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SESSION II: Paper 2

Submaximal Tests for Estimating Maximum Oxygen Intake

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MOST physiologists with experience in measuring the maximum oxygen intakes of peoples of different ages, sexes and races will agree that tests which require maximum effort from the subjects are difficult to apply, except in samples of athletes and those engaged in physical education programs. The reason for this difficulty is that in order to obtain a reliable estimate of the individual's maximum oxygen intake, two or three measurements of oxygen consumption are required at work rates *above* the level at which the maximum oxygen intake occurs. Further, the length of time the individual exercises at these maximum efforts must be long enough for a relative steady state of oxygen consumption and heart rate to occur, that is at least five minutes of effort. Even in young, fit adults considerable motivation is required from the individual to accomplish this satisfactorily. In the older age groups, in the very young, in patients with cardiorespiratory disease, and in primitive peoples, it is not always easy to obtain the motivation required, and in cardiorespiratory patients the maximum effort may be dangerous. In fact, one of the points that emerges from population studies is that, apart from the very small proportion of the population that continues with active sports after leaving school, few individuals in Western Society appear ever to exert themselves to a point where they experience any great degree of physiological strain. They dislike the symptoms which accompany maximum effort and may even be frightened by them.

With these problems in mind, exercise physiologists have tried to develop a test, using submaximal effort, which will give a reliable and accurate estimate of the individual's true maximum oxygen intake. Success in this field of research has been hard to come by. The quest has been as elusive as that for the "philosopher's stone". In consequence there are almost as many submaximal tests of maximum oxygen intake as there are exercise physiologists.

The submaximal tests that have been proposed can be divided into a number of distinct categories depending upon the criteria used for judging when the individual has reached his maximum effort. They are:

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A. *Those in which the estimate is based upon the maximum heart rate*

(a) One group of tests is based upon the measurement of heart rate and the measurement (or estimate) of oxygen consumption at one or more rates of work. That introduced by Astrand and Ryhming in 1954[1] is based upon the measurement of heart rate at one rate of work, the estimation of oxygen consumption from the oxygen consumption against work-rate relationship given in the nomogram, and a straight line fitted between a "common" heart rate of 61 beats/min at zero oxygen consumption and the measured heart rate at the "estimated" oxygen consumption.* The maximum oxygen intake is obtained from an extrapolation of the straight line (by means of the nomogram) to 195 beats/min, and the half maximum oxygen intake from a heart rate of 128 beats/min for males and from 138 beats/min for females. Maritz *et al.*[12] in 1961 based their assessment on the measurement of heart rate and oxygen consumption at four submaximal rates of work, the fitting of a straight line to the four pairs of plots, the extrapolation of the straight line to a maximum heart rate (which was found to be 180 beats/min for Bantu subjects living at Johannesburg's medium altitude of 5784 feet above sea level), and, finally, reading from the graph the oxygen consumption, which is equivalent to the maximum heart rate. This oxygen consumption is an estimate of the individual's maximum oxygen intake. Margaria[13] in 1965 introduced yet another nomogram based upon similar concepts.† In this case he employs two rates of work which were chosen to give heart rates between 100 and 150 beats/min. Adjustments are made in the work rate for very young and very old people. Three maximum heart rate lines are given in the nomogram so as to take into account the effect of age on maximum heart rate (and presumably also the effect of altitude!).

(b) Another group of tests is based upon the increase in heart rate with successive increments

*Editor's note: The rate of 61 at zero oxygen consumption is true only of male subjects. In females the rate is 81 at zero oxygen consumption.

†Margaria also comments on this technique in his contribution on page 734.

in work rate, either on a bicycle ergometer or a step test. The rates of work are increased every two or three minutes until the subject's heart rate reaches 170 to 180 beats/min, or until he is exhausted. The names of Sjöstrand,[15] Wahlund,[16] Lange Andersen,[10] Hettinger,[6] Hollman,[7] Balke,[3] Binkhorst[4] and Kasch[9] are associated with one or other form of test procedure based upon these concepts.

B. *Those in which the estimate is based upon a respiratory quotient exceeding 1.0*

It has been long known that the respiratory quotient (RQ) at high levels of exercise exceeds 1.0. Issekutz, Birkhead and Rodahl[8] proposed that this observation could be made the basis of a new test for estimating the individual's maximum oxygen intake. RQ's are measured at a number of submaximal rates of work. The difference between these values and an RQ of 1.15 is plotted on a logarithmic scale against oxygen consumptions for the various work rates. When the difference on the log scale exceeds 0.4, the rate of oxygen consumption is taken to be the individual's maximum.

C. *That based upon a significant increase above the normal minute ventilation of the lung*

Sadoul,[14] from his studies of miners with pneumoconiosis, proposed that the minute ventilation should be measured at a number of different work loads. He considers that the man has reached his maximum effort when the minute ventilation plotted against work load significantly exceeds that of normal controls.

D. *That based upon the levels of lactic acid, of pH and of Po_2 and Pco_2 in arterial (or arterialized) blood*

Sadoul[14] in 1958 and Lavenne[11] in 1962 have reported on the levels of lactic acid, of the acid-base balance and of Po_2 and Pco_2 when subjects with cardiorespiratory disease performed different levels of exercise on bicycle ergometers. A significant departure from normal in these measurements, especially in Po_2, is used by them to judge when the subject has reached his maximum capacity for physical effort.

Criteria (C) and (D) have been developed specifically for patients with cardiorespiratory disease, and they will not be dealt with here. This paper will concern itself mainly with (A), but (B) will be dealt with briefly.

A. *Tests which are based upon the estimation of oxygen consumption at maximum heart rate from measurements of heart rate and oxygen consumption at one or more submaximal work rates.*

The procedure is to measure the individual's heart rate and oxygen consumption (or to estimate the latter from a "standard" oxygen consumption against a work-rate graph for the population) at one or more rates of work. Heart rate is then plotted against oxygen consumption. A straight line is fitted to the plots and it is extrapolated to the maximum heart rate for the population. The oxygen consumption which is equivalent to the maximum heart rate on the straight line fitted to heart rate against oxygen consumption is taken to be the individual's maximum oxygen intake. Certain modifications have been made to this basic procedure, such as the use of nomograms by Astrand and Margaria (instead of plotting the points and fitting a straight line), and the use of only one measured heart rate (by the Astrands, in their nomogram). The procedure is basically the same in all of these various methods.

(a) *Premises*

The estimate of an individual's maximum intake by this procedure rests upon certain premises which are:

1. That, except for random variations, heart rate and oxygen consumption are, to a close degree of approximation, linear functions of the rate of work.

2. That heart rate and oxygen consumption reach asymptotic maximum values at a common, high level of work.

3. That if (1) and (2) are correct, then heart rate is a linear function of oxygen consumption throughout the entire range of work rates up to the individual's maximum.

4. That the inter-individual variation of heart rate about the population mean is sufficiently small for the population mean heart rate to be used in the above procedure without introducing large errors.

Maritz *et al.*[12] studied a number of subjects in great detail and showed that premise (1) is correct but that premise (2) is not, in that heart rate reaches its maximum value at slightly lower work rates than does oxygen consumption. Accordingly, premise (3) is not fulfilled in that heart rate is *not* a linear function of oxygen consumption throughout the range of work rate up to the individual's maximum. However, the departure from linearity is small; it introduces a bias in the estimate of maximum oxygen in-

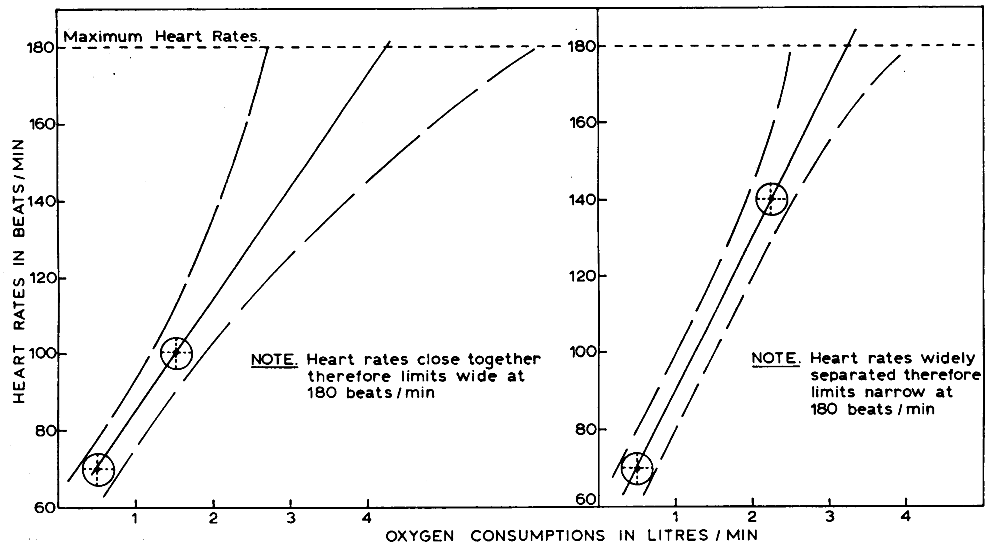

Fig. 1.—Straight line, with 95% confidence limits, fitted to plots of heart rates against oxygen consumptions—illustrating the need to have heart rates widely separated.

take towards values which are about 0.3 l./min lower than direct measurements. Premise (4) is fulfilled in that the coefficient of variation of the population mean heart rate is small—of the order of 5%.

(b) *Errors in the Estimate*

1. *Individual variations in heart rate and oxygen consumption*

Repeated measurements of heart rate and oxygen consumption at various rates of work were made on different days over a period of some months, using a number of subjects. It was therefore possible to calculate intra-individual coefficients of variation for these measurements. Those for oxygen consumption were of the order of 5%, and were similar at the various rates of work. The variability in heart rates was much greater, the "average" coefficient of variation being in the order of 10%.

These intra-individual variations have an important effect on the accuracy with which the maximum oxygen intake can be estimated. A pair of heart rate and oxygen consumption measurements made on a particular day can lie anywhere within an oxygen consumption-heart rate ellipse which encloses the variances of these two measurements. The individual's true heart rate-oxygen consumption value for the particular rate of work must lie in the centre of the ellipse, and can only be estimated from a number of measurements at that work rate.

This phenomenon affects the relative accuracy of procedures for estimating the maximum oxygen intake from a single measurement of heart rate and oxygen consumption at either one, or two, or four rates of work. In the Astrands' procedure, a "common" heart rate of 60 beats/min is joined (by means of the nomogram) to the single heart rate-oxygen consumption point. This point may lie anywhere in the heart rate — oxygen consumption ellipse. The error in use of the nomogram is decreased if the heart rate is ~160 beats/min rather than ~120 beats/min. Irma Astrand[2] in her 1960 paper acknowledges this fact.

It will also be clear from this example that Margaria's procedure[13] of measuring heart rates at two work loads, giving heart rates of 100 and 150 beats/min, is an improvement on the Astrands' method. However, from a statistical viewpoint, fitting a line to only two observations is suspect, because the chances are quite high that the two pairs of observations can be biased compared with the true heart rate — oxygen consumption points. It is for this reason that Maritz *et al.*[12] advocated the use of four pairs of heart rate and oxygen consumption measurements. The chances of the resulting line being biased compared with the individual's true line are much smaller statistically than when only one or two pairs of observations are used.

Wyndham *et al.*[17] showed that accurate estimations of the maximum oxygen intake could only be obtained if the four pairs of measurements were spread over a wide range of heart rate, and if the highest heart rate lay between 140 and 160 beats/min. This point is also made by Margaria.[13] Wyndham *et al.* showed in the paper quoted above that straight lines fitted visually, by trained observers, give as good an estimate of maximum oxygen intake as straight lines fitted by the least-squares technique. This contradicted the point they had earlier made in this regard.

2. *Inter-individual differences in maximum heart rate*

The inter-individual variation about the population mean heart rate is relatively small. The Astrands give a coefficient of variation of about ~1% at the minimum heart rate; the figure of Wyndham *et al.* is ~5% in a population that was less homogeneous from the point of view of the men's physical fitness. This means that if the population mean heart rate is 190 beats/min, only about 5% of the sample will lie outside the range 170 to 210 beats/min. In individuals with a high maximum oxygen intake, say 4.0 l./min, taking a population mean heart rate of 190 would overestimate the maximum oxygen intake of the man with a true maximum of 180 beats/min by about 0.3 l./min and underestimate the man with a true maximum of 200 beats/min by about the same amount.

Irma Astrand[2] draws attention to the greater accuracy of the estimate of maximum oxygen intake when the individual's actual maximum heart rate is known. Williams *et al.* (unpublished observation) showed recently that the error in the determination can be reduced by about 2% when the extrapolation is to the individual's own maximum rather than to the population mean.

3. *Estimation of oxygen consumption from population oxygen consumption against work-rate graph*

The Astrands' nomogram and Margaria's nomogram are based upon the estimation of oxygen consumption (or metabolism in Margaria's case) from the rate of work of the individual (calculated from body weight and rate of stepping, or directly measured when the bicycle ergometer is used).

The Astrands claim that the coefficient of variation in oxygen consumption estimated in this way is of the order of 6%. The figure of Maritz *et al.*[12] is of the same order. However, it needs to be borne in mind that individual variations in oxygen consumption are not randomly distributed about the population mean straight line. Examination of straight lines fitted to each individual's data shows that some individuals are consistently above and some below the population line (an indication of their relative mechanical efficiency). Estimates based on the population mean oxygen consumption against work-rate graph will thus be biased upwards for some individuals and downwards for others.

(c) *"Overall" error in the estimation of maximum oxygen intake*

Maritz *et al.*[12] made an assessment of the random error associated with the estimation of maximum oxygen intake which took account of the various sources of error discussed above. Their estimate was that based on an overall standard deviation, the coefficient of variation in estimated maximum oxygen intake by the above procedure amounting to about 12%. If the oxygen consumptions at the four rates of work were measured instead of being estimated, the coefficient of variation was reduced to about 8%.

(d) *Comparison between maximum oxygen intakes as measured by the submaximal test and by the direct method*

Much has been made of the fact that mean maximum oxygen intakes measured by the submaximal test and by the direct method have not been found to be significantly different, and that the corresponding correlation coefficients have been high. For example, the Astrands give figures for the differences between estimated and determined mean values on 27 males and 31 females at half-maximum oxygen intakes of 0.023 ± 0.059 l./min oxygen consumption. Glassford *et al.*[5] quote correlation coefficients between the Astrands' step test and a direct treadmill method of 0.78, with mean values of 3.714 ± 0.837 and 3.758 ± 0.327 l./min, respectively. Kasch *et al.*[9] show a correlation coefficient of 0.95 between treadmill and step-test maximum oxygen intakes.

Analyses of this type have very little value because they do not give any idea of the possible bias over the whole range of estimated values. Moreover, correlation coefficients should not be calculated between measurements which are both subject to random variation.

The method of choice is to fit regression equations to the plots of one variable against another and to calculate probability limits for this regression line.

Wyndham *et al.*[18] published the results of a comparison between maximum oxygen intakes, as estimated from four submaximal rates of work (obtained by stepping on and off a stool, one foot in height at different rates) and as measured directly on a treadmill. The maximum oxygen intake of the subjects (40 army recruits) was 3.18 ± 0.75 l./min on the step test, and 3.21 ± 0.40 l./min on the treadmill.

A truer idea of differences between the values from the two tests is contained in Fig. 2. Here the regression line between the estimate from the submaximal test and the directly measured

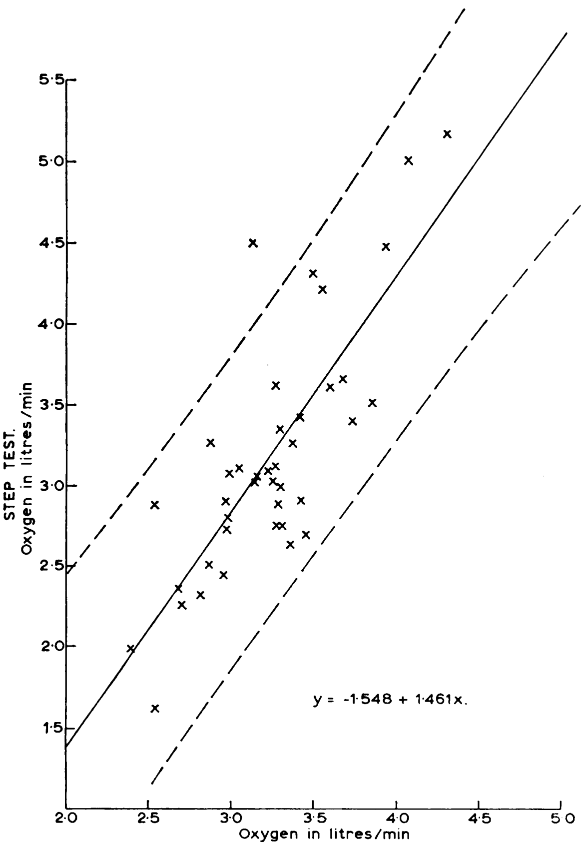

Fig. 2.—Regression line of maximum oxygen intake. Step test against intermittent treadmill test.

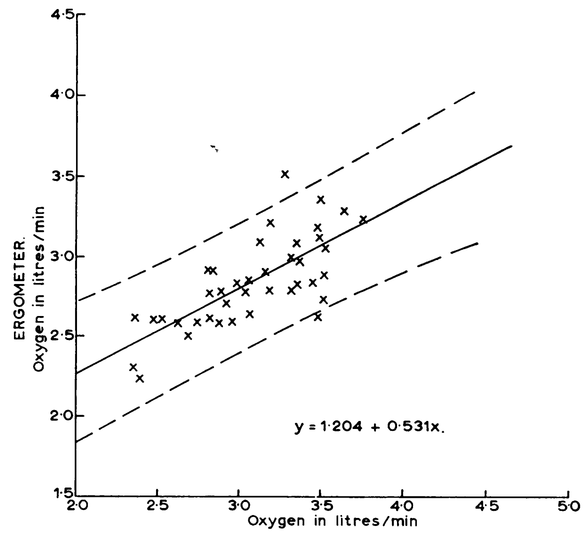

Fig. 3.—Regression line of maximum oxygen intake. Ergometer test against intermittent treadmill test.

values is given. This brings out the fact that when treadmill test values are low, the maximum oxygen intakes estimated from the submaximal test are lower than the treadmill values, and that when treadmill values are high the reverse is true. However, the differences are not significant even at the extremes. This figure also indicates the relatively wide scatter of observations. The limits are such that one can state that there is a 0.95 probability that the step-test values will lie within ± 0.95 l./min of an observed treadmill value. Irma Astrand[2] calculated that for a true maximum oxygen intake of 3.0 l., two or three in 100 individuals would have predicted maximum oxygen intakes which lay above 4.0 or below 2.0 l./min. There would thus appear to be agreement between Irma Astrand's conclusions and ours in this regard.

It is of interest to examine the comparison between maximum oxygen intakes determined directly on the treadmill and those also measured directly on a bicycle ergometer.[18] Maximum oxygen intakes determined on the bicycle ergometer are plotted against those on the treadmill together with the regression line and the 95% confidence limits (Fig. 3). There is a considerable and significant bias between the two values at the higher range of treadmill values; at a treadmill value of 2.5 l./min, the ergometer value is about the same, but at a treadmill value of 4.0, the bicycle ergometer value is only 3.2 l./min, and is significantly lower.* In our view, this is due to the muscle pain which subjects experience in their thighs at high work rates; this limits the maximum effort they will tolerate. Glassford *et al.*[5] came to the same conclusion. The limits are much narrower than in Fig. 2, so that one can say that the 0.95 probability is that the ergometer value will lie within ± 0.4 l./min of the observed treadmill value.

From these comparisons, the conclusion is that the submaximal test gives results which compare favourably with those on the treadmill; however, it is relatively a more crude assessment, as judged by the fact that the 0.95 probability limits are relatively wide.

B. *Estimates of maximum oxygen intake based upon successive increments in work rate until a heart rate of 170 to 180 beats/min is reached*

Sjöstrand[15] can claim to be one of the first to put this particular procedure on a systematic basis in his study of iron-ore-smelting workmen. The men pedalled a Krogh bicycle ergometer at 300, 600, 900 and, in some cases, 1200 kgm/min. At the first three loads the time of pedalling was 10 minutes, but this was reduced to six minutes

*Editor's note: The form of relationship described seems due in part to the choice of dependent variable. If the treadmill test had been the dependent variable, it is possible that the calculated regression would have shown a higher oxygen intake for the ergometer than the treadmill for subjects with large intakes, and the reverse for those with low intakes.

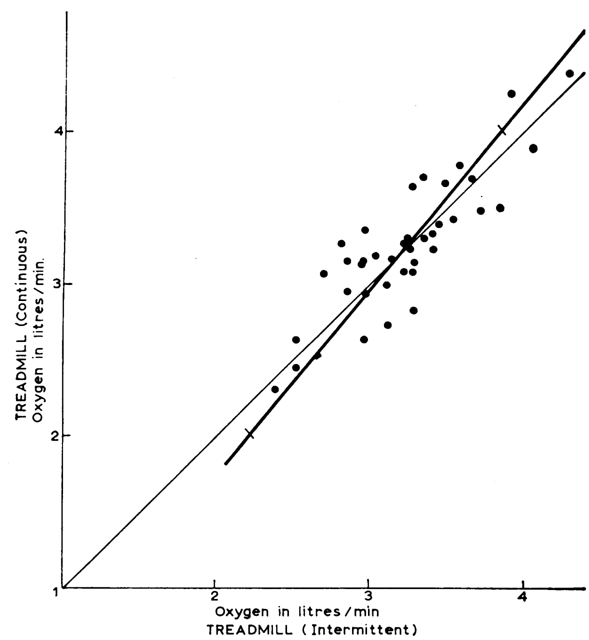

Fig. 4.—Regression line of maximum oxygen intake. Treadmill continuous against treadmill intermittent.

and even four minutes at the highest loads. The criterion for judging the maximum level was "when respiratory and circulatory organs can no longer adapt themselves to the energy consumption of the organism . . . the critical pulse level for adults will be about 180 beats/min."

Many modifications have been made to this test, but they do not differ in principle. There does not appear to have been a really satisfactory comparison between one of the accepted direct methods of determining maximum oxygen intake, on either a treadmill or a bicycle ergometer, and maximum oxygen intake as assessed from the work rate at a pulse of 170 to 180 beats/min. With this point in mind, Wyndham *et al.*[18] carried out a study of 40 army recruits in which maximum oxygen intakes were assessed by an intermittent treadmill test (the men being allowed to rest between successive runs at increasing speeds on the treadmill) and also by a continuous, treadmill procedure in which the level speed was increased by 0.5 mph every three minutes, and oxygen consumptions and heart rates were measured at every whole number mph. The results are given in Fig. 4, in which it can be seen that the regression does not differ significantly from the 45° line. However, the mean heart rate in the continuous treadmill procedure was 196 beats/min. It is clear therefore that any procedure which is based upon an arbitrary maximum heart rate of 180 or 170 beats/min will underestimate the true maximum oxygen intake of most individuals in the young age group at sea level.

C. *Estimates of maximum oxygen intake based upon an increase in RQ*

Issekutz, Birkhead and Rodahl[8] proposed a method whereby maximum oxygen intake is predicted from the respiratory quotient. According to their findings, the increase in carbon dioxide output relative to oxygen intake is the result of accumulation of lactic acid, with a decrease of the body bicarbonate pool. Taking a metabolic RQ of 0.75 as a reference value, the amount of excess "non-metabolic" carbon dioxide was calculated (work RQ *minus* 0.75, described as △ RQ). It was found that △ RQ increased logarithmically with increase in work load, and that a △ RQ of 0.4 corresponded with the individual's maximum oxygen intake.

The method consisted of pedalling at three or four submaximal work loads. The RQ was measured and plotted on a work rate/△ RQ graph. A straight line was fitted to the points, and was extrapolated to a △ RQ value of 0.4. The maximum oxygen intake was then obtained from a standard work-load/oxygen-intake graph.

The mean difference between the predicted oxygen intake and values obtained by direct measurement was 0.002 ± 0.016 l./min with a standard deviation of ± 0.089.

The criteria used to decide whether the maximum oxygen intake of a subject had been reached were as follows:

(a) Increase in work load by 150 kpm/min did not increase oxygen intake more than 100 ml./min.

(b) The measured oxygen intake, at a given maximal work load, was below the expected value by 150 ml./min or more.

(c) The pulse rate reached the maximum value for the corresponding age group.

(d) The RQ measured after 3½-4 minutes of exercise should be 1.15 or higher.

(e) The blood lactic-acid level had to increase by at least 60 mg. % above the pre-exercise level.

At least four of the above-mentioned requirements had to be fulfilled before a measured oxygen intake was accepted as the maximum level.

There is no doubt that Issekutz's basic concepts are sound. The increase in RQ above 1.0 is a clear indication that the individual is employing anaerobic metabolism to a high degree. However, what is not proved to everyone's satisfaction is whether an RQ of 1.15 is in fact present when subjects have reached their maximum oxygen intakes. Looking back on our data, the RQ's show quite a wide variation, from just below 1.00 to well above Issekutz's level of 1.15. It seems clear that a more extensive study of

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RQ's is needed in which the relationship between blood lactic- and pyruvic-acid changes, acid-base balance and changes in RQ will be examined up to maximum levels of effort.

CONCLUSIONS

The following conclusions can be drawn:

(a) A reliable but crude estimate of an individual's maximum oxygen intake can be obtained from a submaximal test, provided the following precautions are taken:

1. Four different submaximal work rates are used.
2. Heart rates at the different work rates cover the range 100 to 160 beats/min.
3. Oxygen consumptions are measured rather than estimated from a work-rate/oxygen-consumption graph.
4. Heart rates and oxygen consumptions are not measured before the tenth minute of exercise at each level of effort.
5. A good mean maximum heart rate is obtained for the population group in question, bearing in mind that age and altitude both affect the maximum.

(b) An underestimate of the individual's maximum oxygen intake will certainly be made in a test in which work rate is increased progressively until a heart rate of 170 to 180 beats/min is reached. Moreover, such a test is very strenuous, and hardly falls into the category of submaximal test procedures.

(c) The test of maximum oxygen intake based upon an increase in RQ to 1.15 appears conceptually sound. However, more information is required on the variance of RQ at different levels of exercise, and of the relationships between RQ's, the state of anaerobic metabolism and the acid-base balance of the body.

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Commentaries

Commentary: P.-O. ÅSTRAND, *Stockholm, Sweden*

I SHALL make some further comments on our nomogram.[1,2] It is of empirical origin. We had a pile of data from submaximal and maximal exercise tests, and were curious to see how a prediction of the maximal oxygen uptake would turn out. It is based on studies of fairly well-trained young adults, and its accuracy is best in such subjects, with a standard deviation (S.D.) of 10% or even less. There is a tendency for the maximal oxygen intake of the untrained to be underestimated,[3] and that of the well-trained to be overestimated. It is not practical to have different nomograms for different groups of subjects. The nomogram, like most submaximal tests, is based on a more or less linear increase in heart rate with work load and oxygen uptake. Since the maximal heart rate gradually drops with age, an "age factor" must be applied, stopping extrapolation at lower levels.[2] In a recent study (Astrand, I., Bergström and von Döbeln, to be published) of 84 building workers, 30 to 70 years of age, the measured maximal oxygen uptake was 2.67 l./min, and the predicted one 2.52 l./min with a S.D. of about 12%. With a mathematical analytical method, using age and submaximal heart rate at a certain load, a new age factor could be calculated, reducing the difference between predicted and measured maximal $\dot{V}_{O_2}$ to zero and the S.D. to 8%. However, the small difference, less than 6% relative to the original nomogram, hardly justifies the introduction of a new age factor until it has been tried on different subjects and under different conditions. (Compare the difference between bicycle ergometer and treadmill tests, p. 732.)

In fact, good agreement has been reported between measured maximal aerobic power