THE PREDICTION OF MAXIMUM OXYGEN UPTAKE (AEROBIC CAPACITY) WITH SPECIAL REFERENCE TO RADIOLOGICAL HEART AREA AND THORACIC AREA

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The performance of work in man is accompanied by readjustment of circulatory and respiratory systems of the body to meet the demands of the active tissues for more oxygen. The greater metabolic demands of the body at submaximal work can be met mainly by increased oxygen uptake. With increasing loads there is a steady increase in oxygen uptake as well as a slow rise in the blood lactate concentration, indicating that anaerobic metabolism is contributing increasingly to the total energy output.[1-6] A point is reached, with further increase in work, where no more oxygen can be taken up. There is a sharp rise in blood lactate at this level, indicating that metabolism is mainly anaerobic. Higher levels of work cannot be sustained for long periods, for exhaustion sets in within a short time. On this basis Åstrand[7] and Taylor *et al.*[8] have defined maximum oxygen uptake as that level of oxygen consumption at which further increase in effort is not associated with any significant additional oxygen uptake.

The relationship of pulse rate and oxygen uptake to work load has been well established since the beginning of this century. Numerous workers[7, 9-16] established the linear relationship of oxygen consumption and pulse rate when exercise was performed in a 'steady state'. At maximal work loads pulse rates of between 170 and 200 beats/min. were noted.[17-20] The average maximum pulse rate at maximum effort was shown to be between 180 and 190 beats/min.[21]

The correlation of pulse rate with oxygen uptake during exercise has been found to be high. Erickson *et al.*[22] found a correlation coefficient of 0·97 between oxygen consumption and pulse rate at work on a treadmill. Taylor[23] observed a similar correlation between pulse rate and work load.

The direct measurement of an individual's maximum work capacity as proposed by Åstrand[7] and Taylor *et al.*[8] has not been found practicable for large-scale testing. In this procedure measurements of pulse rate and oxygen uptake are performed at increasing work loads until an increase in work load is no longer associated with an increase in oxygen uptake. This grade of exercise represents the individual's maximal capacity. A number of testing procedures have been proposed with the object of obviating the direct measurement of maximum oxygen uptake. Wahlund[16] proposed a standardized work test using a bicycle ergometer. The pulse rate was measured with increasing submaximal work loads. Maximal work capacity was estimated from the pulse rate / work load relationship extrapolated to a pulse rate maximum of 170 beats/min. Åstrand and Ryhming[24] presented a nomogram whereby an individual's maximal oxygen uptake (aerobic capacity) could be calculated from heart rate and oxygen intake (or work level) reached during a single submaximal rate of work. By using their nomogram they found a standard deviation of less than 7% between measured maximal oxygen uptake and estimated oxygen uptake, and stressed the necessity for choosing a relatively high work load which would engage large groups of muscles in work. Maritz *et al.*[25] subsequently proposed that pulse rates at 4 work loads should be utilized. Oxygen intake was estimated from a 'standard' graph relating oxygen intake to the rate of work. Pairs of oxygen-intake and heart-rate values for the various rates of work were plotted on a heart rate / oxygen intake 'grid'. A straight line was fitted and extrapolated to the maximum heart rate. The corresponding oxygen intake value was an estimate of the subject's maximum oxygen intake. The standard deviation of the maximum oxygen uptake measured by this method was 0·51 litres as compared with 0·73 litres as found by Åstrand and Ryhming.[24]

The methods of estimating maximal oxygen uptake, as outlined above, are of great value in large-scale testing of normal subjects. If, however, the aim of the study is a more thorough analysis of physical fitness, and comparisons are to be made with other subjects, it is preferable to actually measure the oxygen uptake.[26]

It has been customary to relate the maximum oxygen uptake to age, height, weight, and body surface area, although Buskirk and Taylor[27] found it extremely well correlated with lean body mass. Åstrand[7] and Sjöstrand[28] studied the correlations between maximal oxygen uptake, blood volume, and total haemoglobin. This was found to be higher for total haemoglobin ($r=0·98$ in Åstrand's series). In this study an attempt was made to base the prediction of maximum oxygen uptake on radiological heart area and thoracic area. In normal subjects thoracic area was taken to represent lung area, although this may not apply where the heart is enlarged. Such a relationship would be of practical value in that many cardio-respiratory diseases produce enlargement of the heart and lungs. These diseases, however, reduce the maximum oxygen uptake. In the present study on normal subjects it was found that the size of the heart and thorax was directly related to the estimated maximum oxygen uptake. Others have shown such a relationship for the heart.[29, 30] Normal subjects with a large thorax and heart had a higher maximum oxygen uptake than subjects with a smaller thorax and heart. In cardiac and respiratory disease the reverse holds true, and such dissimilarities would accentuate the differences between normality and disease that would not be apparent when maximum oxygen uptake is related to height, weight, and body surface area.

MATERIAL AND METHODS

The *subjects* on whom tests were performed were males presenting themselves for an initial medical examination at the Miners' Medical Bureau, Johannesburg, with a view to obtaining employment on the Witwatersrand and Orange Free State mines (Government health certificate). They were chosen from the first available applicants each day, and were unfamiliar with the testing procedure. An initial group (A) consisted of 81 subjects who were exercised at 4 submaximal work loads, viz. 200, 300, 400 and 500 kg.-m./min., pulse rates, oxygen consumption and ventilation being measured during the last 2 minutes of each work load. A second group (B) of 481 subjects were tested in sub-groups; the testing procedure was identical to that used for group A except that pulse rate only was measured at each submaximal work load. The 2 groups were essentially similar in regard to age, height, and weight (Table I).

TABLE I. PHYSICAL CHARACTERISTICS OF TEST SUBJECTS

	Group A *81 subjects*	*Group B* *481 subjects*
Mean age (years)	26·1	24·77
Standard deviation	8·7	8·02
Coefficient of variation percentage	33·4	32·4
Range	16–47	15·5–61·5
Mean height (centimetres) ..	175·5	176·35
Standard deviation	6·4	6·32
Coefficient of variation percentage	3·7	3·6
Range	155·5–193·5	155·5–197·5
Mean weight (kilograms)	69·6	71·45
Standard deviation	8·5	9·33
Coefficient of variation percentage	12·2	13·1
Range	49·5–106·5	51·5–105·5

The *methods* used were similar to those described by Maritz *et al.*,[25] who used 4 substandard work loads. The principles involved, however, were no different from those established by other workers.[7-24]

The subjects were required to step up and down from a platform while steadying themselves by holding on to a steel bar in front of them. They were previously instructed merely to use the bar to steady themselves and not to use it for assistance in stepping up and down. The platform consisted of a series of flat boards of varying thickness to allow the step height to be adjusted in conformity with the work load, the subject's weight, and the stepping rate. Step height was calculated from the formula:

$$\text{step height (metres)} = \frac{\text{work load (kg.-m./min.)}}{\text{steps/min.} \times \text{body weight (kg.)}}$$

After preliminary investigations stepping rates of 9, 13·5, 18 and 22·5 steps per minute (for the 4 work loads) were chosen for subjects weighing between 125 lb. (57 kg.) and 200 lb. (91 kg.); 7, 10·5, 14 and 17·5 for those weighing more than 200 lb. (91 kg.); and 11, 16·5, 22 and 27·5 for those weighing less than 125 lb. (57 kg.)

Each subject's resting pulse rate was recorded before the test began, and he was weighed and measured without shoes and shirt. Three ECG electrodes were attached to the upper chest and led to a standard Sanborn electrocardiograph.* A noseclip was applied and the subject placed the mouthpiece of the tubing leading to the oxygen meter and flow meter in position. The rate of stepping was controlled by a metronome, which rang on every fourth beat to indicate the completion of one full step of each test. Subjects were allowed a short training period before the test where oxygen consumption was to be measured. The subjects were exercised for 15 minutes for each work load, at which time a 'steady state' was assumed to have occurred. The tests were carried out at an altitude of 5,760 ft. above sea level. Oxygen uptake and ventilation were measured during the last 2 minutes of each exercise. Pulse rate was recorded during the last half minute of each exercise. The mouthpiece was attached to a low-resistance 2-way valve,[31] from which expired air was led along wire-supported tubing with an inner bore of 35 mm. to a mixing chamber of 4-litre capacity fitted with wet-and-dry-bulb thermometers. A sampling tube led from this chamber to a Beckman F_3 Oxygen Analyzer,† and expired air was withdrawn by means of a small suction pump from the mixing chamber at a rate of 165 ml./min. A DC amplifier and Sanborn oscillograph were used for the recording of the oxygen consumption. The time lag of this system was 3·6 seconds, for which suitable correction was made in the calculations. The remainder of the expired air passed through a previously calibrated Parkinson and Cowan‡ flow meter. The linear oxygen meter was calibrated daily, room air and a 15% oxygen mixture being used as a reference gas. The results for oxygen uptake were converted to STPD, while those for ventilation were expressed at **BTPS.**

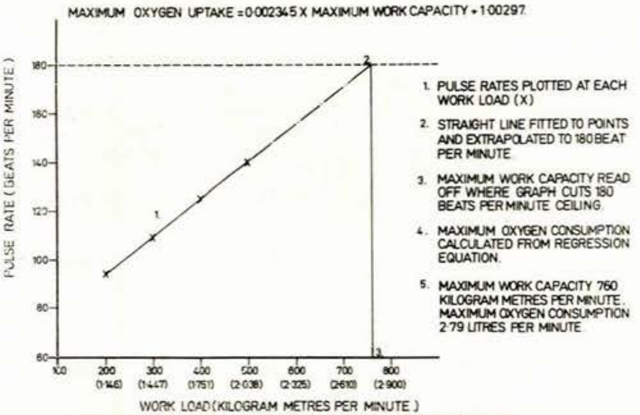

Fig. 1. The estimation of maximum oxygen uptake from pulse rates at 4 submaximal work loads.

Pulse rate at varying work loads bears a linear relationship to the work load and maximum oxygen uptake. The pulse rate at the 4 submaximal work loads are extrapolated to an arbitrary maximum pulse rate of 180 beats/min., and the maximum oxygen uptake (litres STPD) and the maximum work capacity (kg.-m./min.) can be read off as shown in the diagram. In this example the pulse rates at 200, 300, 400 and 500 kg.-m./min. work were 94, 108, 127 and 140 beats/min. The maximum oxygen uptake is 2·79 litres STPD, and the maximum work 760 kg.-m./min.

Where both pulse rate and oxygen uptake were available at the various submaximal work loads it was possible to extrapolate the pulse rate to an arbitrary upper limit of 180 beats/min., to obtain the oxygen uptake that would be expected at this pulse rate. Such a procedure is justified because of the linear relationship of pulse rate and oxygen uptake with exercise in the steady state, up to maximal work capacity (Fig. 1). Pulse rate and oxygen uptake are also linearly related with the work load. It is possible to extrapolate the pulse rates at submaximal work loads to 180 beats/min., and so obtain an estimate of a subject's maximum work load capacity.

In group B, in whom only the pulse rate had been measured at the various submaximal work loads, maximum oxygen consumption was predicted as follows:

> Maximum oxygen uptake was highly correlated with maximum work capacity in group A ($r=0{\cdot}9$) and could be represented by a regression equation, where

Maximum oxygen uptake (litres STPD)=
0·002345 × maximum work capacity (kg.-m./min) + 1·00297

Maximum work capacity was calculated from the heart rates (h) at the various work loads (w) by the following formula, where each work load from 200 to 500 kg.-m./min. is represented by a subscript 1, 2, 3 and 4 respectively:

$$\text{Maximum work load} = \left[\frac{w_4+w_3-w_2-w_1}{2}\right]\times\left[\frac{360-h_2-h_1}{h_4+h_3-h_2-h_1}\right]+\left[\frac{w_2+w_1}{2}\right]$$

$$= 200\left[\frac{360-h_2-h_1}{h_4+h_3-h_2-h_1}\right]+250$$

Such a calculation could be obviated by using graphical methods (Fig. 1).

In the initial group (A) teleroentgenograms of the chest had been taken in 68 of 81 subjects, and in 48 of these the pulse rate, oxygen uptake, and ventilation had been measured at all 4 submaximal work loads. In 20 of the 68 subjects the pulse rate or oxygen uptake was not available at one or other work load. In the second group examined (B) teleroentgenograms of the chest were available in 384 of the 481 subjects.

Thoracic area and heart area were estimated from standard inspiratory postero-anterior teleroentgenogram films. Both the thoracic area and the heart area were measured planimetrically, after the outlines of the heart had been drawn in to make this resemble an ellipse according to conventions previously described by Van Zwaluwenberg and Warren,[32] Ungerleider and Gubner,[33] and Ludwig.[34] These areas were found to be highly correlated with a calculation of the area based on the product of the length (height in the case of the thorax) and breadth of the thorax and heart (correlation coefficient $r=0{\cdot}94$ for the thorax and $r=0{\cdot}94$ for the heart). In order to make these measurements comparable it was necessary to introduce a factor that was obtained by dividing the planimetric area by the length or height times breadth area. The final formulae used to measure these areas were:

thoracic area (sq. cm.) $= 0{\cdot}856 \times H \times B \pm 29{\cdot}0$ and
heart area (sq. cm.) $= 0{\cdot}774 \times L \times B \pm 5{\cdot}2$
where H is the height of the thorax, L is the length of the heart and B is the breadth of the thorax or the heart.

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†Beckman Co., Spinco Division, Stanford Industrial Park, Palo Alto, California, USA.

‡Parkinson & Cowan Industrial Products, Cottage Lane, City Road, London, E.C.1, England.

The longest diameter (L) of the heart was measured from the junction of the right auricle and superior vena cava to the apex. The broad diameter (B) was measured as the greatest diameter of the heart shadow at right-angles to the long diameter of the heart. In the determination of frontal thoracic area, the height of the lung (H) was measured from the highest point within the concavity of the first rib to the midpoint between a horizontal line connecting both costodiaphragmatic recesses and the right cardiophrenic angle. The broad diameter of the thorax (B) was measured between the widest points on the inner aspect of the ribs, and varied in position in relation to the conformity of the thoracic cage in each subject.

RESULTS

From the knowledge that the pulse rate / oxygen uptakes during work are highly correlated it was logical to assume that the maximum oxygen uptake predicted by linear extrapolation of observed pulse rates and oxygen uptakes, at the 4 submaximal work loads, was a reasonably close determination of the actual maximal aerobic capacity.

It was possible to predict maximal oxygen uptake from body weight with a fair degree of accuracy (r=0·399). A significant improvement in the prediction was obtained from a combination of body weight, heart area, and thoracic area (r=0·500). A considerable improvement in the prediction of maximal oxygen uptake was evident when the pulse rate at 500 kg.-m./min. was used (r=0·783). Although a correlation coefficient of r=0·804 was obtained when the pulse at 500 kg.-m./min. was combined with heart area and thoracic area, this was not shown to be significantly different from the pulse rate at 500 kg.-m./min. alone. No significant improvement in the prediction of maximum oxygen uptake resulted by including body weight in these latter correlations (Table II).

From the point of view of predictive value it is important to consider the scatter of the results around the respective regression lines. In comparison with body weight alone, heart area, thoracic area and weight reduced the scatter by 6%, the pulse at 500 kg.-m./min. reduced the scatter by 32%, while the addition of heart area and thoracic area to the pulse at 500 kg.-m./min. reduced the scatter by 35%.

The relationship between maximum oxygen uptake, heart area, thoracic area, weight, and age, was higher in the group A, in whom oxygen uptake and pulse had been measured at the 4 submaximal work loads, than it was in group B, in whom only pulse rates had been so measured (Table III). A multiple regression equation including heart area, thoracic area and weight was significantly related to maximum oxygen uptake in group A, whereas no significant relationship was found in group B when the maximum oxygen uptake was predicted from the pulse rate alone (Table II).

DISCUSSION

The prediction of maximum oxygen uptake from submaximal work loads performed at a steady state allows an important parameter of physical capacity to be measured with relative ease. The subject's maximal capacity for effort is determined by his maximum oxygen uptake, and to avoid fatigue it has been estimated that he should not exceed half of this during a day's work.[7] It follows that this measurement can be used for purposes of com-

TABLE II. REGRESSION EQUATION FOR THE PREDICTION OF MAXIMUM OXYGEN UPTAKE, USING BODY WEIGHT, HEART AREA, THORACIC AREA, AND PULSE RATE AT 500 kg.-m./min. WORK LOAD AS PREDICTOR VARIABLES

	Number of cases	*Regression equations*	*Multiple correlation coefficient (r)*	*Conditional standard deviation*	*Range 1·96 × standard deviation l./min.*
Body weight	68	Predicted max. 0_2 uptake = 0·0247 W + 1·0096	0·399	0·515	1·010
Heart area (HA), thoracic area (TA) and body weight (BW)	68	Predicted max. 0_2 uptake = 0·0078 HA + 0·0015 TA + 0·0138 BW — 0·1920	0·500	0·486	0·954
Pulse rate (PR) at 500 kg.-m./min.	68	Predicted max. 0_2 uptake = 6·6526 — 0·0252 PR	0·783	0·349	0·685
Pulse rate at 500 kg.-m./min. (PR), heart area (HA) and thoracic area (TA)		Predicted max. 0_2 uptake = 5·2310 — 0·0230 PR + 0·002 HA + 0·0012 TA	0·804	0·334	0·655

TABLE III. A COMPARISON OF THE CORRELATION COEFFICIENTS BETWEEN MAXIMUM OXYGEN UPTAKE, HEART AREA, THORACIC AREA, WEIGHT, PULSE AT 500 kg.-m./min., AND AGE, IN (1) GROUP A AND (2) GROUP B

	Maximum oxygen uptake		*Heart area*		*Thoracic area*		*Weight*		*Pulse at 500 kg.-m./min.*		*Age*	
	A	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*
Maximum oxygen uptake	1·000	1·000	0·414*	0·241*	0·407*	0·154*	—0·399*	0·398*	—0·783*	—	—	—0·034
Heart area	0·414*	0·241*	1·000	1·000	0·586*	0·327*	0·448*	0·363*	—0·377*	—	—	0·098†
Thoracic area	0·407*	0·154*	0·586*	0·327*	1·000	1·000	0·450*	0·231*	—0·306*	—	—	0·003
Weight	0·399*	0·398*	0·448*	0·363*	0·450*	0·231*	1·000	1·000	—0·430*	—	—	0·270*
Pulse at 500 kg.-m./min.	—0·783*	—	—0·377*	—	—0·306*	—	—0·430*	—	1·000	—	—	—
Age	—	—0·034	—	0·098†	—	0·003	—	0·270*	—	—	—	1·000

In group A both pulse rate and oxygen were measured at each substandard work load, while in group B only the pulse rates were measured. The relationship between these variables is much higher in group A than in group B.
*Significant at the 1% level.
†Significant at the 5% level.

pensation when disability is claimed, and allows a patient to be placed in an occupation that will not exceed his physical resources. It is equally applicable to the selection of subjects for training in various types of athletics and in recruitment for military purposes or hard manual labour.

Maritz *et al.*[25] have shown that the prediction of maximal oxygen uptake from the results obtained at 4 submaximal work loads is superior to that from the method suggested by Åstrand and Ryhming,[24] who used only one substandard work load. The standard deviation of maximum oxygen uptake of a test subject when the method of Åstrand and Ryhming[24] was used, was 0·73 as compared with a 0·51 standard deviation when the method of Maritz *et al.*[25] was used.

The performance of exercise at a number of work loads is time-consuming, for each exercise has to be continued long enough to achieve a steady state. As such the single-load method of Åstrand and Ryhming[24] has the merit of simplicity and less expenditure of time. In the present study a single work at 500 kg.-m./min. showed a significant correlation ($r=0{\cdot}783$) with the maximum oxygen uptake predicted from 4 submaximal work loads. A similar correlation coefficient ($r=0{\cdot}718$) was found between the predicted and actual maximal oxygen uptake by Åstrand and Ryhming[24] when the prediction was based on pulse rate and one work load. Where time is an important consideration it is possible to use a single work load. The pulse rate obtained at a work load of 500 kg.-m./min. can be substituted in the formula obtained in this study, viz. predicted maximal oxygen uptake $=6{\cdot}6526-0{\cdot}0252\times$ pulse at 500 kg.-m./min. work, and a reasonable estimate of the maximal oxygen uptake can be derived.

In order to simplify the testing procedure still further it is tempting to measure only the pulse rates at the 4 substandard work loads, omitting the measurement of the oxygen uptake. In this instance the extrapolation of the pulse rates to 180 beats/min. allows a prediction of maximum oxygen uptake based on the average found for the group as a whole (Fig. 1). Pulse rate is linearly related to work load and oxygen uptake so that the work load corresponding to 180 beats/min. in any particular extrapolation will also correspond to an equivalent oxygen uptake at this grade of work. Such a procedure, however, may obscure relationships found to be valid where both pulse rate and oxygen uptakes are measured. The correlation coefficients between maximum oxygen uptake and weight, heart area, thoracic area, and pulse at 500 kg.-m./min. work, are all very much lower where only pulse rates have been measured (group B) than they are in group A, in whom both the pulse rate and the oxygen uptake have been measured (Table II). It follows that prediction of maximum oxygen uptake based on pulse rate measurements only will be inferior to those based on both oxygen uptake and pulse rate measurements. This was amply demonstrated by the fact that a multiple regression equation including heart area, thoracic area, and weight, showed a significant correlation with maximum oxygen uptake when both pulse and oxygen uptake had been measured but not when this was based on pulse rates alone.

The choice of a maximum pulse rate of 180 beats/min. is in itself a compromise in that this is an average and the pulse at maximum oxygen uptake may vary from 171 to 210 beats/min. in young men.[7] The use of an arbitrary rate of 180 beats/min. would overestimate the maximum oxygen uptake in those whose maximum is less than average, and would underestimate the maximum oxygen uptake in those whose maximum pulse rate exceeds this. A similar wide distribution is found in maximum oxygen uptake, with the result that the use of any 'average' figure for this conceals the true maximum oxygen uptake capacity of many subjects. It is understandable, then, that the use of pulse rate alone will impair the relationship between maximum oxygen uptake and the various predictor variables used in this and other studies.

It has been well established that physical characteristics are related to the maximum oxygen uptake.[7, 27, 28] Of these, weight is most frequently used in the prediction of maximum oxygen uptake. The correlation coefficient (r) between weight and maximum oxygen uptake varies between 0·28 and 0·63.[16, 27] However, Buskirk and Taylor[27] found a higher correlation ($r=0{\cdot}85$) between maximum oxygen uptake and lean body mass, and this obviously would be the ideal physical characteristic on which to base the prediction of maximum oxygen uptake. However, the estimation of lean body mass is beyond the capacity of the average laboratory and of necessity weight is the most popular reference.

In the present study it was found that radiological heart area and thoracic area were related to maximum oxygen uptake, and it appeared profitable to predict maximum oxygen uptake from these variables, for a number of reasons that are discussed below. Weight (w) alone showed a correlation coefficient (r) of 0·399 where the predicted maximum oxygen uptake $=0{\cdot}0247\ w+1{\cdot}0096\pm0{\cdot}515$ litres. With the inclusion of heart area (HA) and thoracic area (TA) the multiple correlation coefficient (r) was 0·50 where the predicted maximum oxygen uptake $=0{\cdot}0078\ \mathrm{HA}+0{\cdot}0015\ \mathrm{TA}+0{\cdot}0138\ w-0{\cdot}1920\pm0{\cdot}486$ litres. The inclusion of thoracic area and heart area, however, only reduced the scatter about the regression line by 6% as compared with the scatter about the regression line for weight (Table I).

The inclusion of the pulse rate at 500 kg.-m./min. exercise with heart area and thoracic area resulted in a multiple correlation coefficient (r) of 0·804 where the predicted maximum oxygen uptake $=5{\cdot}2310-0{\cdot}0230\ P_{500}+0{\cdot}0020\ \mathrm{HA}+0{\cdot}0012\ \mathrm{TA}\pm0{\cdot}334$ litres. The scatter about this regression line reduced the scatter by 35% as compared with that for weight, while the scatter about the regression for pulse rate at 500 kg.-m./min. was reduced by 32%. It was shown that the prediction based on the pulse at 500 kg.-m./min. work and that including thoracic area and heart area was not significantly different.

The inclusion of thoracic area and heart area with weight in the first instance, and with the pulse rate at 500 kg.-m./min. work in the second instance, did not improve the prediction of maximum oxygen uptake more than slightly. Based on the findings in normal subjects there would be little justification for their inclusion in the regression equations. In disease, however, both the lungs or the heart may increase in size, and this will be reflected in the radiological heart area and thoracic area. These same diseases can be associated with a reduction in the maximum oxygen uptake. However, the large size of the lungs or heart in disease would predict a large maximal oxygen uptake with the use of the regression equations established. The difference between the low maximal oxygen uptakes actually found with disease of the heart or lungs, and the high maximal oxygen uptakes predicted for these large organs, would accentuate the differences between disease and health. Radiological study of the chest is a statutory procedure in the Miners' Medical Bureau, Johannesburg, and does not incur additional expense or expenditure of time. With the availability of a chest X-ray, and for the reasons given above, it appears justifiable to use regression equations incorporating thoracic area and heart area for the prediction of maximum oxygen uptake.

A higher degree of correlation would almost certainly have been obtained if radiological thoracic volume and heart volume had been used instead of the areas. This follows from the fact that heart and thoracic volume is a true representation of the size of the organ, whereas area is only a 2-dimensional representation. In health, as will be discussed later, increased performance capacity is associated with increased size of an organ such as the heart. The significant correlation between maximum oxygen uptake and heart area and thoracic area found in the present study bears this out. However, in the present study this would have required the taking of lateral views of the chest, which is not a routine procedure of the Miners' Medical Bureau. It is well known that a thin chest will be associated with a narrow sagittal size of the heart and thorax, and *vice versa*. Both Kahlstorf[35] and Roesler[36] have noted that an increase in heart volume is often not accompanied by an increase in the frontal heart area, and that in left ventricular enlargement the increase in volume of the heart considerably exceeds the increase in frontal area. Ludwig,[34] however, noted a good correlation ($r=0{\cdot}72$) between heart area (rectangle) and heart volume.

A further difficulty may arise in the use of thoracic area when concomitant cardiac enlargement is present. In the present study thoracic area has been taken to represent lung area. When cardiac enlargement is present it is possible to overestimate lung area where this is judged from thoracic area. However, this is not of importance in normal subjects and in disease a true estimate of lung area could be obtained by subtracting heart area from thoracic area.

Considerable interest has been shown in the relationship of cardiac size and performance capacity.* Karvonen,[29] in a study on Finnish athletes, found the heart volume to average 970 cu.cm. in Olympic athletes, 904 in athletes taking part in national events, 831 in Army skiers, and 702 in policemen who acted as controls. Where body surface area (sq.m.) was taken into consideration the heart volume in the Olympic athletes was 540 cu.cm./sq.m., in National athletes 506, in the Army skiers 462, and in the policemen 367. Comparable results were obtained in women. The hearts of ski runners of both sexes was about 50% larger than that found in untrained controls. Similar results were presented by Mellerowicz,[30] and it can be concluded that the heart of athletes involved in physical endurance is larger than that of subjects not subjected to great physical demands.

It has been argued by some workers that the cardiac enlargement associated with endurance sports is the result of training rather than of the fact that an innately large heart predisposes a subject to a better performance capacity.[37] However, heart size is related to physical characteristics such as height, weight, and body surface area, and in some respects must be constitutionally determined. In addition, the present study has shown a relationship between maximum oxygen uptake and heart size, which is not likely to be related to training, in the sense that the subjects were an unselected group seeking employment. It would be a more accurate assessment of the problem to state that constitutional variables determine the size of the heart and the subject's innate potential for performance capacity. Undoubtedly the potential can be improved by training, but the extent to which this can be improved will be limited by the innate size of the heart in this instance.

Performance capacity is directly associated with maximum oxygen uptake. As yet we are unaware of any previous studies relating thoracic size to performance capacity as has been demonstrated in the present study. Such an association would appear to be logical in that quantitative ventilation must be intimately associated with quantitative oxygen uptake. It is of interest that radiological heart area and thoracic area are significantly related, yet it can be visualized that lung size or heart size independently may set a limit to oxygen uptake. If this is not apparent in health then certainly it applies to disease of these organs. For this reason it appears advantageous to include both heart area and thoracic area in the prediction of maximum oxygen uptake.

SUMMARY

1. Maximum oxygen uptake (aerobic capacity) has been estimated in 81 healthy adult males from 4 submaximal work loads (200, 300, 400 and 500 kg.-m./min.) performed in the steady state at an altitude of 5,760 ft. above sea level.

2. The estimation of maximum oxygen uptake is a good measure of a subject's maximum performance capacity, and is of value in the selection of subjects for athletic training, military purposes and hard physical labour. It is applicable to the determination of disability for compensation purposes and in the placement of patients in occupations that will not exceed their physical resources.

3. Normal standards for maximum oxygen uptake are required to determine a subject's performance capacity. The present and other studies have shown that this is normally extremely wide and is by itself of little value in assessing normality or abnormality.

4. A reduction in the normal range of maximum oxygen uptake can be obtained by relating this to body weight, and this relationship is commonly used.

5. In the present study it has been shown that maximum oxygen uptake is significantly related to radiological thoracic area and heart area, which have been used as a measure of the size of these organs. Although the inclusion of radiological thoracic area and heart area with weight improved the relationship with maximum oxygen uptake, as opposed to weight alone, this improvement was not marked. A similar slight but not statistically significant improvement resulted when the pulse rate at 500 kg.-m./min. work was combined with thoracic area and heart area. However, the justification for including thoracic area and heart area into regression equations for the prediction of maximum oxygen uptake is dependent upon the fact that disease of the heart and lungs is commonly associated with enlargement of these organs. Normally there is a bigger maximum oxygen uptake with increase in the size of these organs. When, however, enlargement results from disease, there

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*Both Sjöstrand[28] and Holmgren and Strandell[39] have found heart volume to be related to physical work capacity.

is a reduction in the maximum oxygen uptake. This discrepancy accentuates the differences between health and disease and is of value in the diagnosis of impaired physical capacity and an estimation of the degree of disability.

6. The performance of 4 substandard work loads in the steady state for the estimation of maximum oxygen uptake is time-consuming. A single work load of 500 kg.-m./min. shows a good correlation with maximum oxygen uptake and could be used to shorten the testing procedure. Such a work load only slightly exceeds in severity a test (Master's 2-step test[38]) commonly used in clinical medicine for cardiac patients and should not be considered too severe for disability assessment.

7. It has been shown that a simplified testing procedure in which the pulse rate alone is measured is much inferior to the measurement of the pulse rate and oxygen uptake, in the estimation of maximum oxygen uptake. Such deficiencies are so marked as to destroy the relationship between maximum oxygen uptake and thoracic size and heart size found when both pulse and oxygen uptake are measured. If only pulse rates are to be measured then the shortcomings of this procedure should be recognized.

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