PHYSIOLOGICAL REQUIREMENTS FOR WORLD-CLASS PERFORMANCES IN ENDURANCE RUNNING*

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Modern physiological techniques allow the measurement of a number of important determinants of aerobic and anaerobic metabolism in an athlete who is running at different speeds. One is the rate of oxygen consumption, which is a measure of the rate of aerobic metabolism at the different speeds. Another is the concentration of lactic and pyruvic acids in blood plasma from which the level of oxygen consumption, or speed of running, can be determined at which anaerobic metabolism will first occur, and also the extent of anaerobic metabolism at levels of oxygen consumption which are close to the individual's maximum. The third determinant is the individual's maximum oxygen intake, which is a measure of the athlete's maximum capacity for aerobic metabolism. With these 3 measurements it is possible to decide whether an athlete is capable of running a mile or any other endurance event, such as a marathon, at the speed required for success in international competitions.

This scientific approach to endurance running will be illustrated by the results of physiological studies of a number of marathon runners and of the two most outstanding mile runners in the last decade in the Republic of South Africa—the two sub-4-minute milers, L. and Z.

METHODS

The studies were carried out on the treadmill of the Human Sciences Laboratory in Johannesburg at an altitude of 5,784 feet above sea-level. The speed of the treadmill can be varied between 2 and 15 m.p.h.

In each study the men were allowed to warm-up by running at 6 m.p.h. on the level for about 15 minutes. After a rest they then entered the main study and ran for 5 minutes, or at higher speeds for at least 3 minutes at 6, 8 and 12 m.p.h. Expired air was collected between the 2nd and 4th minutes when the men ran for 5 minutes or between the 2nd and 3rd minutes when the longer length of time of collection was not possible. Special low-resistance valves and connecting tubing were used between the face-mask and the Douglas bags. Expired air was analysed for oxygen concentration in a Beckman paramagnetic gas analyser by the procedure used in the laboratory for minimizing observer errors.[1]

The method of determining the maximum oxygen intake is described in full in a recent publication from this laboratory.[2]

Lactic and pyruvic acid concentrations were determined in the plasma of arterialized finger-tip blood by means of a method described in a recent publication from this laboratory.[3] Finger-tip blood of the marathon athletes, running at one speed on the treadmill, was arterialized by heating the hand to 45°C in an electrically heated glove during the period of exercise. However, in order to determine on L. and Z. the levels of oxygen consumption at which lactic and pyruvic acid concentrations first increased, and the increase with rise in oxygen consumption, they pedalled a bicycle ergometer at different work loads with one hand immersed in a water-bath controlled at a temperature of 45°C. With this procedure one could be more certain that the finger-tip blood was arterialized and it was also easier to obtain adequate samples of arterialized blood for the determinations.

RESULTS

Rate of Oxygen Consumption at Different Speeds of Running

The oxygen consumptions at different speeds are plotted in Fig. 1 for 4 marathon athletes and the sub-4-minute miler L., and at 5, 6 and 7 m.p.h. for 2 very fit, middle-aged men. Straight lines were fitted to the plots.

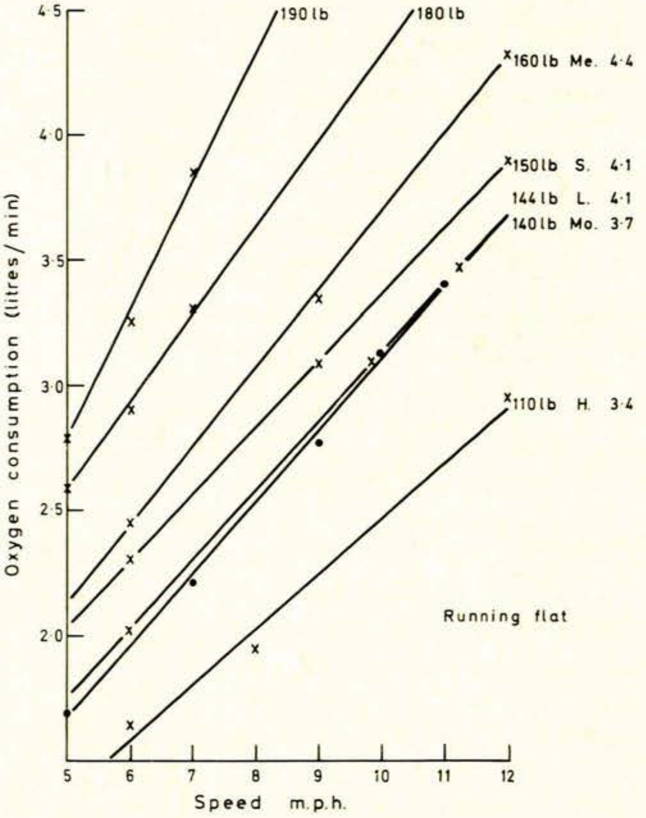

Fig. 1. Oxygen consumption of athletes while running on the level at different speeds.

These particular results were chosen because they illustrate the point very clearly that the rate of increase in oxygen consumption with increase in speed of running is strongly dependent upon body-weight.

Moreover, there is little difference in the lines of men of similar weight, even when one is a 4-minute miler.

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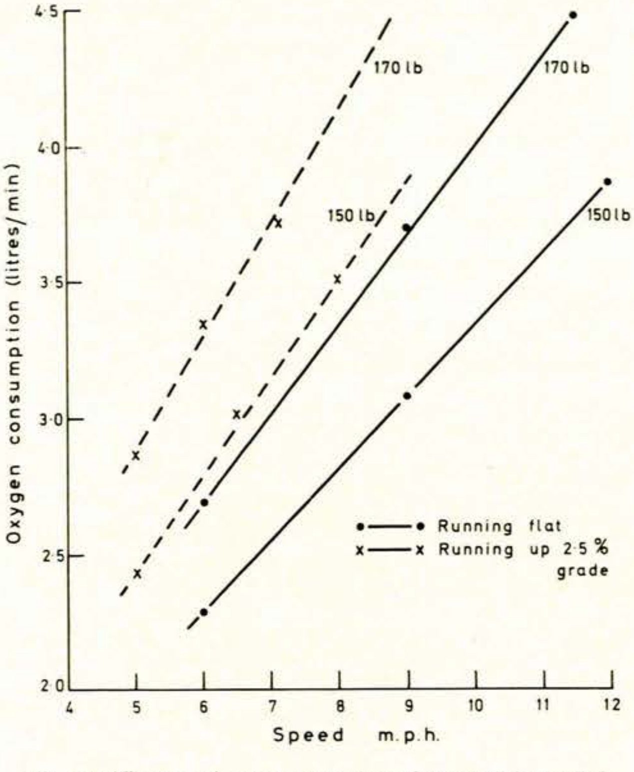

Fig. 2. Differences in oxygen consumption of athletes while running on the level and up a 2·5% grade at different speeds.

This point is illustrated by the results on Mo. (weight 140 lb.) and L. (weight 144 lb.).

The sub-4-minute miler L. was studied in December 1967, during an early phase of his training for the 1968 South African Championships, and again in May 1968, just after the Championships at which he won the 800- and 1,500-metre events. There was no change in the regression lines of oxygen consumption/speed over that period, which indicates that there was no significant change in his mechanical efficiency due to the intensive training programme he underwent for the Championships.

When the men ran up a 2·5% gradient, there was a very considerable increase in oxygen consumption (Fig. 2). For example, at 8 m.p.h. the increase in the 150-lb. man was from 2·80 to 3·50 litres/min. and in the 170-lb. man from 3·35 to 4·15 litres/min.

Maximum Oxygen Intake of Athletes and Other Men of Different Weight

In Fig. 1 are given the maximum oxygen intakes of 4 of the marathon runners and the sub-4-minute miler L. This indicates that there is some association between maximum oxygen intake and body-weight in athletes. This is confirmed in Table I where the maximum oxygen intakes, body-weights and heights are given of the 6 marathon runners. The maximum oxygen intakes of these 6 men were plotted against body-weight and these plots together with the regression line for the plots are given in Fig. 3. Also given in Fig. 3 are plots of maximum oxygen intake against body-weight of the two sub-4-minute milers, L. and Z., and the two fit, middle-aged men of 190 lb. and 180 lb. in weight. Fig. 3 also contains

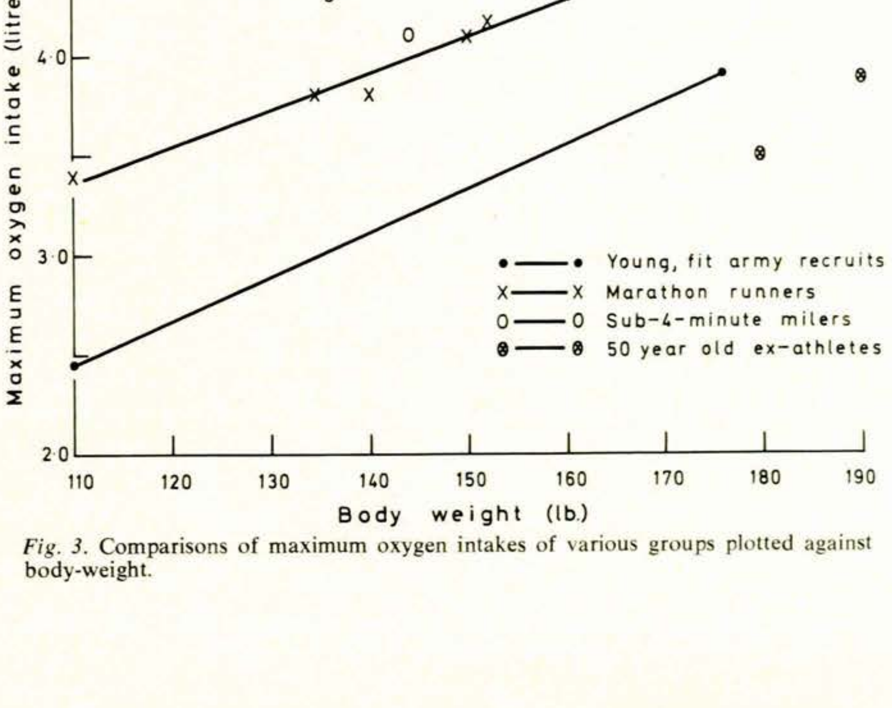

Fig. 3. Comparisons of maximum oxygen intakes of various groups plotted against body-weight.

TABLE I. PHYSICAL AND PHYSIOLOGICAL CHARACTERISTICS OF ENDURANCE ATHLETES

Subjects	*Age (years)*	*Height (cm.)*	*Weight (kg.)*	*Max.* $V.O_2$ *(litres/min.)*	*Max.* $V.O_2$ *(ml./min./kg.)*
Marathon runners					
Mou.	22	175·6	61·05	3·87	63·39
Mo.	21	182·2	63·65	3·67	57·66
H.	18	164·9	51·05	3·42	66·99
P.	20	176·5	68·90	4·28	62·15
Me.	20	183·5	71·55	4·40	61·50
S.	34	177·8	65·45	4·09	62·49
Mean	22·5	176·7	63·61	3·95	62·36
Sub-four-minute milers					
Z.	19	174·4	62·00	4·32	69·68
L.	24	183·4	65·35	4·13	63·19 (Johannesburg)
	—	—	—	5·10	77·98 (sea-level)
Army recruits					
80 men	17–19	174·4	66·30	3·15	47·21

the regression line obtained on 80 fit, young army recruits.[4]

Fig. 3 brings out the following facts:

(*i*) That the regression line of the marathon runners lies well above that for fit, young army recruits of comparable age and weight. Thus the average maximum oxygen intake of marathon runners of 130 lb. in weight is 3·7 litres/min. compared with the average of 2·9 litres/min. in fit, young army recruits of the same weight.

(*ii*) That the plots of maximum oxygen intake against weight of the two 4-minute milers, L. and Z., lie above the regression line for the marathon runners, indicating that the 4-minute milers have a greater aerobic power/weight ratio than the marathon runners.

(*iii*) That the plots of maximum oxygen intake against weight of the two fit, middle-aged men lie below the regression line of the fit, young army recruits and well below that of the marathon runners.

Maximum oxygen intakes were measured on athlete L. in December 1967, which was early in his training for the 1968 S.A. Championships, and again in May 1968 just after the Championships. These measurements show an increase from 3·88 to 4·13 litres/min. over the period of training, an increase of approximately 5%.

Lactic and Pyruvic Acid Levels

The changes in pyruvic acid concentration followed closely those of lactic acid concentration and therefore only the latter will be dealt with in this section.

Lactic acid concentrations in plasma were obtained at different levels of oxygen consumption up to close to the maximum in L., both in the early stages of his training and again just after the S.A. Championships. The results are given in Fig. 4. This figure brings out two points. The first is that, in the early stages of his training, lactic acid concentrations increased above approximately 2·35 litres/min., i.e. at about 60% of his maximum oxygen intake at that time. After he had reached his peak of fitness for the S.A. Championships the increase occurred at approximately 2·7 litres/min., i.e. about 67% of his maximum oxygen intake at that time. Secondly, at the higher level of oxygen consumption the concentrations of lactic acid were very much lower when he was highly trained than in the early stages of his training. For example, the concentrations were 55·4 mg./100 ml. at an oxygen consumption of 3·75 litres/min. early in training and only 27·6 mg./100 ml. at an oxygen consumption of 3·85 litres/min. just after the Championships.

Unfortunately only one study could be made on Z., which was during January 1968 when he was not in training. This showed that lactic acid increased above an

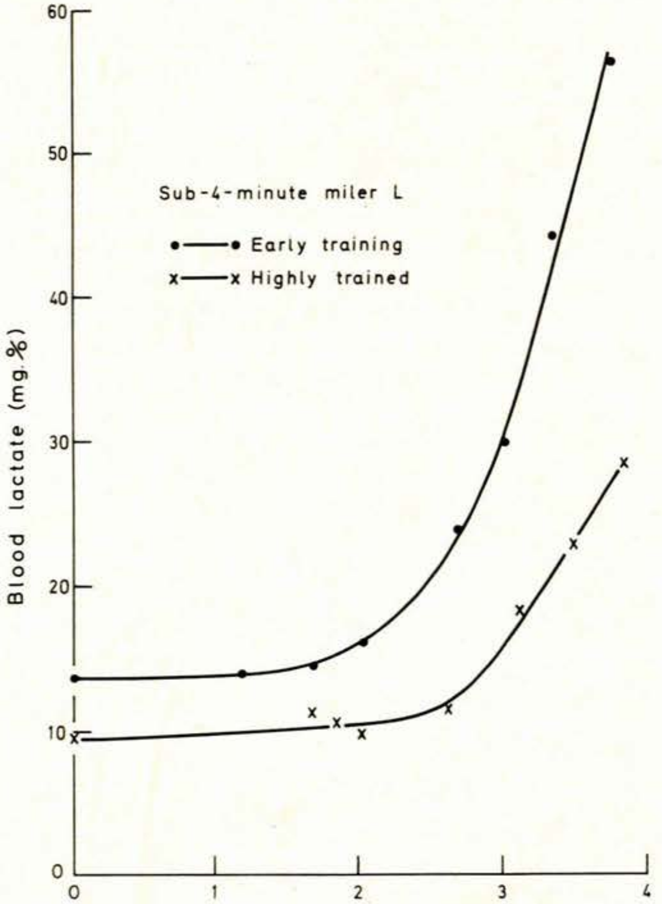

Fig. 4. Lactic acid concentrations in blood plasma at different levels of oxygen consumption before and after training (athlete L.).

oxygen consumption of approximately 2·0 litres/min., which is 47% of his maximum (Fig. 5). This is a clear indication that he was unfit at the time of the study.

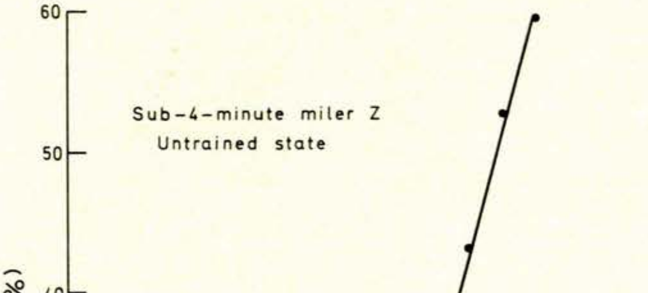

Fig. 5. Lactic acid concentrations in blood plasma at different levels of oxygen consumption measured in the untrained state (athlete Z.).

We also could not prevail upon the marathon runners to give the time needed to obtain the full curve of lactic acid against oxygen consumption, and compromised by having the men run for 30 minutes at 10 m.p.h. and measuring oxygen consumptions and lactic acid concentrations in the last few minutes of the run. The results are given in Table II. This shows that the men were running at between 80 and 90% of maximum oxygen intake at this speed. Only one marathon runner, P., had a marked increase in lactic acid concentration in plasma; he was relatively less fit than the others at the time he was studied. H., who came 1st and 3rd in the two 'Sugar Marathons' of 20 miles distance in the time of 1 hr 58 min. and 2 hr 8 min., respectively, had only a small rise in lactic acid above resting level. Mo., who came 1st in the 10,000-metre race at the 1968 S.A. Championships, had virtually no increase in lactic acid concentration at 10 m.p.h. Yet both of these men had been running for 50 min. at about 80% of maximum oxygen intake when the lactic acid concentrations were measured.

Fluid Losses

The volume of fluid lost by the 6 marathon runners during the period of 30 minutes at 10 m.p.h. was determined from the weight losses in that period as the men did not drink or urinate during that period. The mean loss was 662·5 ml. (or 1 pint), which is equivalent to a loss of 1,325 ml./hr (or 2 pints/hr).

DISCUSSION

Has the Athlete the Capacity to Run in International Competitions?

The results of these studies can be used to determine whether an athlete has the capacity, and is sufficiently well trained, to compete in international events with a good chance of success. Two factors need to be taken into account: One is the percentage of the maximum oxygen intake which the athlete would use in running at the required rate, and the other is the degree of anaerobic metabolism the athlete would develop in running at the required rate for the length of time of the race.

TABLE II. LACTATE RESPONSE OF MARATHON RUNNERS AFTER THIRTY MINUTES AT 10 M.P.H.

Subjects	*Speed (m.p.h.)*	*Lactate (mg./100 ml.)*	*$V.O_2$ (litre/min.)*	*$V.O_2$ as % of max.*	*Heart rate (beats/min.)*
Mou.	Rest	10·86	—	—	—
	10	21·85	3·54	91·4	180
Mo.	Rest	9·90	—	—	—
	10	13·12	2·98	80·5	156
H.	Rest	9·34	—	—	—
	10	17·27	2·58	75·4	162
P.	Rest	13·72	—	—	—
	10	68·25	3·66	85·5	182
Me.	Rest	13·31	—	—	—
	10	18·29	3·42	77·7	178
S.	Rest	7·67	—	—	—
	10	27·37	3·38	82·7	189

The method of determining the percentage of the man's maximum oxygen intake he would use when running at the required speed is illustrated in Fig. 6 for a 4-minute mile. In the figure, regression lines for oxygen consumption against speed of running of a number of athletes are extrapolated to 15 m.p.h. This is the speed at which the men would have to run in order to achieve a 4-minute mile. A hypothetical regression line is given for Z., based upon his body-weight of 136 lb. It is clear from this figure that if Me. was to run at 15 m.p.h. he would require an oxygen consumption of 5·0 litres/min. This is 116% of his maximum oxygen intake. At the other extreme is Z., who would require an oxygen consumption of 3·9 litres/min. to run at 15 m.p.h., which is only 91% of his maximum.

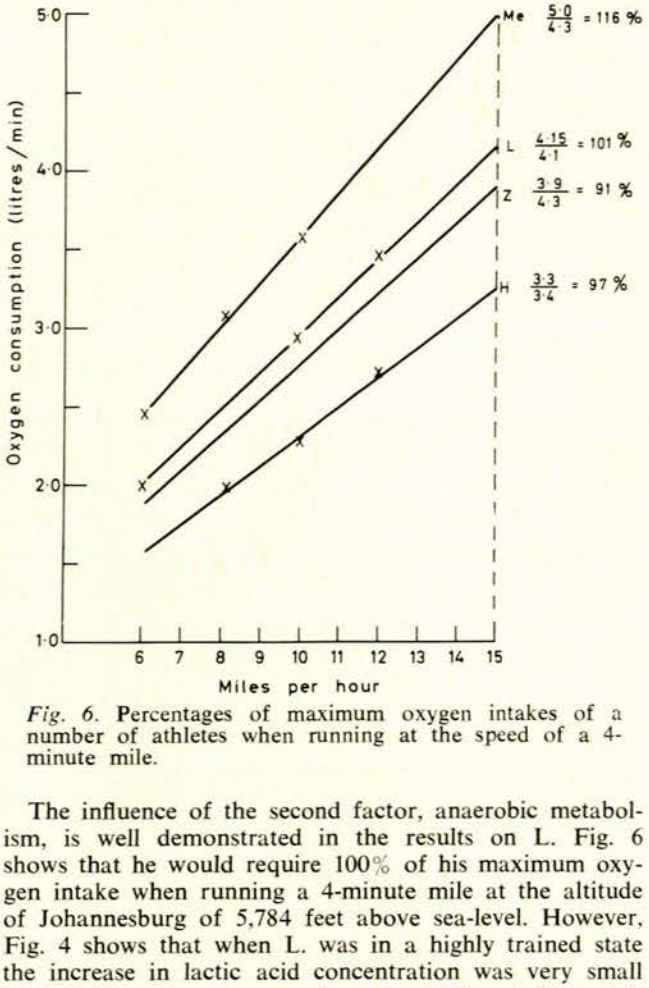

Fig. 6. Percentages of maximum oxygen intakes of a number of athletes when running at the speed of a 4-minute mile.

The influence of the second factor, anaerobic metabolism, is well demonstrated in the results on L. Fig. 6 shows that he would require 100% of his maximum oxygen intake when running a 4-minute mile at the altitude of Johannesburg of 5,784 feet above sea-level. However, Fig. 4 shows that when L. was in a highly trained state the increase in lactic acid concentration was very small even at an oxygen consumption of 3·85 litres/min. and it can safely be assumed that at his maximum oxygen intake of 4·13 litres/min. the increase in lactic acid concentration would not be greater than 30 mg./100 ml. L. should be able to tolerate this degree of anaerobic metabolism for 4 minutes. Therefore, although he would use 100% of his maximum oxygen intake in order to run a 4-minute mile, he would not develop a high degree of anaerobic metabolism at that speed of running.

The differences between Me., L. and Z. can now be summarized by saying that even if all three men were in the same very highly trained state, Me. would be forced to use some degree of anaerobic metabolism if he tried to run a 4-minute mile (oxygen consumption 116% of maximum) and this would lead to a marked increase in lactic acid in blood plasma which he would be unlikely to tolerate for the full 4 minutes. Z. would have a small advantage over L. in running a 4-minute mile in that he would be required to use less anaerobic metabolism than L. (by virtue of his required oxygen consumption being 90% of his maximum compared with L.'s 100%). However, as the results of the lactic acid studies on L. showed, the increase in lactic acid concentration would be small even when he was running at maximum oxygen intake, and should be quite tolerable. Where Z. might gain the advantage is that, in a tight finish after a fast 3 laps, he would have very little lactic acid in his blood plasma and could afford to sprint to the tape for a longer distance than L. could do.

The results on the marathon runners can be examined in the same way. In order to achieve an international time they would have to run at 11 m.p.h. (this would be a time of approximately 2 hr 22 min. for the standard Olympic marathon of 26 miles 385 yards). From Fig. 1 it is clear that the oxygen consumptions for 11 m.p.h. would be about 82 - 94% of their maximum oxygen intakes. Lactic acid determinations at about 80% of their maximum oxygen intakes showed that H. and Mo. could tolerate this percentage of maximum without much increase in blood lactic acid or, therefore, in anaerobic metabolism. They should, in consequence, be able to run at the speed required without developing an intolerable level of anaerobic metabolism in a standard Olympic marathon.

These results should make it clear that we have available the physiological procedures with which we can determine whether an athlete has the capacity to run at the speed required if he is to stand a good chance of success in endurance running events, and also to judge whether he is in a sufficiently highly trained state for the event. It seems logical, therefore, that rather than waste money in sending large groups of athletes overseas, many of whom have no chance of success in international competition, scientific studies should be made of the possible contenders along the lines indicated above. By this means it would be possible to select only those who have the capacities for competing successfully in international circles. These men could then be assisted to reach a high degree of training for their events by applying modern, scientific knowledge. This scientific approach would be much cheaper and should be more effective than the present, very expensive, hit-and-miss method of selecting athletes for international competitions.

Effect of Altitude

These results were obtained in Johannesburg at an altitude of 5,784 feet above sea-level. When athletes run at sea-level they gain in two ways. Maximum oxygen intake increases by an average of 12% as shown in recent unpublished results from this laboratory. A study in a laboratory at sea-level on L. gives a maximum oxygen intake of 5·1 litres/min. compared with 4·1 at Johannesburg's altitude of 5,784 feet above sea-level, an increase in maximum oxygen intake of about 25%. This would decrease the stress of running considerably. For example, Z.'s maximum oxygen intake would increase to about 4·8 litres/min. Even if his oxygen consumption for a 4-minute mile remained at 3·9 litres/min., it means that at the coast he would consume oxygen at only 80% of maximum, instead of 90% of maximum at Johannesburg. This would reduce the extent of anaerobic metabolism that would occur. Running at sea-level also reduced the respiratory ventilation considerably[5] and this, in its turn, reduced the oxygen consumption at a particular speed of running. The net result is an increase in maximum oxygen intake and a reduction in oxygen consumption so that the athlete would be under far less physiological strain at sea-level, judged in terms of the smaller percentage of maximum oxygen intake required and the resultant decrease in anaerobic metabolism needed.

Influence of Training

The results on sub-4-minute miler L. show, firstly, that in an endurance athlete there is no improvement in mechanical efficiency as a result of training; secondly, that the maximum oxygen intake increases during training but the improvement is relatively small, being about 5%; and thirdly, that the main effect of training is in the anaerobic metabolic processes where the percentage increases by 10% of the maximum oxygen intake at which lactic acid concentration in blood rises above normal and, further, the extent of increase at high rates of oxygen consumption is much less in the trained than in the untrained state.

The results on marathon runners show that when these men are highly trained they can run for prolonged periods at 80% of maximum oxygen intake without much evidence of anaerobic metabolism (as indicated by the low levels of lactic acid in blood plasma). It appears that in order to achieve this state of physical conditioning men have to run about 20 - 25 miles per day at a high proportion of their maximum oxygen intakes.

The physiological reasons for these improvements during training are not clear. Central circulation improves in that stroke volume decreases for a given level of oxygen consumption[6] and plasma volume also expands.[7] These factors could account, in part, for the increase in maximum oxygen intake. The reasons for decrease in anaerobic metabolism have not been clarified. It appears that there is improved transport of oxygen from blood to working muscle and this might be due to improved blood supply to the muscle, or to a better local blood supply in muscle due to the development of new collateral blood-vessels, or to some change in the aerobic metabolic processes in muscle cells. Evidence on these alternatives is lacking.

Differences between Endurance Athletes and Non-Athletes, and the Influence of Age

The endurance runners were both lighter and taller than young, fit South African males of the same age. This confirms an earlier observation in this regard[8] and is in line with Tanner's anthropometric characterization of different types of athletes.[9] The regression line of maximum oxygen intake against body-weight indicates that endurance runners are a unique group in the population in their very high aerobic power to weight ratio. In the example given in the results the average maximum oxygen intake of endurance runners of 130 lb. in weight is 27% higher than the average of fit, young men of the same weight. As this study and another from the laboratory have shown, one cannot expect, even with rigorous athletic training, to improve maximum oxygen intake by more than 10%.[10] It is clear, therefore, that good endurance athletes are 'born and not made' or as Astrand, the distinguished Swedish exercise physiologist, puts it, 'if you want to be a world beater then you must choose your parents carefully'.

This study also shows the effect of age on the maximum oxygen intake against weight relationship. Both the two fit, middle-aged men had been good athletes in their youth and it can be assessed that in their 20s their plots would have fallen onto the regression line of the endurance athletes. However, the increase in body-weight and decrease in maximum oxygen intake that occurs in most males in the late 40s and early 50s causes their plots to fall below the regression line of the fit, young men and well below that of the endurance athletes.

Fluid Losses Due to Sweating

The average loss of fluid of the marathon runners was 1,325 ml./hr (or just over 2 pints). The extent of fluid loss by sweating during marathon running is not generally realized. A recent paper from this laboratory[11] on the fluid losses and body temperature responses of marathon runners in the two 'Sugar Marathons' showed that fluid deficit of over 3% can lead to serious rises in body temperature. At a fluid loss in sweat of 2 pints an hour, the average marathon runner would be in 3% water deficit within 1½ hours if he drank no water, and the ridiculous international rule forbidding the drinking of any water in the first 10 miles (or hour of running) makes this loss almost certain. It is clearly high time for sports administrators and medical officers at athletic meetings to learn a little about the physiology of exercise and especially about body temperature regulation, because, as Sir Adolphe Abrahams puts it, 'in a healthy athlete the only potential risk to life is heat stroke'.[12]

SUMMARY

Oxygen consumptions were measured at different speeds on 6 marathon runners and two sub-4-minute milers. Regression lines fitted to plots of oxygen consumption against speed of running showed that body-weight is the main determinant of the rate of oxygen consumption at different speeds, the heavier man having much higher rates of oxygen consumption.

Maximum oxygen consumptions were also measured, and regression lines fitted to plots of maximum oxygen intake against body-weight showed that the maximum oxygen intake (or aerobic power): weight ratio is much higher in marathon runners than in fit, young army recruits. The difference between marathon runners and fit, young army recruits in the aerobic power: weight ratio is about 30%. This is much larger than the increase of 10% in this ratio which is seen with rigorous physical training. It appears that endurance runners are 'born and not made' and this suggestion is supported by the fact that, on the average, endurance runners are lighter and taller than fit, young men in the same age-group.

When the regression lines fitted to plots of oxygen consumption against speeds of running for the different endurance runners are extrapolated to 15 m.p.h. it is possible to decide whether the various athletes have a sufficiently high aerobic

power: weight ratio to run a 4-minute mile at Johannesburg's altitude of 5,784 feet above sea-level. In deciding whether the athlete is capable of running at the speed required for a sufficient time, the extent of anaerobic metabolism he may incur must also be considered. Details of such findings are given.

At sea-level the maximum oxygen intake would increase by about 12% on average and oxygen consumption at the different speeds would decrease so that the percentage of the maximum the athlete would use when running at 15 m.p.h. at the coast would be reduced markedly and he would run in less anaerobic metabolism.

The results show how a scientific assessment can be made of an athlete's ability to achieve world-class times in endurance running and are suggested as an aid in the selection of athletes for competition in international events. This would be considerably less expensive than sending large teams of athletes that are selected on the present hit-and-miss basis.

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