres may place further demands on the oxygen transport system, for example, crews may insert a "spurt" during the middle phase of the race which consists of a stro rate of 43-44 $st.min^{-1}$ for 20-30 strokes. Training programmes are therefore, designed "primarily to enhance maximal oxygen uptake and increase the upper limits of oxygen debt" (Hagerman et al., 1972:12). It would appear that maximal aerobic power combined with muscular strength and endurance are requisite physiological capacities for rowing performance (Di Prampero, 1971; Hagerman et al., 1978; Jackson & Secher, 1976).

The contribution of the energy systems

The quantification of the contribution made by the energy systems in response to the unique pacing style of competitive rowing is an area which has received scant consideration in the literature.

Szogy and Cherebutiu (1974) found a mean ratio of 68.4 % to 31.6 % between the aerobic and anaerobic (respectively) rate of energy demand in rowers determined during an incremental bicycle ergometer test over a 6 min period. It was considered that the high anaerobic rate is indicative of an inefficient use of energy and that a 69-71 % aerobic rate is the "optimal range" for a 6 min maximal effort.

The extent to which this "optimal range" is applicable to rowing is difficult to determine as the authors base their findings on a limited number of studies (N=4), using subjects other than rowers (athletes [?], ice skaters, long distance runners, swimmers) and utilizing intra and extrapolation wherever work periods were not of 6 min duration (Szogy and Cherebutiu, 1974:219).

Also the mean ratio of aerobic/anaerobic energy demand was determined using an incremental (step-wise) test but, as mentioned previously, the pacing style of competitive rowing is more spasmodic than incremental in nature. Therefore, it is not clear how effective a relatively small (1.6-2.6 %)

increase in mean aerobic rate will be in terms of a 6 min maximal rowing effort.

Jackson and Secher (1976:170) provide information regarding the metabolic requirement for rowing a 2,000 m race. The authors indicate that the aerobic requirement would be 206 kcal. (6 $l.min^{-1}$ x 7 min x 4.9 $kcal.l^{-1}$) with an anaerobic expenditure of 45 kcal. The total energy requirement would therefore, be approximately 251 kcal., which allows for an aerobic/anaerobic ratio of 82.1/17.9 % respectively.

Howald (1983) sees the high energy phosphates as supplying approximately 5 % of the total energy requirement of competitive rowing with anaerobic glycolysis providing approximately 15 % and oxidation being responsible for the remaining 80 % of the total energy needs (Figure 1).

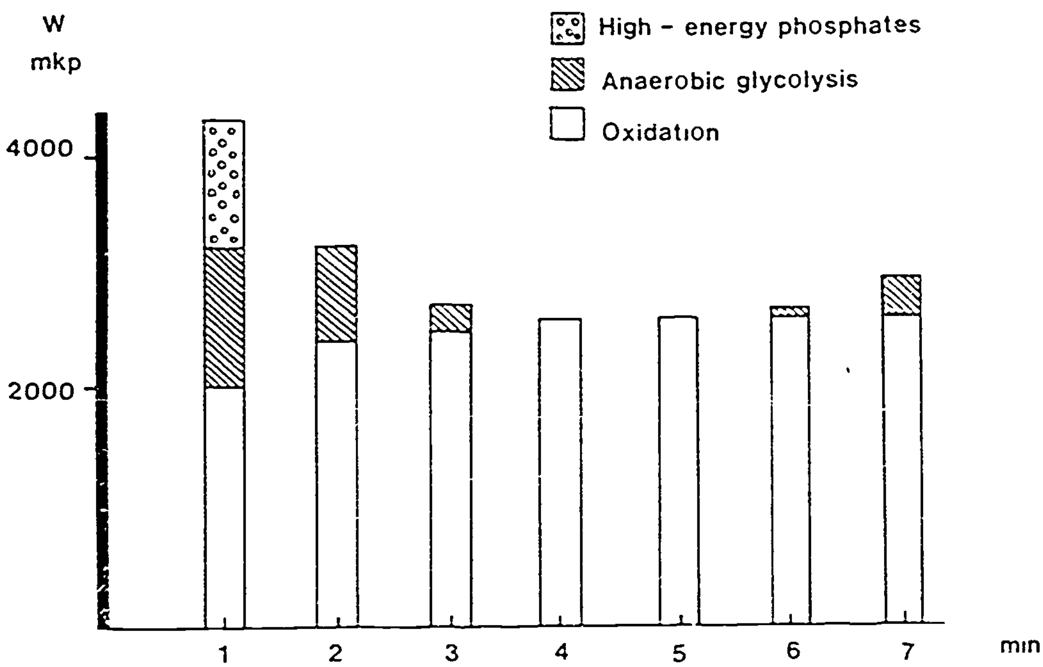


Figure 1

Energy supply pattern for rowing (Howald, 1983)

Hagerman et al. (1978;1979) and Mickelson and Hagerman (1982) found that the aerobic metabolism contributes approximately 70 % of the total energy production while the anaerobic component is responsible for the remaining 30 %. No attempt was made to quantify the contribution of the high energy phosphates.

By examination of the "anaerobic threshold" of oarsmen, Michelson and Hagerman (1982:441-442) claimed to demonstrate that elite oarsmen generate 72 % of total power output by utilizing 83 % of aerobic capacity. Thus the ability of elite oarsmen to exercise at levels of intensity very close to VO_2 max. without incurring a significant level of metabolic acidosis.

Hagerman et al. (1978:90) cite several workers as a measuring total energy expenditure, through indirect calorimetry, for a 6 min maximal effort on a rowing ergometer that was in excess of 185 kcal. min^{-1} (30.1 $kcal.min^{-1}$). When relative comparisons are made, the authors claim that their results are supported by other research yet only one of these is cited (Hagerman et al., 1978:90-91). Gollnick and Hermansen (1973) demonstrated an 80/20 % aerobic/anaerobic contribution for a 5 min maximal exercise and these figures are seen as being relatively proportional to the values obtained from a 6 min maximal rowing effort. Figure 2 indicates the approximate interaction of the energy systems in rowing.

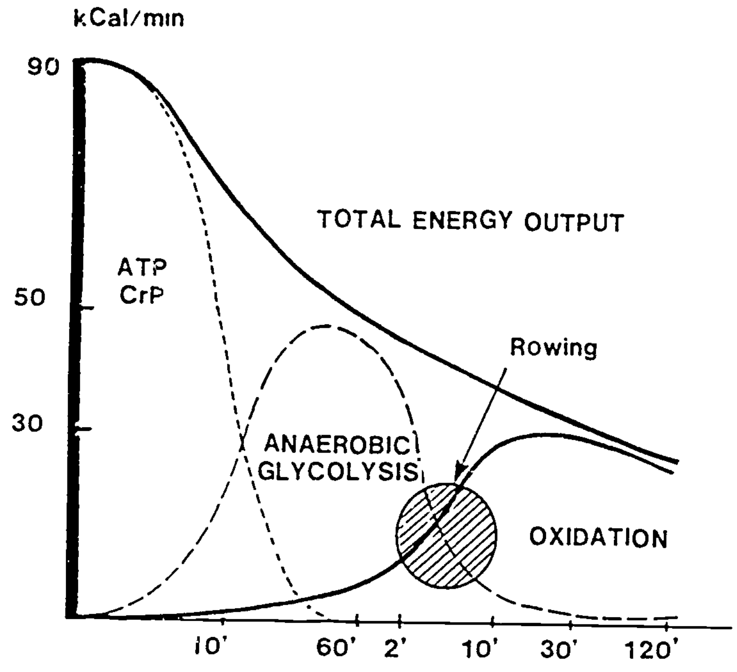


Figure 2

The interaction of the energy systems in rowing (Howald, 1983)

The shorter and more intense efforts engaged in by female rowers (prior to 1984!) is seen by Hagerman et al. (1979:81) as preventing a steady state response, therefore, female rowers depend to a greater extent on the anaerobic mechanism which is seen as providing approximately 45 % of the total energy expenditure. Hagerman et al. (1978, 1979) utilize net oxygen cost and and the calculation of "oxygen deficit" and "debt" to estimate the total energy cost and the relative contribution of aerobic and anaerobic metabolic pathways. The tabulated data for female rowers clearly indicates the net "oxygen debt", however, it is necessary to compute the net oxygen cost from the mean VO_2max for the 3 min ergometer effort:

Exercise duration	= 3 min, ( ) = range
Mean VO_2max ($l.min.^{-1}$)	= 4.1 $\pm$0.4
Net oxygen cost (l)	= 12.3 l (13.5-11.1)
Kilocalorie equivalent	= 12.3 x 5 kcal.10_2^{-1} (assuming R = 1.00)
Net oxygen debt (l)	= 10.2 $\pm$5.5
Anaerobic cost (kcal)	= 10.2 x 5 kcal.10_2^{-1}
	= 51 kcal (78.5-23.5)
Total energy cost (kcal)	= 112.5 kcal (146-79)
% aerobic cost	= 54.7 % (46.2-70)
	= 23.8 % differential
% anaerobic cost	= 45.3 % (53.8-30)
	= 23.8 % differential
	100.0 % (100-100 %)

Intra component range variability is 23.8 % in both cases while inter component range variability is 7.6 % (aerobic) at the high end and 40 % (anaerobic) at the low end. No attempt was made to explain the impact of the range of scores, however, it would appear that such variance would make it difficult to use mean score data for setting criteria related to the planning and modifying of training programmes and race strategies.

Ishiko (1967) determined that the metabolic requirements for rowing a 2,000 m race is 200 kcal while Jackson and Secher (1976:170) believe that the aerobic requirement would be 206 kcal (6.0 10_2 x 7 min x 4.9 kcal.10_2^{-1}). On the basis of the high values produced by one of their two subjects (a world champion in double sculls) the authors assumed a high anaerobic work capacity with the subject expending 45 kcal of anaerobic work during this same period. Therefore, the total energy requirement for an international level race would be approximately 250 kcal. No measurement was made of the anaerobic demands, however, as anaerobic demand is greater with increased speed, one would expect a more nearly exponential relationship between speed and total metabolic cost. Figure 3 summarizes the energy cost data as reported by Hagerman et al. (1978; 1979).

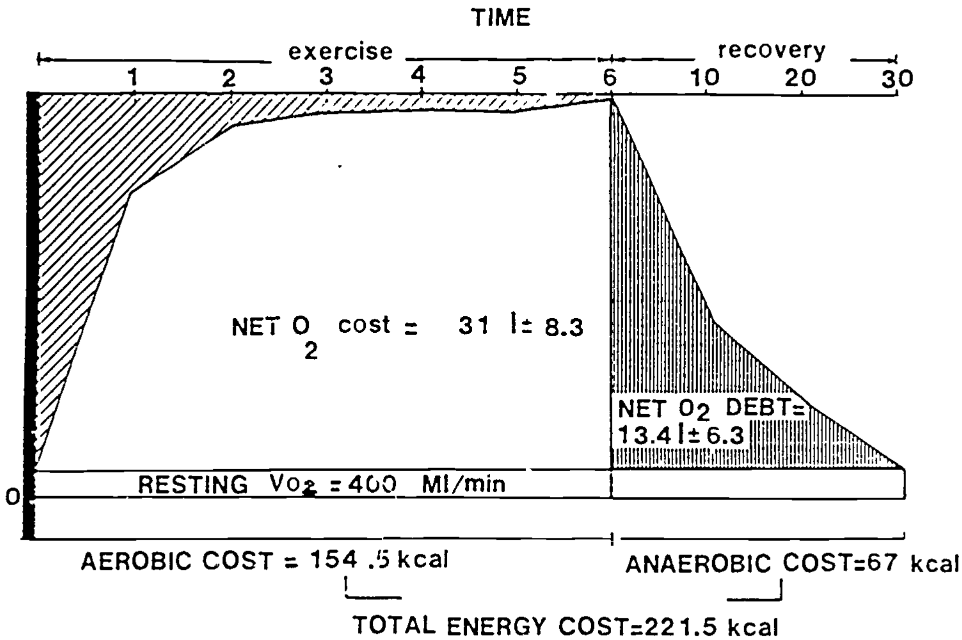


Figure 3

Summary of energy cost data (Aerobic and anaerobic cost values are means of 310 subjects) (Hagerman 1978:89)

Anaerobic metabolism

Asami et al. (1978:110) report that maximum "oxygen debt" is an important factor in the total energy requirement for rowing. While aerobic metabolism is adequately represented by the oxygen uptake rate, Hagerman et al. (1979:82) concede that the indirect assessment of anaerobic metabolism is much more difficult to determine. Secher (1983:37) states that "there is no simple way to express the contribution of the anaerobic metabolism to exercise".

Hagerman et al. (1979) compute the anaerobic component from the "oxygen debt" and state that despite the "controversy" surrounding this method that it was the method that best suited the circumstances. The nature of these "circumstances" are not expanded upon. However, the authors do acknowledge other methods of determining the anaerobic component.

The muscle biopsy is seen as being the most accurate alternative method (Hermansen, 1969; Hultman et al., 1967; Karlsson and Saltin, 1979) but reports of its use have only recently appeared in the rowing literature (Larsson and Forsberg, 1980; Howald, 1983).

In order to reach maximum performance potential it is apparent that the rower must have high level capacity in terms of maximal aerobic power, muscular strength and endurance. However, as pointed out by Larsson and Forsberg (1980:239) aerobic power and endurance depend on a high content of type I muscle fibres with a large number of capillaries surrounding the fibres while strength is reliant on a high proportion of type II fibres and large fibre areas (Table 1). What then is the relative importance of muscle quality for rowing performance? The research indicates that the muscles of oarsmen exhibit a fibre composition that is characteristic of endurance athletes. Elite oarsmen have been found to have approximately 70 % slow twitch (type I) fibres in both the vastus lateralis and deltoid muscle groups, and only very few fast twitch type IIb fibres (Bonde-Petersen et al., 1975; Larsson and Forsberg, 1980; Secher et al., 1981).

FUNCTIONAL CHARACTERISTIC	FIBRE TYPE Slow Twitch (ST)	Fast Twitch (FT)
Myoglobin content	High	Low
Triglyceride stores	High	Low
Glycogen stores	High	High
Mitochondrial density	High	Low
Oxidative (aerobic) enzyme activity	High	Low
Capillary density	High	Low
PC stores	Low	High
Relaxation time	Slow	Fast
Twitch (contraction) time	Slow	Fast
Glycolytic enzyme activity	Low	High
Fatigability	Low	High

Table 1

Functional characteristics of slow-twitch (ST) and fast-twitch (FT) muscle fibres (Fox & Mathews, 1981:100)

Group n	Percent type I fibres		Mean fibre areas		Capillary density	
	m.v.l. %	m.d. %	m.v.l. ($um^2 x10^2$)	m.d. ($um^2 x10^2$)	m.v.l. (cap x mm^{-2})	m.d. cap x mm^{-2})
Rowers 12	70.1 ± 3.6	74.0 ± 3.9	39.7 ± 3.1	35.8 ± 2.8	598 ± 62	599 ± 39
Sedentary 11	40.5 ± 3.9	-	33.3 ± 2.3	-	329 ± 11	-

Table 2

Percent type I fibres, mean fibre areas and capillary densities in the vastus lateralis (M.V.1) and deltoid muscle (M.d) in rowers. (N=12) as compared to sedentary men (N=11) (Larsson & Forsberg, 1980:241)

Howald (1983) proposes that the muscle fibre composition of elite oarsmen is predominantly 80 % type I and 20 % type II.

Larsson & Forsberg (1980:241) found a high percentage of type I fibres, large mean fibres areas and high capillary densities in elite oarsmen but the authors also found that international class (IC) rowers (N=2) differed from national class (NC) rowers (N=10) in that they had a high percentage (70 ±3.6 %) of type I fibres in the vastus lateralis muscle. A similar trend was observed in the deltoid muscle although the difference was not statistically significant (Figure 4).

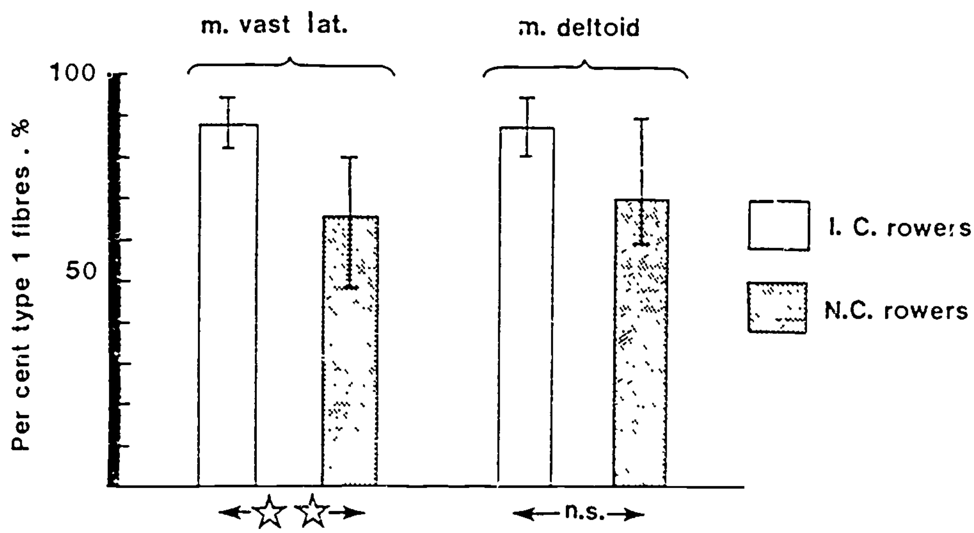
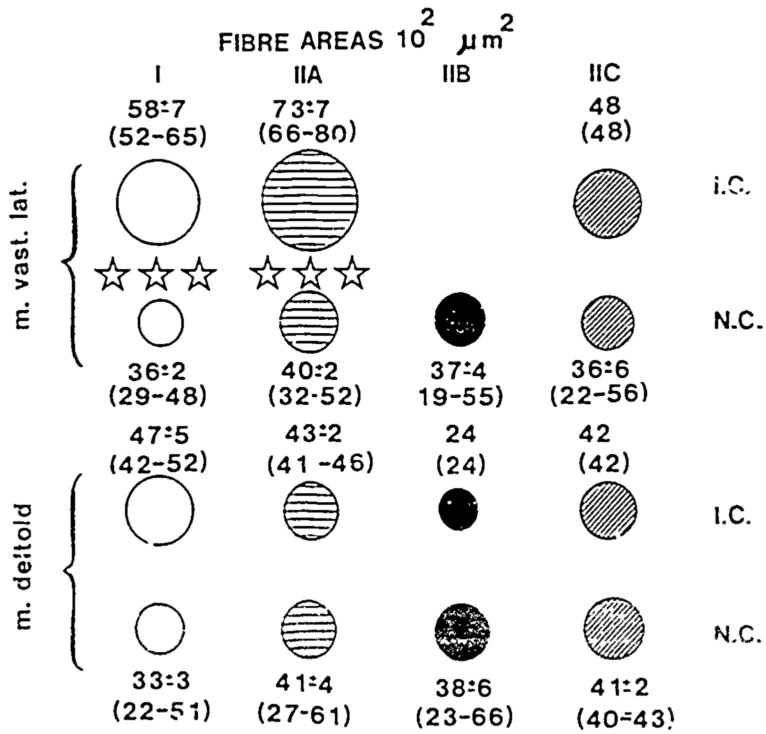


Figure 4

Percent type I fibres in internationally (I.C.) and nationally (N.C.) competitive rowers both in the vastus lateralis and deltoid muscle. (n.s. = not significant ** p < 0.01) (Larsson & Forsberg, 1980:241)

Within the type II fibre subgroups, both groups showed a very low proportion of the high glycolytic type IIb fibres in both muscle sites. Large type I and IIa fibre areas were seen in the vastus lateralis muscle in the IC rowers while no differences in fibre areas were observed in the deltoid muscle (Figure 5). The IC rowers also showed a large number of capillaries per fibre in both muscle groups. However, the capillary density did not differ between the groups although higher mean values were found in the IC rowers.

Clear cut differences between IC and NC rowers were seen in the morphological muscle characteristics studies. These muscle characteristics also correlated significantly with VO_2max and strength. These relationships range from r = 0.62 to r = 0.78 (0.76, type I fibres and VO_2; 0.62, capillary density and VO_2; 0.78 number of capillaries per fibre and VO_2max) and remained positive (even more so) when the independent influence of body weight on VO_2max was controlled.



<u>Figure 5</u>

Areas of type I, IIa, b and c fibres in I.C. and N.S. rowers both in vastus lateralis and deltoid muscle. (Circular areas are proportional to the fibre areas (lesser fibre diameter).) (Larsson & Forsberg, 1980)

The extent to which these morphological muscle characteristics are determined by the physical activity level and/or the genetic influence is not well understood at this stage. It is suggested (Larsson & Forsberg, 1980:242) that the distribution of type I and type II fibres is entirely due to genetic factors, while the distribution of type II fibre subgroups have been shown to be influenced by environmental factors such as training. Therefore, the lack of high glycolytic type IIb fibres in the IC rowers as well as the low content of the same fibres in the NC rowers may then be seen as an adaptive response to training.

Increases in capillary numbers and fibre area enlargement are also known to occur in response to an increase in physical activity. It may well be that the extreme physical training common to elite level rowers may overcome the strong genetic influence reported on the distribution of main fibre types. Increases of from 5-25 % of type I fibres have been found in rowers studied over a period ranging from winter training to the end of the competition season (Larsson et al.; to be published). Type I fibre areas and capillary density in the deltoid muscle also increased in all subjects, however, there were no changes in the vastus lateralis muscle. On these results, it is apparent that winter training (running) is sufficient to maintain a high capillarization and percentage of type I fibres in leg muscles but not in the upper body where competition and "in-boat" training may be needed to improve the oxygen utilizing capacity of the upper body muscles. It also appears that intensive training may alter the distribution of type I and II fibres. Therefore, Larsson & Forsberg (1980:243) are tempted to suggest that the "higher percentage of type I fibres in the IC rowers was in part, due to their longer exposure to intense endurance training as well as the large amount of rowing training performed every year

(4,000-6,000 km for IC rowers as against 1,500-2,500 km for NC rowers)".

Secher (1983:41) believes that the competitive stroke rate (33 st.m^{-1}) allows adequate time for force to be developed in the slow twitch fibres with the fast twitch fibres contributing only during the initial phases of a stroke.

However, the inclusion of metabolic potentials in the naming of fibre types has been criticized by Saltin et al. (1977) since training has been shown to increase the oxidative capacity of both types of fast twitch fibres (types IIa (oxidative glycolytic) and IIb (Glycolytic)) with the effect of exceeding the aerobic capacity of the slow twitch (type I (oxidative)) fibres.

Also the muscle biopsy technique is not considered to be an exact measurement technique. Significant variation of between 5 % and 10 % has been found for repeat samples from the same muscle, with even larger variability for biopsy samples from different muscles of the same subject (Gollnick et al., 1974; Gollnick & Hermansen, 1973; Saltin et al., 1977). Therefore, the results of a single biopsy should be interpreted with caution particularly when extrapolating to specific individual contractile or metabolic characteristics.

The use of post-exercise serum lactates and phosphagen depletion measures is mentioned and extensively studied (Fox et al., 1969; Margaria et al., 1933; 1963; McKenzie and Rhodes, 1982). However, lactate measures are viewed with some suspicion as there is some debate in the literature as to the accuracy of the energy equivalence (kcal) of this substrate (Thomson and Garvie, 1981:25).

Also, Secher (1983:37) reports considerable variation in the maximum blood lactate concentrations in oarsmen with values ranging from 11 $mmol.l^{-1}$ after maximal treadmill work to 15 $mmol.l^{-1}$ and 17 $mmol.l^{-1}$ following national and international competition respectively.

Venous lactate concentration following maximal rowing performance is also evident of the severity of this type of exercise (Figure 6). Hagerman et al. (1978:90) report a mean venous lactate concentration of 168 mg% with some subjects exceeding 180 mg%. These figures are somewhat higher than those reported by Saltin & Astrand (1967:355) (the mean for males was 13.8 mmol and 12.4 mmol for females), Cunningham et al. (1975:39) (the mean being 104 mg% for experienced rowers and 108 mg% for inexperienced rowers) and Wright et al. (1976:35) who reported an average lactate concentration of 127.5 ±31.3 mg% at the end of winter training and 127.6 ±33.6 mg% at the end of the competitive rowing season. However, of the 13 subjects originally tested at the end of winter training only 6 were retested at the end of the competitive rowing season, the isolated winter training data for these 6 subjects was 128.0 ±42.4 mg%.

Mean lactate values reported by Hagerman et al. (1979:81) reflect a significant anaerobic response with male heavyweight rowers recording 168.0 ±15.6 mg%, male lightweight rowers recording 164.0 ±13.4 mg% and female heavyweight (assumed) reaching values of 149.0 ±14.2 mg%. As pointed out by the authors very light exercise during the recovery period seems to facilitate lactate resynthesis. Research (Hermansen & Stensvold, 1972) indicates that a mild increase in circulatory function following severe exercise increases lactate oxidation.

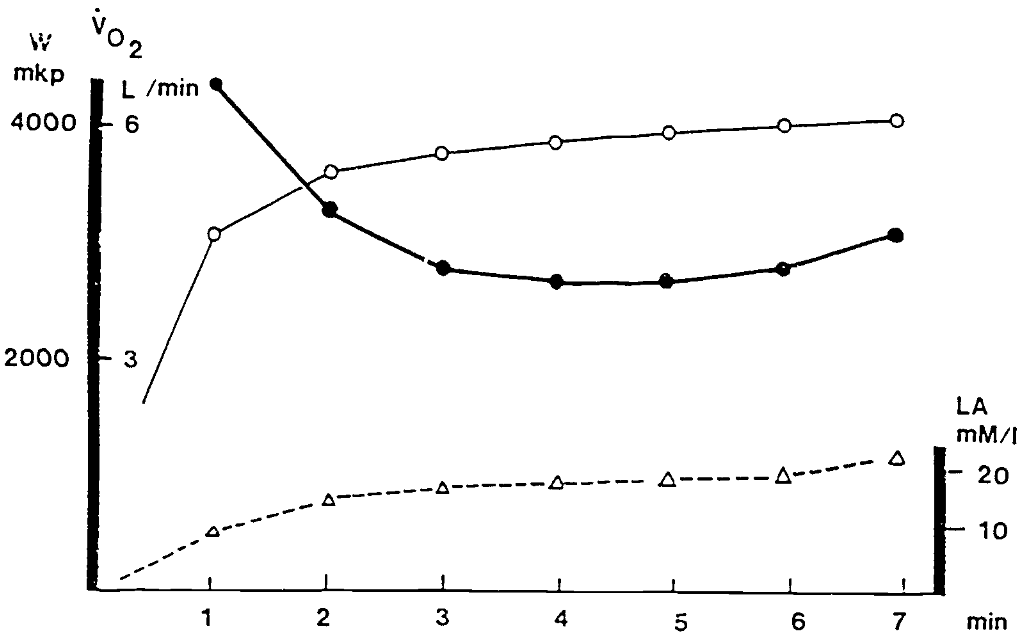


Figure 6

Lactate accumulation relative to power output and oxygen uptake during a maximal rowing effort (Howald, 1983)

Hagerman et al. (1979:81) report lactate levels exceeding 170 mg% between the first and second minute of exercise with the values remaining elevated but stable until the end of the ergometer exercise. This pattern differs from athletes who compete in endurance events of similar time. Runners are careful not to exceed the "anaerobic threshold" in the early stages of a race in order to avoid fatigue. Efforts resulting in a significant anaerobic response are usually reserved for the final sprint in the race. On the other hand, rowers begin a race with a high level of energy expenditure accompanied by a marked anaerobic response. Rowers therefore, need to develop a tolerance to a high level of blood lactate.

McKenzie & Rhodes (1982:21) utilized an indwelling teflon catheter which was inserted in the cephalic vein of the right arm. Blood samples were taken at rest, after each minute of exercise, during the final 10 s of work and 2 min into the recovery period. The authors found that serum lactate values were elevated at 1 min and continued to rise throughout the exercise to reach a maximum value of 14.7 $mmol.l^{-1}$ (Figure 7). These values were slightly lower than those recorded by Hagerman et al. (1979) and the 2 min recovery value of 13.85 $mmol.l^{-1}$ was surprising as serum lactate values usually increase during recovery as lactate diffuses from muscle (Diamant et al., 1968).

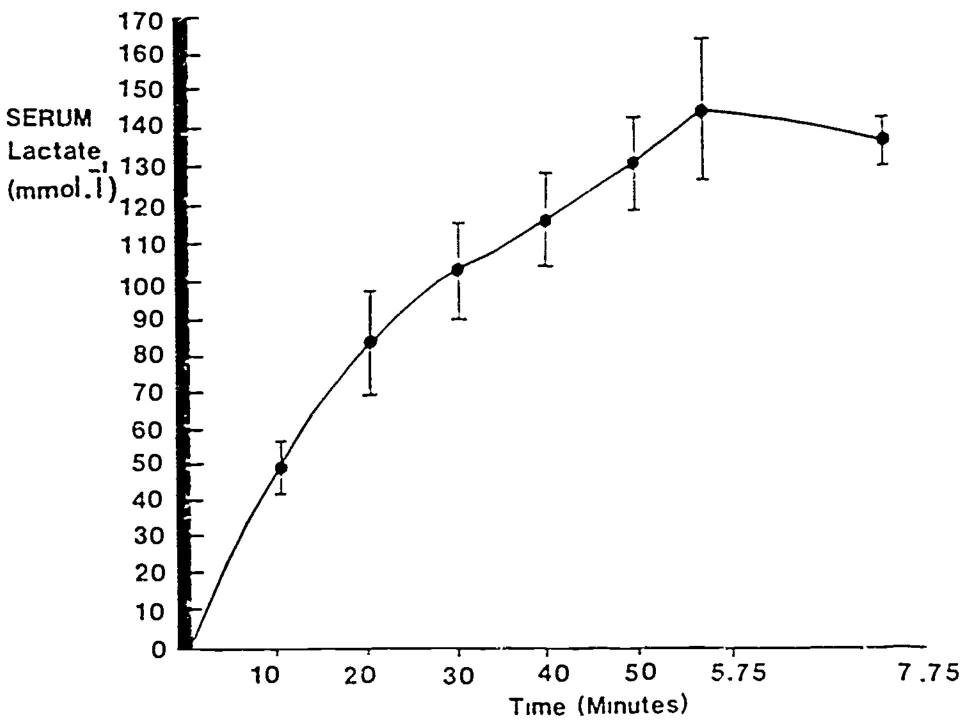


Figure 7

Serial blood lactate values during rowing ergometer work (McKenzie & Rhodes 1982:22)

It is suggested (Gollnick & Hermansen, 1973) that highly trained athletes may be able to oxidize lactate within the skeletal muscle. However, Hagerman et al. (1978:92) utilized variable time studies (subjects randomly stopped at either minute 1, 2, 3, 4 or 5 of the work test and venous blood withdrawn) and found that 90 % of the lactates were formed during the first minute and peaked at the second minute and as mentioned previously these values remained elevated but stable until the end of the exercise. The authors state that there is little, if any resynthesis of lactate during work, therefore, the rower must sustain most of his/her (in particular) work with very high lactate levels.

If the exercise is short term (less than 2-3 min) and is steady state, some authors believe that it is possible to use the "oxygen deficit" to estimate the anaerobic component (Knuttgen, 1970; Margaria et al., 1933: 1963; Martin, 1974). Secher (1983:38) believes that the "oxygen deficit" would probably be a more accurate measure of anaerobic metabolism. but is concerned about the indirect nature of its measurement. Values of 8 l have been determined for lightweights and 6 l for women (Hagerman et al., 1979). These figures are seen to represent a 14 % contribution by the anaerobic metabolism for males during a 6 min maximal rowing effort and a 23 % contribution for females during a maximal 4 min rowing effort (Secher et al., 1982).

However, Martin (1974) and McMiken (1976) believe that the "oxygen debt" is always larger than the "deficit" and increases significantly with increasing work intensity. Hagerman et al. (1978:91) believe that a major part of the "oxygen debt" is being utilized for purposes (not specified) other than muscle metabolism. Roberts (1977:6) does attempt to specify these purposes by suggesting increased body temperature, elevated ventilation and cardiac work, metabolite and ion redistribution, circulating hormones and tissue repair as being responsible for the utilization of a major portion of the "oxygen debt".

Gaesser and Brooks (1984) state that the metabolic basis of the elevated post exercise VO_2(EPOC) may be understood in consideration of those factors which directly or indirectly affect mitochondrial VO_2. These factors are catecholamines, thyroxine, glucocorticoids, fattyacids, calcium ions and perhaps most importantly, elevated temperature.

Although Hagerman et al. (1978) describe a maximal rowing effort as "severe steady state" (the first minute being the only exception) they were unable to accurately determine the "oxygen deficit" due to fluctuation in the average VO_2 measures. It would appear that ease of application is the main criterion for using the "oxygen debt" method even though Hagerman et al. (1979:82) claim that it was chosen because "oxygen debt" measures are approximately 40 % higher than "oxygen deficit" measures.

However, there are certain methodological difficulties in assessing the anaerobic component via the "oxygen debt". One of these is the choice of a base line for the measurement of "oxygen debt". Due to the factors mentioned above (Roberts, 1977; Gaesser & Brooks, 1984) the pre-exercise metabolic level may be an inappropriate criterion. These factors may lead to a situation where recovery from high intensity exercise may take a considerable time leading to a possible over-estimation of the "oxygen debt"; for example, a 40 $ml.min^{-1}$ over-estimated by 1.2 l for 30 min.

Hagerman et al. (1978:88) appear to recognize that there can be little justification in using the resting oxygen uptake as the base line for the measurement of "oxygen debt" as they utilize the average VO_2 from a 10 min submaximal rowing effort (1 kg resistance at 26 $st.min^{-1}$ as the base line value for the calculation of net VO_2). Following the maximal effort the subjects continued to row at this submaximal pace for 30 min. The authors obviously support the theory that examination of the recovery curve dynamics provides an appropriate base line for "oxygen debt" measurement, the recovery being followed until a steady state VO_2 is established.

Sechrr (1983:37) sees the choice of a 30 min recovery period for the collection of expired gas as an arbitrary one. On the other hand, Shephard (1982:31) suggests arbitrarily restricting examination of the VO_2 recovery curve to the first 15 min.

A number of researchers (Thomas et al., 1965; Wright, 1972; Roberts and Morton, 1978) have utilized a steady state recovery base line comprising resting VO_2 plus 10 % for the measurement of "oxygen debt". VO_2 is measured continuously throughout the time period with the emphasis being on multiple measures in the early stages of recovery followed by less frequent measurements later in recovery. Roberts (1977:7) sees this procedure as tailoring the method of analysis to the true nature of the recovery process where the rate of change in VO_2 is greatest in the early recovery period.

Various methods of mathematical interpretation of the recovery curve have been attempted and it appears that non-linear regression and subsequent integration of the recovery curve is the most appropriate analytical method (Roberts, 1977:7). Hagerman et al. (1978:89) appear to have simplified the "oxygen debt" measurement by estimation of the recovery curve using a simple exponential expression. Roberts (1977:8) believes that there can be little support for attempts to simplify "oxygen debt" measurement as these methods "are diverse from the true nature of the process they purport to measure".

In determining the "oxygen debt" it is also necessary to take into account the training status of the athlete, the athlete's nutritional status (muscle glycogen content may influence the "lactacid oxygen debt"), subject motivation, sex, age and body dimensions. "Oxygen debt" values have been found to be smaller in novices (9 l) than in experienced oarsmen (14 l) (Asami et al., 1978; Hagerman et al., 1978, 1979) with a maximum value of 33 l (Secher et al., 1982). For women and lightweight oarsmen, values of 10 l and 12 l respectively have been determined (Hagerman et al., 1979).

The "alactacid" component

At this stage, all of the attempts to quantify the "energetics" of maximal rowing performance have centred upon the aerobic and "lactacid" energy systems with apparently little or no attention being paid to the "alactacid" component of the "oxygen debt". Due to the unique pattern of energy utilization in competitive rowing it would appear that there is a large dependence on the muscle phosphagens and glycolytic activity during the first minute of exercise. Trained athletes (both short and long distance) demonstrate superior alactacid energy capacity (Thomas and Garvie, 1981:26) and it is well documented that the phosphagens are never completely exhausted even after supramaximal work (Bergstrom et al., 1971; Gollnick and Hermansen, 1973; Karlsson and Saltin, 1970) plus it has also been determined that intense long-term training will significantly improve the capacity of the "alactacid" energy sources (Eriksson, 1972; Komi et al., 1977; Pattengale and Holloszy, 1967).

Hagerman et al. (1978:91) state that it is possible to determine the contributions of the "alactacid" and "lactacid" fractions from the "oxygen deficit", however, no attempt was made to estimate these fractions. The authors state that the intensity of rowing causes a more rapid depletion of phosphagen and a more acute rise in blood lactates than other forms of exercise utilizing a similar pattern of total anaerobic energy usage. In furthering this argument, it is pointed out that the majority of an oarsman's "oxygen deficit" is incurred within 1-1.5 min of the rowing effort (determined randomly during maximal efforts) and that 90 % of the lactates are formed during the first minute and peak at the second minute (Hagerman et al., 1978:92). However, these results are at odds with those of McKenzie and Rhodes (1982:22) who report that serum lactate values are elevated at the 1 min mark and that they continue to rise throughout the rowing task reaching maximum values at the completion of the effort. McKenzie and Rhodes (1982:22) use measures of excess CO_2 to indicate that the "anaerobic threshold" has been exceeded. These values were elevated after the first 30 s of exercise. As mentioned previously, the variation in lactate measures makes it difficult to use serum lactate analysis to determine the anaerobic glycolytic events in rowing.

Wright et al. (1976:28) estimated the "alactate" and "lactate" components of the "oxygen debt" from the excess oxygen consumption of the recovery period by fitting a two term exponential function:

$$Y = C + A_1 e^{b1t} + A_2 e^{b2t}$$

The fitted estimate of the total debt was 8.32 $\pm$1.35 l while the corresponding estimate for the lactate component was 5.67 $\pm$1.33 l. There was a significant correlation between these levels and both the "lactacid" component of the "oxygen debt" (r=0.88) and the total debt (r=0.80).

Thomson and Garvie (1981:25-26) believe that the "alactacid" component cannot be directly determined and see potential sources of error in utlizing the first 2 min of the "oxygen debt" as being representative of the "alactacid" energy expended. Doubt is also cast on the capacity of muscle biopsy surveys to adequately quantify all of the potential sources of energy. Therefore, in order to obtain a quantitative measure of "alactacid" energy expenditure it appears necessary to use derived measures (Thomson & Garvie, 1981:26).

METHODS OF RESEARCH

Work test instrumentation

In the determination of physiological capacity for rowing, it is obviously important to select an appropriate test that involves a large muscle mass that makes optimal use of the specifically trained muscle fibres. Therefore, the most reliable procedure would be to determine the physiological variables during the specific sport performance, the assumption being that a reasonably large (and specific) muscle mass is engaged in the activity (Stromme et al., 1977:836).

A number of methods have been used to measure the physiological responses of rowers. These have included actual rowing on-the-water, in a rowing training tank, treadmill and bicycle ergometer tasks and simulated rowing on a mechanical rowing ergometer.

On-the-water studies have involved telemetric recording of heart rate (HR) (Di Prampero, 1971; Hagerman and Lee, 1971; Stromme et al., 1977) utilizing the relationship between HR and VO_2 and the direct measurement of VO_2 usually in the smaller single or double scull or pair oared boats (Jackson and Secher, 1976; Stromme et al., 1977) although Stomme et al. (1977:834) indicate that they used four oared boats as well. Although the authors claim that the work situation allowed for full freedom of movement and therefore, full expression of the demands of rowing, Hagerman et al. (1978; 1979), believe that this technique presents unique logistical problems making it difficult to collect adequate gas samples from subjects particularly in four and eight oared boats. Although these logistical problems are not expanded upon one assumes that they relate to the lack of space for gas collection apparatus (Douglas bag technique).

Rowing tank information was gathered by Di Prampero et al. (1971), and Hagerman and Lee (1971). However, Di Prampero et al. (1971:857) conclude that rowing in a tank with practically still water is an entirely different process than actual rowing, from both a mechanical and physiological viewpoint. The authors found that the stroke rate is higher in the tank than in actual rowing and that this leads to a high level of wasted energy due to an increase in transverse force and the greater energy needed to move the rower's body as the stroke rate increases. It is suggested (Di Prampero et al., 1971:857) that for tank rowing to simulate actual rowing there is a need to take the geometry and shape of the blade and the hydrodynamics of the tank into account. It is also suggested that the water in the tank be moved at known speeds, this was done by Asami et al. (1978:113) who utilized a water circulation speed of 4 $m.s^{-1}$. No comment was made as to the value/effect of this action or even if the authors were acting on the advice of Di Prampero et al. (1971), or of Jackson and Secher (1976:170) who stated that reduced working capacity while rowing in stationary water may be attributed to excessive water resistance and resultant local fatigue which prevents large workloads from being obtained.

Hagerman and Lee (1971:159) found that a larger body mass seemed to favour increased work output in the tank as smaller subjects found it difficult to maintain the set stroke rate of 33 $st.min^{-1}$ at the required catch pressure. It appears that in tank rowing, increased mass does not contribute to increased resistance as is the case in actual rowing. The authors found it difficult to achieve comparative conditions between the river and the tank. They believed that the difficulty arose from a slower positive water flow rate than normally experienced on-the-water and over-reaction of the subjects to the tank situation, which was reflected in significantly higher HR readings.

Stromme et al. (1977), compared on-the-water performance with treadmill measures and found that most oarsmen attained higher VO_2max measures during actual rowing (the mean difference being 0.23 $l.min^{-1}$ (4.2 %) the largest difference observed being 0.89 $l.min^{-1}$ (14.3 %). Secher et al. (1982), consider that VO_2max values for well trained oarsmen, determined during running or bicycling, would be 200 ml smaller than would be expected during rowing. However, comparisons between treadmill, bicycle ergometer and rowing ergometer results have produced conflicting findings. Carey et al. (1974) found that the same VO_2max could be generated during rowing (5.32 $l.min^{-1}$) and treadmill running (5.34 $l.min^{-1}$). On the other hand, Cunningham et al. (1975) reported slightly higher values when using the bicycle ergometer as against the rowing ergometer (the average difference in VO_2max being 0.27 $l.min^{-1}$). This is an interesting result as measured VO_2max on bicycle ergometers is usually somewhat lower than values obtained by treadmill tests (Astrand and Rodahl, 1977).

Carey et al. (1974:103) believe that the rowing ergometer may not be the best method of determining maximal work capacity as there may be less muscle mass involved (particularly the legs) than in running. Also the stroke rate of 32-36 $st.min^{-1}$ is seen as representing intermittent work in comparison to running. Cunningham et al. (1975:42) also believe that the rowing ergometer may not be able to simulate all aspects of the rowing activity as in a shell, the argument being that the mechanics of effectively transferring power to the blade while the shell moves through the water cannot be duplicated exactly. Rowing is described as a technically difficult exercise where slight discrepancies in mechanics might be crucial for the complete involvement of specifically trained muscle fibres and thus for the elicitation of maximal aerobic power (Stromme et al., 1977:836).

Despite these factors, Cunningham et al. (1975:42) were unable to distinguish any significant differences between experienced and inexperienced rowers when tested on bicycle and rowing ergometers. Jackson and Secher (1976:170) also found that arm and leg work during rowing produced a similar oxygen cost as did work on the bicycle ergometer (6.1 - 6.4 $l.min^{-1}$ for rowing, 5.2 $l.min^{-1}$ on the bicycle ergometer).

Although treadmill and bicycle ergometer exercises are seen by Hagerman et al. (1975) as providing valid and reliable maximal work conditions, the authors believe that these measures tend to underestimate aerobic capacity in some athletes. This is seen as being particularly applicable to technique based endurance sports such as rowing where the emphasis is on repetitive muscular efforts of the upper extremity. Rowing ergometer tests are seen by Hagerman et al. (1975:46) as simulating actual rowing conditions with a more accurate evaluation of VO_2 max.

Stromme et al. (1977:835) also consider that treadmill protocols are inadequate, particularly when one considers the involvement of peripheral factors in the achievement of a high VO_2max (factors no specified) and especially when one is assessing athletes whose endurance fitness is based on the muscle groups of the upper extremities such as rowers.

This position is supported by Pyke (1979:6) who states that bicycle work or treadmill running are not appropriate methods of assessment for rowers as improvements in performance capabilities of the muscle groups could go undetected on ergometers which fail to fully stress the specific muscle groups involved in rowing.

Several authors (Hagerman et al., 1975; 1978; 1979; Pyke, 1979; McKenzie & Rhodes, 1982) claim that the rowing ergometer has been shown to accurately reflect the rowing task, however, there is no evidence of any such studies in the literature. Also all of these authors utilize different types of ergometers, all of which are equipped with the fixtures of a racing boat but which also consist of different forms of resistance, clutch and cam arrangements. Stuart (1984:26-27) indicates that discrepancies in measured work output between 2 different rowing ergometers can be partly explained by the manner in which the two ergometers create their rowing resistance. It is recommended that scores from different ergometers should be considered independently when evaluating elite rowers.

Martindale and Robertson (1984) determined that additional energy savings achieved with a wheeled rowing ergometer allows one to conclude that the addition of wheels to rowing ergometers will permit rowers to work at stroke rates similar to racing levels.

Perhaps the most important feature of the rowing ergometer for testing purposes is the fact that it is used extensively as a training device with most rowers being familiar with its operation thus providing "the ideal stationary apparatus suitable for laboratory experimentation" (Hagerman, 1978:87). The current author's experience (and that of Stuart (1984)) is that rowers make their own subjective comparisons between ergometers, rating a machine on "degree of closeness" to the "real thing".

Work test characteristics

Two important variables in the determination of physiological capacities are the types of work loads and work rates chosen to elicit the necessary physiological response. In particular, the determination of VO_2 is not only affected by the magnitude of the load (flywheel resistance, slope of treadmill, time on task, peak revolutions) but also by the work rate (pedal frequency, stroke rate, treadmill speed). In the surveyed research, there is a great deal of variability in the types of work tests chosen.

Work output on rowing ergometers can be altered by changing the weight resistance, by altering the stroke rate and by exerting greater or less force on the oar. Hagerman et al. (1975:44) decided to use a constant resistance and increase the work load by increasing the stroke rate and by encouraging the rower to exert greater effort during the pull in order to more closely simulate the demands of actual rowing.

Saltin and Astrand (1967:353) utilized progressive maximal-type arm and leg exercise on a specially arranged (not specified) bicycle ergometer with a pedal frequency of 50 $revs.min^{-1}$ for maximal work. Di Prampero (1971:853) had subjects exercise in a rowing tank at various rowing frequencies (not specified) imposed by a metronome for a 4 min period. Hagerman and Lee (1971:156) utilized a stroke rate of 33 $st.min^{-1}$ over a 6 min period. Correct stroke rate was maintained by timing and verbal assistance from the coxswain. According to the authors, this protocol resulted in strenuous but submaximal exertion that was equivalent to 80 % of the maximal ergometer workload that the rower was normally capable of maintaining for the test period (Hagerman et al., 1972.13).

Carey et al. (1974:101) set a submaximal treadmill load of 10 min on a 14 % incline at 5.6 $km.hr^{-1}$ in order to achieve an estimated VO_2 of 32 $ml.kg^{-1}.min^{-1}$. If the predicted VO_2max was less than 50 $ml.kg^{-1}.min^{-1}$ the treadmill was operated at 12.48 $km.hr^{-1}$ at 5.2 % incline. However, if the predicted VO_2max was greater than 50 $ml.kg^{-1}.min^{-1}$, the work rate was set at 14.88 $km.hr^{-1}$ with the incline being increased by 2.7 % every third min until voluntary cessation by the subject. A 5 min test period was chosen for the rowing ergometer test in order to ensure a steady rate of VO_2 and maximum level of intensity (load was chosen by "trial and error" from the coach's "experience" with the subjects). Neither the stroke rate nor the resistance for this test was mentioned, however, the authors describe the 5 min effort as leading to exhaustion (criteria for "exhaustion" level not specified).

Szogy and Cherebetiu (1974:218) determined total work performed during a 6 min bicycle ergometer effort, starting at a work load of 23 $kpm.rev^{-1}$ at 75 $revs.min^{-1}$ until the fourth and fifth min where the work rate was increased to 90 rpm (at 23 $kpm.rev^{-1}$) followed by a sixth min effort of 23 $kpm.rev^{-1}$ at maximal revolutions. Hagerman et al. (1975:43) also selected a 6 min work test with selection of the work load based upon previous work data reported for the subjects (Hagerman et al., 1972). A constant resistance was chosen (not specified) and the work load was increased by raising the stroke rate (not specified) and the pulling effort on the oar (not specified). One must assume that same basic stroke rate (33 $st.min^{-1}$) was used as in the 1972 research (Hagerman et al., 1972:13).

The subjects involved in Jackson and Secher's (1976:169) work were instructed to row a number of 500 m efforts in a given time. The subjects were described as being very accurate in rowing to a time criterion, however, no evidence was given to support this contention. The subjects were also instructed to row at a constant pace and power over the whole distance. Again no evidence is provided regarding the control of these variables. These shortcomings are curious as the aim of the study was to examine the aerobic demands of rowing at speeds required to win international races in the single, double and coxless pair shells (276, 286 and 295 $m.min^{-1}$ respectively).

Cunningham et al. (1975:38) utilized three submaximal work periods of 5 min each on a bicycle ergometer to produce a HR of less than 160 and 170-180 $beats.min^{-1}$. The maximal work load was then set by extrapolating the HR-work load relationship to 190 $beats.min^{-1}$. The loads were set at 900 and 1,440 $kpm.min^{-1}$ (50 and 60 $revs.min^{-1}$ respectively with the maximum load determined at a pedal frequency of 70 $revs.min^{-1}$ for the heavier subjects and 60 $revs.min^{-1}$ for the lighter subjects). On the rowing ergometer the subjects were required to maintain a rate of 30 $st.min^{-1}$ with the resistance modified to produce moderate (1.34 kg), heavy (1.82 kg) and maximal (2.27 kg) work.

A treadmill run for 3 min at each of three increasing slopes (2,4 and 6%) was used by Wright et al. (1976:25). The slope was then increased to a predicted maximal effort and was further increased by 1-2 % at 2 min intervals "until signs of centrally limited VO_2max were noted". The exact nature of these "signs" were not indicated. Stromme et al. (1977:834) conducted their research on-the-water with high intensity (not specified) rowing in single scull, double scull and two and four oared shells. The work situation supposedly gave "full credit to the specifically trained muscle mass of the individuals being tested". Unfortunately, details regarding time taken and distance covered for the work test were not given. The authors also incorporated a treadmill test with an incline of 3 degrees with the speed adjusted (not specified) so that the running time at maximal speed was approximately 4 min.

Williams (1977:179) had his subjects produce a maximal effort (not specified) for 6 min on a rowing ergometer with the accumulated stroke rate gathered for each min. In a later study, the author (Williams, 1978:13) specified a resistance of 5.4 kg "since it closely resembled the load experienced in a top-level eight-oared race". Once again the author does not indicate how this criteria was established. Subjects were required to rate at 30-33 $st.min^{-1}$. The issue is further confused by Hagerman et al. (1978:88; 1979) who used a 3 kg resistance and instructed their subjects to row at a "competitive performance" level of 32-36 $st.min^{-1}$ with a greater impetus on the oar (specified as increasing flywheel revolutions).

Asami et al. (1978:109) involved their subjects in a 6 min exhaustive tank test with all subjects required to maintain a constant 35 $st.min^{-1}$. The treadmill tests used in this study are simply described as "gradually increasing running tests" and "exhaustive short duration running (about 1 min) at high speed". Pyke et al. (1979:278) also used an "exhausting" 6 min effort aimed at simulating a 2,000 m rowing event. However, no mention was made of stroke rate or peak flywheel revolutions (an important aspect of the Repco rowing ergometer used by the authors).

Moncrieff and Spinks (1980) and Spinks et al. (1984) utilized a 6 min "maximal" effort for male heavyweight and lightweight rowers with a 4 min effort for female rowers. "Maximal" effort was specified as "at race pace" ($\geq$34 $st.min^{-1}$). The rowers were given verbal feedback every 30 s regarding stroke rate, peak flywheel revolutions and total flywheel revolutions. Larsson and Forsberg (1980:240) measured VO_2max

during treadmill running but did not provide details of the test protocol.

McKenzie and Rhodes (1982:21) also attempted to simulate a 2,000 m international class race in an eight-oared shell by imposing a 5 min 45 s time limit on the maximal task. The effort supposedly simulated the race experience in time, pace and intensity of effort. A coxswain was present to ensure that the stroke rate, time and effort was maintained, however, no further details were provided. Mickelson and Hagerman (1982:441) utilized a step-wise progressive test to exhaustion using the rowing ergometer (the first such test protocol reported). For a period of 15-18 min the stroke rate was limited to 28-32 $st.min^{-1}$ with the flywheel spinning at a (near) constant 550 $revs.min^{-1}$ (in order to keep the min power increments at 27.0 $\pm$5.0 %). Each subject began at an initial power output of 47.2 W (unloaded ergometer). After the first min the power requirement was increased to 101.2 W with the resistance being increased by 27.0 W for each min thereafter until VO_2max was reached or the subject could no longer maintain the required $rev.min^{-1}$ within the limited stroke rate range. The subjects had continual visual feedback of flywheel speed, total flywheel revolutions and elapsed time.

MEASURED PHYSIOLOGICAL CAPACITIES

Due to the considerable variation in research methodology (see Table 3), in particular work test characteristics, it is necessary to closely examine the results of the surveyed research. Unless otherwise stated, all values relate to exercise based data collected from male subjects.

Pulmonary ventilation, ventilatory efficiency and oxygen pulse

Di Prampero et al. (1971:855) determined the ventilatory efficiency (VE/VO_2) in the range of VO_2 values between 20 and 45 $ml.kg^{-1}.min^{-1}$ (although this range is low for elite rowers the correlation is more likely to be linear in this range). The relationship was expressed in terms of the energy expenditure per litre of expired air and was 0.259 $\pm$0.027 kcal. According to the authors this value indicates that the pulmonary ventilation (VE) of elite rowers is "about the same as in ordinary fit subjects in walking". The authors also believe that the movements of the arms in rowing "do not seem to interfere appreciably with the chest expansion, and the VE is not a limiting factor of the performance".

Hagerman and Lee (1971:158) demonstrated a mean VE of 161.0 $\pm$20.4 $l.min^{-1}$ which was considerably higher than the average VE of 121.0 $l.min^{-1}$ recorded for the same subjects during vigorous treadmill running. Hagerman et al. (1972:18) found significant differences in the VE of Olympic (110.79 $\pm$19.1 $l.min^{-1}$) and non-Olympic (132.25 $\pm$13.15 $l.min^{-1}$) rowers

AUTHOR (DATE OF PUBLIC-ATION/STUDY	METABOLIC ANALYSIS PROCEDURE AND VARIABLES ASSESSED	CALIBRATION (CAL)* RESISTANCE OF SYSTEM (RES)* DEAD SPACE OF VALVE (D)* MEASUREMENT ERROR MENTIONED (LC)*	HEART RATE DETERMINATION	LACTATE DETERMINATION	
				METHOD	TIME
Saltin & Astrand (1967)	Open Circuit (DB) Ex* VO_2, VE, ENV (T & H)	Cal* Res* - Flow Rate	Conventional ECG (APP) Ex*	Micro-heated finger tip	2-3mins
Di Prampero (1971)	On-the-water : Indirect assessment from heart rate. Tank - open circuit (DB) VE, VO_2, Ex*		Telemetry/ECG. EX*	Venipuncture 2 ml.	3-4mins Rec*
Hageman & Lee (1971)	Open circuit (DB) (APP) R*Ex* VO_2,VCO_2 percent. BTPS & STPD Corr. VE		Telemetry/ECG (APP) R*Ex* - Discontinuous		
Hageman & al. (1972)	Open circuit (DB) (APP) Ex* VE, VO_2, VCO_2, R, VT BTPS & STPD Corr.	Res* - Flow rate D* - valve modified	ECG (APP) - Discontinuous last 15 secs of each min. in Ex* - end of each min. in R*		
Bloomfield et al. (1973)	Indirect determination of VO_2 from heart rate extrapolation, haemoglobin brachial pulse wave, FVC, (APP)		ECG - R*, Ex*		

Table 3: Procedures Followed in Assessment of Physiological Variables of Rowers

Carey et al. (1974)	Open circuit (DB), VO_2, VCO_2 Ex* - last 1-2 mins used for analysis ENV (T)	Res* - valve type (Rowers used mask) LC* (100 ml)	ECG - Ex*		
Szogy & Cherebetiu	Closed circuit (?) - Spirometer (App) - SIPD Corr. VO_2max, O_2pulse, heart volume - Ex*				
Hagerman et al. (1975)	Open circuit (DB) (APP), VE, VO_2, R.ex* - BIPS & SIPD Corr.	Cal*, D*, Res* - I.D.	Telemetry/ECG (APP) Ex*		
Cunningham et al. (1975)	Open circuit (DB) - last minute VO_2, VE Ex* ENV (T)	Cal*	ECG - 10 secs for 30 secs period of each work min. plus last 10 secs.of each work interval . Ex*	Venipuncture - 10 cc.	2-3mins (APP)
Jackson & Secher (1976)	Open circuit (DB) (APP) VO_2Ex*	Res* - Flow + I.D. Cal*	Telemetry/ECG Ex*		
Wright et al. (1976)	Open circuit (DB) (APP) VO_2, $FEV_{1.0}$, $FEV_{1\%}$, VE, R. SIPD & BIPS Corr. Ex*, ENV (T,H)	D* - valve type Res* - L.T. (not specified)	ECG - continuous CM5 - cf	Micro	2 mins
Strome et al. (1977)	Open Circuit (DB) (APP) VO_2	Cal*			

Table 3 (Cont.): Procedures Followed in Assessment of Physiological Variables of Rowers

Williams (1977)			ECG - Ex*, Rec*, HRmax		
Williams (1978)			ECG - Ex*, Rec*, Rec* Index		
Asami et al. (1978)	Open Circuit (DB) (APP) VO_2max, VO_2, O_2debt	Cal*			
Hagerman et al. (1978)	Open circuit (GA) (APP) VO_2, VE, R*, Ex*, Rec* BTPS & STPD Corr. Aerobic & anaerobic cost	Cal*	ECG - R*, Ex*, Rec*	Venipuncture (APP)	5 mins 30mins Rec*
Pyke et al. (1979)	Open circuit (GA) (APP) VO_2max (STPD)	Cal* Res* - valve type, I.D.			
Hagerman et al. (1979)	Open circuit (DB & GA) VO_2, VE, R*, Ex*, Rec*, BTPS & STPD Corr. Aerobic & anaerobic		Telemetry/ECG R*, Ex*, Rec*		R*,Rec*
Moncrieff & Spinks (1980) (u)	Open circuit (GA) (APP) VO_2, VE, FVC, PFR, net aerobic work, alactacid debt. R*, Ex*, Rec*, ENV(T). STPD & BTPS Corr.	Cal* D* Res* - I.D. & L.T.	ECG - continuous CB5 - cf R*, Ex*, Rec*		

Table 3 (Cont.): Procedures Followed in Assessment of Physiological Variables of Rowers

Larsson & Forsberg (1980)	Open circuit (DB) (APP) VO_2max, Ex*				
McKenzie & Rhodes (1982)	Open circuit (GA) (APP) VO_2max, VE, FVC, FEV_1, FVC/FEV_1. Ex*		ECG - Bipolar cf Ex*	Indwelling catheter	R*, Ex* 2 min. Rec*
Mickelson & Hagerman (1982)	Open circuit (GA) (APP) VO_2max, VE, VCO_2, FeO_2(%) anaerobic threshold. Ex*	Cal* D* Res*	Telemetry/ECG (APP) Ex*		
Hagerman & Staron (1983)	Open circuit (GA) (APP) VO_2max, VE, HT, muscle biopsy, BTPS, STPD Corr.	Cal*	ECG (APP), Ex*		
Clark et al. (1983)	Pneumotacograph - transducer + DB. VEmax, VT, f, VCO_2	Cal* (APP) I.D. L.T.			

R* = resting values; Ex* = exercise values; Rec* = recovery values; DB = Doublas bag; GA = automated gas analyzer; APP = measuring instrument brand name or method name mentioned; ENV = environment characteristics (T = temperature; h = humidity); cf = electrode configuration; Cal* = calibration technique mentioned; D* = dead space of respiratory valve mentioned; Res* = resistance of respiratory analysis system mentioned (I.D. = internal diameter of gas collection tubing; L.T. = length of gas collection tubing); (?) = method unclear; LC* = limits of confidence in measurement techniques; BTPS & STPD Corr. = correction of gas volumes.

Table 3 (Cont.): Procedures Followed in Assessment of Physiological Variables of Rowers

under normoxic (normal oxygen supply) submaximal exercise conditions. Significant variations also existed under hypoxic (reduced oxygen supply) conditions (16 % PO_2) with Olympic level rowers achieving a VE of 134.0 $\pm$18.18 $l.min^{-1}$ and non-Olympic rowers recorded at 153.0 $\pm$23.54 $l.min^{-1}$. The differences were attributed to the Olympic subjects' greater fitness and exercise adaptability (Hagerman et al., 1972:21). In later research, Hagerman et al., (1975:46) found a mean VEmax of 186 $l.min^{-1}$ obtained for conditioned rowers with 3 subjects attaining volumes in excess of 195 $l.min^{-1}$ (unconditioned rowers had a mean VEmax of 171 $l.min^{-1}$).

Cunningham et al. (1975:38) found higher values for VE on the bicycle ergometer as compared to the rowing ergometer. The mean maximum VE on the rowing ergometer for experienced and inexperienced rowers was 160 $l.min^{-1}$ and 138 $l.min^{-1}$ respectively whilst on the bicycle ergometer the respective readings were 175 $l.min^{-1}$ and 155 $l.min^{-1}$. (N.B. all readings are approximate as the authors did not produce tabulated results with the above readings being extrapolated from diagrammatic representations of the results). The authors report an apparent attempt made by the rowers to attain a high VE while rowing by increasing the rate of breathing (fr = 70 breaths.min^{-1} during the last min of work) but this was not sufficient to compensate for the restriction imposed on the tidal volume.

The cramped body position is seen by the authors as "appearing to constrict the abdominal muscles which could limit their ability to aid in the expiratory phase of each breathing cycle" (Cunningham et al., 1975:42). This constriction of the abdominal viscera is also seen as possibly constricting the action of the diaphragm during inspiration. Compensation for the lower VE during rowing was provided by an increase in the oxygen extraction rate as demonstrated by a lower VE/VO_2 on the rowing ergometer for both experienced and inexperienced rowers:

	VE/VO_2	
Experienced rowers	30 1.1^{-1}	(rowing ergometer)
	31.5 1.1^{-1}	(bicycle ergometer)
Inexperienced rowers	30.5 1.1^{-1}	(rowing ergometer)
	33 1.1^{-1}	(bicycle ergometer)

The authors also report a VE of 288 $1.min^{-1}$ for one elite male rower, however the peak VE in their study was reported to be 219 $1.min^{-1}$ (BTPS).

Jackson and Secher (1976:169) report VE values for on conditioned oarsman who obtained a peak VE of 206 $1.min^{-1}$ in the double scull, 204 $1.min^{-1}$ in the pair and 201 $1.min^{-1}$ in the single scull. On the bicycle ergometer, the same subject had a maximum VE of 243 $1.min^{-1}$, a 15 % variation. Hagerman et al. (1978:89) reported a significant response in VE of 190 $1.min^{-1}$ with several (number not specified) subjects exceeding 200 1 min^{-1}. VE/VO_2 was 26 5 1 $\pm$1.9 (range 22.8-34.2) while oxygen pulse was measured at 32.2 $\pm$2.7 $ml.beat^{-1}$ (range 27.4-38.6). In later research, Hagerman et al. (1979:80) found the mean maximum VE to be 192 $\pm$10.8 $1.min^{-1}$ while lightweight male rowers recorded a mean VEmax of 164 $\pm$4.6 $1.min^{-1}$ and heavyweight (assumed) female rowers 165 $\pm$15.6 $1.min^{-1}$.

Hagerman et al. (1978:90) believe that these figures indicate an excellent level of cardiorespiratory efficiency for rowers even though their figures were lower than those reported by Saltin and Astrand (1967) and Cunningham (1975). However, the authors found no evidence to "indicate an impairment of pulmonary ventilation during the rowing technique even though inspiration occurs while sustaining a cramped body position" (Hagerman et al., 1978:90). Cunningham et al. (1975:42) also suggested that cyclic breathing by the rower (one breath per stroke) further reduced VE. However, Hagerman et al. (1978:90) are of the opinion thε a single breath per stroke is more than adequate to fulfill VEmax needs. The authors cite research using continuous multistage treadmill tests on elite male rowers where VEmax values were found to be marginally higher than those reported for simulated rowing in the current study. The authors also believe that their metabolic and respiratory data reflects an "exercise of higher intensity than those city (Saltin and Astrand, 1967; Cunningham, 1975), thus placing greater demands on the respiratory system."

Moncrieff and Spinks (1980) determined VEmax, VE/VO_2 and oxygen (O_2) pulse values for elite Australian rowers. VEmax values ($l.min^{-1}$) (determined at peak VO_2) for heavyweight male, lightweight male, heavyweight female and lightweight females were 168.3 $\pm$14.23, 149.53 $\pm$13.14, 102.86 $\pm$12.1 and 111.6 $\pm$20.6 respectively. VE/VO_2 measures (1) for the same groups were 33.1 $\pm$3.26, 36.3 $\pm$10.3, 29.8 $\pm$5.1 and 27.6 $\pm$3.98 respectively. O_2pulse values ($ml.beat^{-1}$) were 27.7 $\pm$2.4, 23.5 $\pm$4.8, 18.6 $\pm$1.9 and 19.6 $\pm$2.4 respectively.

Only 2 of the male heavyweight rowers achieved VEmax rates exceeding 190 $l.min^{-1}$ (190.3 and 194.6 $l.min^{-1}$). However, McKenzie and Rhodes (1982:22) reported VEmax data for elite heavyweight male Canadian rowers as averaging 200 $l.min^{-1}$ with 3 subjects exceeding this value in the last 2 min of work and with one of these subjects ventilating at 223 $l.min^{-1}$ at the end of the ergometer task. More recent Australian data (Morton et al., 1984) indicates a mean VEmax of 200.6 $\pm$21.19 $l.min^{-1}$. This data is comparable with that reported by Hagerman et al. (1979), McKenzie and Rhodes (1983) and Secher et al. (1983). Elite lightweight oarsmen recorded VEmax values of 169.7 $\pm$15.30 $l.min^{-1}$. These figures are in close agreement with the literature (Hagerman et al., 1974; Secher et al., 1983). McKenzie and Rhodes (1982) also disagree with the assertion by Cunningham et al. (1975:42) that the rowing action impairs VE. Di Prampero et al. (1971:855) also indicate that the rowing action does not interfere with chest expansion and does not limit rowing performance.

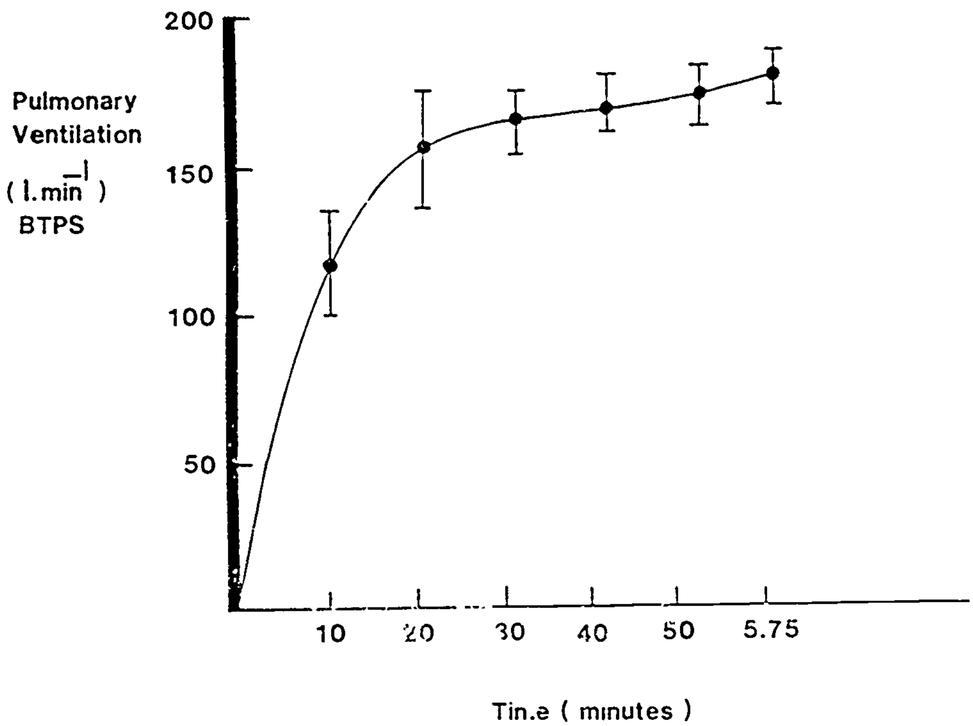


Figure 8

Mean minute pulmonary ventilation during rowing ergometer work (McKenzie & Rhodes, 1982:22)

Spinks et al. (1984) examined selected physiological values characteristic of physiological efficiency for elite and novice male and female rowers, for each min of work during a maximal rowing ergometer test (males 6 min, females 4 min). The results of this study indicate significant differences between elite and novice male rowers on O_2pulse (2nd min) and VE (1st to 6th min inclusive) at the 0.01 level of significance and on O_2 pulse (3rd, 4th and 5th min), rate of

O_2 removal (1st min), VO_2 (2nd, 3rd, 4th, 5th and 6th min), exercise volume and "oxygen deficit" at the 0.05 level of significance.

Significant differences were found between elite and novice female rowers on O_2 pulse (2nd, 3rd and 4th min), rate of O_2 removal (2nd min), VE/VO_2 (2nd min), VO_2 (1st to 4th min inclusive), exercise volume and "oxygen deficit" at the 0.01 level of significance and on O_2 pulse (1st min), rate of O_2 removal (1st, 3rd and 4th min) and VE/VO_2 (1st, 3rd and 4th min) at the 0.05 level of significance.

The authors state that the higher level of physiological efficiency values between elite and novice rowers may be attributed to the specific nature of training regimes that increase oxidative capacity of the muscle fibres and significantly improve the efficiency of the cardiorespiratory system.

Maximum oxygen uptake

As stated by Secher et al. (1982) increases in the total aerobic metabolism during a 4-6 min maximal exercise will be reflected in a "similar increase in the maximal oxygen uptake (VO_2max)". This finding is seen as justification for the use of aerobic power for the determination of aerobic metabolic capacity in rowers.

The VO_2max values of competitive rowers are very high with recent studies indicating values in the vicinity of 6.2-6.4 $l.min^{-1}$. Of the 30 studies reported by Spinks (1983), heavyweight male rowers were reported in all 30 and were found to have a mean VO_2max of 5.2 $\pm$0.43 $l.min^{-1}$, lightweight male rowers, reported in 3 studies, were found to have a mean

VC_2max of 4.69 ± 0.38 $1.min^{-1}$ and lightweight female rowers, reported in only one study, produced mean VO_2max of 2.95 $1.min^{-1}$. Relative VO_2max ($ml.kg^{-1}.min^{-1}$) scores were reported as follows

. Heavyweight males (22 studies, N=769)
= 61.8 ± 6.7 $ml.kg^{-1}.min^{-1}$

. Heavyweight females (2 studies, N=48)
= 55.8 ± 6.3 $ml.kg^{-1}.min^{-1}$
= 90.3 % of heavyweight male values or 72.9 % in absolute terms ($1.min^{-1}$)

. Lightweight males (3 studies, N=148)
= 65.5 ± 5.6 $ml.kg^{-1}.min^{-1}$
= 105.9 % of heavyweight male values or 90.2 % in absolute terms ($1.min^{-1}$)

. Lightweight females (1 study, N=3)
= 50.8 $ml.kg^{-1}.min^{-1}$
= 91 % of heavyweight female values or 77.8 % in absolute terms ($1.min^{-1}$)

As pointed out by Hagerman et al. (1978:89), and McKenzie and Rhodes (1982:22), the above figures indicate the severity of the work and the aerobic capacity needed to perfor ı that work. Although the relative VO_2max is somewhat lower than that reported for cross country skiers and runners (Saltin and Astrand, 1967) the absolute values are amongst the highest for such a homogeneous group of subjects (Hagerman et al., 1978:89). Relative VO_2max figures tend to be lower because of the greater average weight of rowers (this explains the higher relative VO_2max figures of lightweight male rowers in comparison to heavyweight male rowers). However, Hagerman et al. (1978:89), believe that the absolute VO_2max is more important in assessing a rower's maximal aerobic capacity as the body weight is supported by the boat. This opinion is supported by Wright et al. (1976:34) who believe that the division of the VO_2max by total body weight could penalize the heavier but not necessarily fatter individual (although, as the authors point out, there is a close relationship between aerobic power and lean body mass) and that "being tall with adequate muscle strength is an asset in rowing giving advantages of leverage and stroke" (Wright et al., 1976:34). Di Prampero et al. (1970) also found that rowers possessed the highest aerobic power of the athletes they tested but found that their relative values were not as outstanding.

Pyke et al. (1979) also believe that an individual should not be penalized by dividing the weight of a heavy body which provides effective forward propulsion and yet does not have to be carried. McKenzie and Rhodes (1982:22) also see absolute VO_2max as being more important due to the non weight-bearing nature of the activity while Larsson and Forsberg (1980) found no significant differences between the relative VO_2max of international and national class rowers which left the authors doubting the importance of this variable in predicting rowing performance, especially as:

> "the body weight is carried by the buoyant shell and any extra energy cost caused by stronger water resistance produced by the heavier rower and shell is well compensated for by the beneficial effects of the greater muscle mass." (Larsson and Forsberg, 1982:242)

Of course, from an efficiency viewpoint any "extra" mass should be lean body mass developed at the expense of excess fat content.

Apart from the first min of work, when circulatory adjustment is taking place, the average minute-by-minute VO_2 responses reveal a high steady rate of oxygen utilization. Hagerman et al. (1978:89) report that the elite male rower works at 96–98 % of his maximal aerobic power during the last five min of work, the authors describe this as "severe steady-state work". Similar results were found for Australian rowers (Moncrieff and Spinks, 1980) with heavyweight male rowers working at 96 % of their maximal aerobic power, lightweight males at 93 %, heavyweigh females at 97 % and lightweight females at 98 % of their maximal aerobic power (values for female rowers were determined on the last 3 min of a 4 min effort).

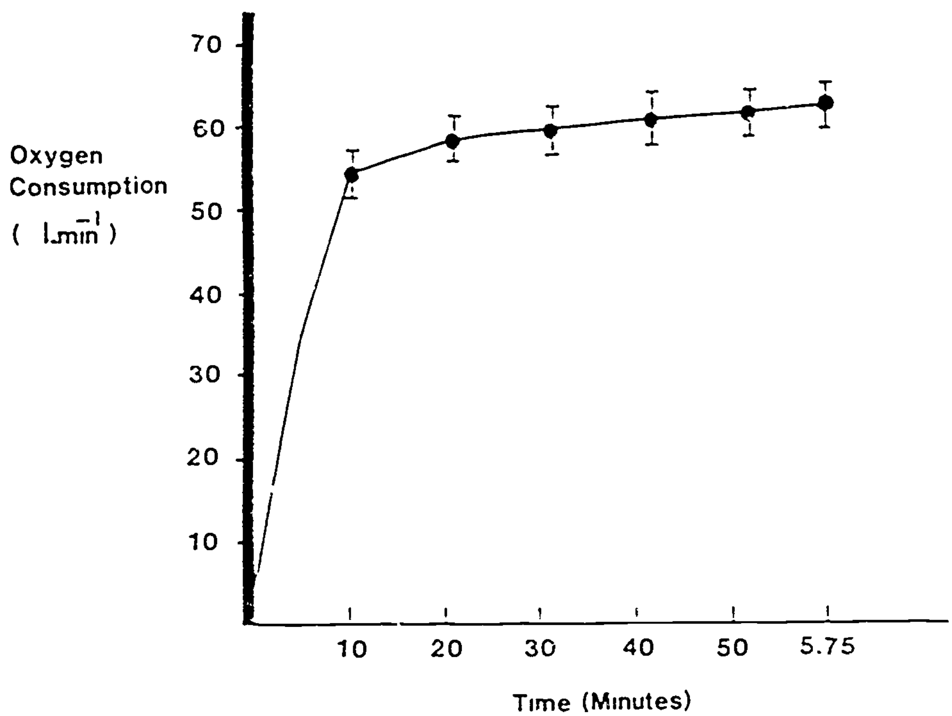


Figure 9

Mean minute values of oxygen consumption during rowing ergometer work. (McKenzie & Rhodes, 1982:22)

Hagerman and Staron (1983) examined seasonal variation (in-season [IS] to off-season [OS]) in elite oarsmen and found significant decreases in VO_2max (18 % absolute VO_2max and 22 % relative VO_2max) from IS to OS. This was a surprising finding as only minimal changes (about 10 %) have been reported or predicted. Also, elite rowers (including those in this study) spend much of the OS engaged in vigorous aerobic conditioning (running, cross country skiing and rowing ergometer work). Hagerman and Staron (1983:146) believe that the specific aerobic training effects of actual rowing have been underestimated with the OS aerobic activities combined with weight training, reducing the specificity. duration and intensity of the aerobic stimulus gained during twice daily rowing sessions during the IS. This finding would seem to indicate that peripheral (local muscular) rather than central (cardiovascular) factors are of importance for rowing performance. If peripheral factors are not of importance, then all types of exercise known to increase VO_2max (for example, running or cycling) could be used for rowing training (Secher, 1983:48).

Secher et al. (1983:45) found a direct relationship between a place (X) in an international regatta and the average VO_2max of a crew (Y). Where, $Y = 6.15-0.08X$, $r = 0.87$, $n = 10$ giving a VO_2max value of 6.11 $l.min^{-1}$ for 1st place and 5.11 $l.min^{-1}$ for 13th place. With 15-20 crews competing, the VO_2max of the best oarsmen decreases by 0.3-0.5 $l.min^{-1}$ below the estimated metabolic cost of rowing at racing speed (6.38 $l.min^{-1}$). When VO_2max is related to body weight to the power 2/3 (Vaage and Hermansen, 1977), the indication is that oarsmen possessing a weight of 93 kg should be able to develop a VO_2max of approximately 7.5 $l.min^{-1}$.

Secher (1983:35) indicates that the mechanical efficiency of rowing should be 22 %. However, this calculation is based on the assumption that rowing velocity is close to constant throughout a race. However, the unique pacing demands of race rowing results in the highest velocity occurring at the beginning of the race, over the next 1500 m the velocity gradually diminishes and then increases to near the average velocity for the final 500 m (Schneider, 1980; Secher et al., 1982). The reason for the initial spurt is not known even though it also occurs during simulated rowing (Hagerman et al., 1978; Schneider, 1980; Secher et al., 1982).

Secher (1983:37) states that the total VO_2 and work output during a given period of exercise is greater when an initial spurt is performed than when efforts are made to row at an average intensity. The author indicates that the initial spurt can be performed without an increase in the total anaerobic metabolism as indicated by lactate concentration and the size of the "oxygen debt".

The reported VO_2max data from the surveyed research is outlined in Table 4.

AUTHOR	YEAR OF PUBLICATION/ RESEARCH	COUNTRY OF ORIGIN	N.	VO_2MAX Litres min^{-1}	VO_2MAX $ml.kg^{-1}$ min^{-1}	COMPETITION LEVEL	EXERCISE MODE
Henderson and Haggard	1925	U.S.A.	8	3.27	-	Elite	RE
Ceretelli and Radova	1960	Italy	6	5.00	58.70	Elite	TM
Medved et al.	1967	Yugoslavia	45	4.43	-	Elite	TM
Saltin and Astrand	1967	Sweden	5	5.10	62.50	Elite	BE
Strydom et al.	1967	Sth Africa	10	3.63	47.72	Elite	BE
Nowacki et al.	1969	West Germany	8	5.63	61.20	Elite	BE
Di Prampero et al.	1970	Argentina, Italy	17	4.40	52.50	Elite	ST
Hageman	1971	U.S.A.	5	5.81	66.20	Elite	RE
Hagerman and Lee	1971	U.S.A.	7	4.69	54.00	Elite	TA

Table 4: Reported Maximum Oxygen Uptake of Rowers
(N.B. Except where indicated all data refers to male heavyweight rowers)

Di Prampero et al.	1971	Italy	5	5.01	59.01	Elite	TA/OW
Hagerman et al.	1972	U.S.A.	26	4.50 ($20.9\% O_2$) 4.40 ($16\% O_2$)	-	Elite	TM/SM
Carey et al.	1974	U.S.A.	5	5.32/5.34	59.3	Elite	RE/TM
Szogy and Cherebetiu	1974	Roumania	32	4.72	53.1	Elite	BE
Cunningham et al.	1975	Canada	8	4.69/4.95	54.52/57.93	Elite	RE/BE
Hagerman et al.	1975	U.S.A.	9	5.8/4.75	66.2/53.4*	Elite	RE
Jackson and Secher	1976	Denmark	2	5.8/6.0	-	Elite	OW
Wright et al.	1976	Canada	6	4.93/4.86*	-	Elite	TM
Hagerman et al.	1978 (1967/1977 data)	U.S.A.	310	5.95	67.6	Elite	RE
Strome et al.	1977	Norway	8	5.71	65.7	Elite	OW/TM

Table 4 (Cont.): Reported Maximum Oxygen Uptake of Rowers
(N.B. Except where indicated all data refers to male heavyweight rowers)

Asami et al.	1978	Japan	9 14 15	4.71 4.02 3.51	- - -	Elite Varsity Novice	TM/TA
Pyke et al.	1979 (B)	Australia	11	4.89	-	Elite	RE
Hagerman et al.	1979+ (1967-1977 data)	U.S.A.	(503*) 193 120 (LM) 40 (F)	6.1 5.1 4.1	68.9 71.1 60.3	Elite	RE
Moncrieff and Spinks	1980 (u)	Australia	15 6 (LM) 8 (F) 3 (LF)	5.07 4.34 3.49 2.95	56.18 59.78 51.32 50.80	Elite	RE
Larsson and Foresberg	1980	Sweden	12	6.4/5.1	65/62	Elite (Internat./ National)	TM
McKenzie and Rhodes	1982	Canada	8	6.26	68.9	Elite	RE
Mickelson and Hagerman	1982	U.S.A.	25	5.63	-	Elite	RE
Secher et al.	1982	Norway/Sweden	37	5.50	64	Elite/ National	TM/BE

Table 4 (Cont.): Reported Maximum Oxygen Uptake of Rowers
(N.B. Except where indicated all data refers to male heavyweight rowers)

Hagerman and Staron	1983	U.S.A.	9	5.09 OS 6.02 IS	56.5 OS 69.1 IS	Elite	RE
Clark et al.	1983	U.S.A.	21	6.6	73.5	Elite	TM
Morton et al.	1983	Australia	30 22 (LM)	5.62 4.63	64.9 65.5	Elite/ National	RE
		TOTAL	1120	(* Assume 310 of these subjects pertain to 1978 publication)			

u = unpublished; * = unconditioned; L = lightweight rowers; F = female rowers; TA = rowing tank;
TM = treadmill; ST = step test; BE = bicycle ergometer; OW = on-the-water; RE = rowing ergometer;
SR = surveyed research; C = cited in Cunningham (1975:42)
SM = submaximal work rate, OS = off season IS = in season; $\%O_2$= partial pressure of oxygen

Table 4 (Cont.): **Reported Maximum Oxygen Uptake of Rowers**
(N.B. Except where indicated all data refers to male heavyweight rowers)

Maximum heart rate

An earlier survey of the working capacities of rowers conducted by Shephard (1978:158-160) made provision for examination of maximal heart rate (HRmax) but no values were reported. Hagerman et al. (1978:89) believe that the HRmax of elite level rowers (mean = 185 beats.min^{-1}) are comparable with other HRmax data reported by Saltin and Astrand (1967) where the mean HRmax data for elite male athletes (mean age = 25.8 years) was 186 beats.min^{-1} (range 169-205 beats.min^{-1}) and for elite female athletes (mean age = 22.0 years) the HRmax was 194.8 beats.min^{-1} (range = 185-204 beats.min^{-1}). However, while rowers were included in the above sample, no separate data for these subjects was published. Di Prampero et al. (1967) utilized HR data to extrapolate VO_2max but the HR information was not reproduced in a format which would allow accurate listing of mean HRmax. However, Jackson and Secher (1976:170) cast doubt on the determination of VO_2max from HR data when they found that HR responses at a given VO_2 differed by several beats.min^{-1}.

Hagerman et al. (1972:20) used HR data to examine the impact of hypoxic conditions (simulation of Mexico City altitude) on rowing performance. No significant differences were found for either end-exercise or during-exercise HR as a result of decreasing the partial pressure of oxygen available to the subject. Carey et al. (1974:103) found that HRmax results on the rowing ergometer were less than those for treadmill work which the authors believe is "due to a greater stroke volume secondary to a greater muscle pump utilizing both arms and legs which is known to occur with large muscle group exercise". Williams (1977:180) published HR data for each min of work as well as HRmax data and data covering 3 min of recovery. The author found that "the small differences in HR appears to reflect the effect of aging on HRmax and when HR values are expressed as a percentage of HRmax then the 3 groups of subjects (juniors, colts, seniors) are markedly similar" (Williams, 1977:179). It was also determined that HR variables fail to differentiate between successful and unsuccessful oarsmen.

Mickelson and Hagerman (1982:443) determined HR at the ventilatory threshold (VT) believing that such data provides the most useful information of all for training purposes. The authors state that the VT heart rate could be particularly useful to coaches and rowers in determining the intensity of training sessions. The mean HRmax was 183 $\pm$9.3 beats.min^{-1} while the mean HR at VT was 167 $\pm$10.2 beats.min^{-1}.

Di Prampero et al. (1971) measured HR at various submaximal work levels in order to predict the metabolic cost of rowing. However as Secher (1983:38) indicates, a fixed VO_2 does not always result in a constant HR, there being considerable intra-individual variability. Also HR during submaximal arm exercise is higher than leg exercise at the same VO_2 (Astrand et al., 1964; Stenberg et al., 1967; Vokac et al., 1975). Also, the HRmax appears to be dependent upon the muscle mass involved in the exercise (Stenberg et al., 1967; Klausen et al., 1982) and also may vary from one type of exercise to another. particularly where the activity involves repeated maximal efforts (Secher, 1983:40). Secher (1983) and Klausen et al. (1982) determined that HR during dynamic exercise was due to the specific work situation rather than on the muscle groups involved, particularly when specific high level training is apparent.

Table 5 summarizes the reported HRmax data from the surveyed research.

AUTHOR	MAXIMAL HEART RATE (beats min^{-1})	COMPETITION LEVEL	EXERCISE MODE
Hagerman and Lee (1971)	184 (±6.7)	Elite	TA
Hagerman et al. (1972)	174 (±16.42) 182 (± 5.23) 174 (±10.17) 176 (±10.67) 178 (±10.21) 181 (± 8.03)	Olympic Non-Olympic Olympic Non-Olympic Olympic Non-Olympic	RE (80%max) TM (20.9%O_2) (SM) TM (16%O_2) (SM)
Carey et al. (1974)	191 (± 5.2) 185 (± 5.8)	Elite	TM RE
Hagerman et al (1975)	184 192	Elite Elite *	RE
Cunningham et al. (1975)	184 (approx) 186 (approx) 183 (approx) 188 (approx)	Elite Novice Elite Novice	RE BE
Wright et al. (1976)	188 (approx LT) 184 (approx WT)	Elite	TM
Williams (1977)	190 (±12.37) 187.5 (±6.17) 183.1 (±8.73)	Junior Elite Colt Elite Senior Elite	RE
Hagerman et al. (1978)	185 (±6.9)	Elite	RE
Hagerman et al. (1979)	187 (± 2.5) 179 (± 2.2) 190 (± 1.8)	Male (HW) Male (LW) Female (Elite)	RE
McKenzie and Rhodes (1982)	182	Elite	RE
Mickelson and Hagerman (1982)	183 (± 9.3) 167 (±10.2) (AT)	Elite	RE

SM = submaximal work; WT = water training; AT = anaerobic threshold; HW = heavyweight; LW = lightweight; * = unconditioned; LT = land training; %max = percentage of maximal work; %O_2 = partial pressure of oxygen.

Table 5: Reported Maximal Heart Rates of Rowers

Ventilatory threshold characteristics

Recent research (Brooks, 1985) indicates the fallacy of equating non-linear fluctuations in VE during exercise with muscle O_2 insufficiency (anaerobiosis) and lactate production. Thus the use of the term ventilation threshold (Jones and Ehrsam, 1982) rather than the more commonly used "anaerobic" threshold (Wasserman et al., 1973).

As previously described, VO_2max has been widely used as an objective measure of physical work capacity for rowers. However, these values are generally only used to rank rowers of various levels with respect to previously determined norms or expected maximal criteria. While this information is useful for motivation purposes and for determining the effectiveness of training programmes, it provides little specific information for the design of aerobic and anaerobic work sessions to meet individual or crew training needs.

The measurement of VT during step-wise progressive VO_2max tests enables determination of individual power output, HR and VO_2 at VT in addition to maximum values for VE, VO_2, VCO_2 and HR. VT information allows one to plan for training programmes of varying intensity (in relation to VT power output and HR) which minimizes the limiting effects of metabolic acidosis. The determination of VT as a percentage of VO_2max allows an analysis of the effectiveness of training programmes in raising an athlete's VT and/or VO_2max. At this point in time, only one study (Mickelson and Hagerman, 1982) has attempted to determine the VT's of rowers and to compare these VT's to the percentage of VO_2max at which they occur, to work rate at VT, and to HR at VT. VT's were determined from plots of VE and gas exchange variables (VO_2, VCO_2, ΔFEO_2, $FECO_2$) versus time.

Michelson and Hagerman (1982:441) chose the "exercise intensity or VO_2 just below the non-linear inflection in the VE and VCO_2 responses during which time VO_2 continued to increase linearly" as the VT. Table 6 indicates the physiological responses obtained during the above study.

VARIABLES	MEAN $\pm$ SD (RANGE)
VO_2 at VT ($1.min.^{-1}$)	4.77 $\pm$ 0.58 (3.50 - 5.43)
VO_2max ($1.min.^{-1}$)	5.63 $\pm$ 0.46 (4.29 - 6.16)
VT (% VO_2max)	83.5 $\pm$ 5.10 (71.8 - 90.0)
HR at VT (beats $min.^{-1}$)	167.0 $\pm$ 10.2 (151 - 190)
HRmax (beats $min.^{-1}$)	183.0 $\pm$ 9.3 (166 - 208)
Power at VT (W)	282.0 $\pm$ 44.0 (204.4 - 343.9)
Power max (W)	392.5 $\pm$ 34.8 (283.5 - 471.5)

Table 6

Physiological and ergometer data at ventilatory threshold for male elite rowers. (Mickelson & Hagerman, 1982:442)

It is apparent that the elite male heavyweight rower can generate approximately 72 % of his power output at VT (72 % of power is generated aerobically). The VO_2 at VT was approximately 83 % of VO_2max indicating the ability of rowers to exercise at intensities very close to VO_2max. Therefore, the elite male heavyweight rower generates 72 % of his total power output by utilizing 83 % of his aerobic capacity.

Spinks (1983[b]) determined VT values of 3.9 $l.min^{-1}$ (79 % VO_2max) for elite lightweight male rowers, 2.4 $l.min^{-1}$ (76 % VO_2max) for elite heavyweight female rowers and 1.6 $l.min^{-1}$ (68 % VO_2max) for novice lightweight female rowers. Differences between the groups for absolute VT ($l.min^{-1}$) were significant at the 0.01 level, while differences between the groups for relative VT (%VO_2max) were significant at the 0.05 level excepting for the difference between elite and novice females which was not significant ($P>0.05$). Significant differences between groups were attributed in part, to adaptations to training viz. the oxygen cost of ventilation, the accumulation of blood lactate and depletion in glycogen stores at given power outputs.

The high VT's and large aerobic power outputs of rowers can be partly attributed to the specific nature of their training programmes of which some 75-80 % is devoted to aerobic work. This type of work results in increased aerobic capacity at the cellular level, most likely due to changes in mitochondrial and capillary density and possible enzyme changes.

Along with this improvement in the cardiovascular and respiratory delivery systems, the resulting high VT is most likely a function of the strenuous training programme. The increase in oxygen utilization could delay the deleterious effects of lactic acid accumulation during high intensity exercise (Mickelson and Hagerman, 1982:443).

Ultra-long steady-state training sessions aimed just below a rower's VT are currently in vogue and are designed not only to develop aerobic capacity and local muscular endurance but also to train the neuro-muscular pathways. VT measurements not only allow monitoring of aerobic conditioning but they also provide information regarding the power output at VT, that is, the maximum power that can be generated without accumulation of lactic acid and a resultant drop in blood pH.

It is obvious that further research is necessary in this area as it provides the coach and the rower with a useful tool with which to evaluate relative fitness levels and at the same time services as a beneficial guide in determining the intensity of training programmes for rowers.

FUTURE RESEARCH DIRECTIONS

From the foregoing analysis of selected research in the physiological aspects of rowing, it is apparent that further research is indicated, viz.:

1. Physiological profiles of all classes of rowers using standardised testing procedures and equipment.
2. Quantification of energy cost data for rowers as they progress from novice to elite class.
3. Task specific versus non-task specific ergometry in the assessment of maximal rowing performance.
4. Ventilatory threshold and respiratory compensation threshold characteristics of rowers with respect to lactate accumulation.
5. The determination of predictor variables for accurate crew selection in novice rowers.
6. Discriminant analysis of physiological differences between good and elite rowers.

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