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Indirect estimation of maximal oxygen uptake for study of working populations

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ABSTRACT A total of 345 shipyard workers (aged 23 to 47) volunteered to perform progressive exercise on a cycle ergometer (15 W/min increments) up to the symptom limited maximum. The results were used to obtain maximal oxygen uptake ($\dot{n}O_2$ max), the oxygen uptake at a respiratory exchange ratio of unity ($\dot{n}O_2$ at $R_{1\cdot0}$), and cardiac frequency at an oxygen uptake of 45 mmol/min (fC_{45}). In this group 156 men (45% of initial population) attained $\dot{n}O_2$ max as defined, 108 (31%) withdrew or did not exercise maximally, and 49 (14%) had transient electrocardiographic abnormalities. For the 156 men extrapolation of the relation of cardiac frequency on oxygen uptake to the predicted maximal cardiac frequency resulted in overestimation of $\dot{n}O_2$ max by 9·6%. $\dot{n}O_2$ Max per kg body mass was negatively correlated with body mass. $\dot{n}O_2$ Max (mean value 130·6 mmol/min) was described in terms of age, fat free mass, smoking (yes or no), and level of habitual activity (rated 1 to 4): the standard error of the estimate (SEE) was 17·3 mmol/min (R^2 0·42); the equation was suitable for reference values. For estimating the $\dot{n}O_2$ max of individual men an empirical relation based on $\dot{n}O_2$ at $R_{1\cdot0}$, fC_{45}, fat free mass, and % body fat had an SEE of 12·1 mmol/min (R^2 0·67). Seventy six per cent of men (88% of those who exercised) attained $\dot{n}O_2$ at $R_{1\cdot0}$ (oxygen uptake approximately 73% of maximum). Thus the $\dot{n}O_2$ max could be estimated in a higher proportion of men than could achieve $\dot{n}O_2$ max. The estimate is appropriate for assessing exercise capacity in relation to employment. For investigating the determinants of exercise capacity in groups of subjects the submaximal index, $\dot{n}O_2$ at $R_{1\cdot0}$, is more informative.

Maximal oxygen uptake ($\dot{n}O_2$ max) reflects the power output for work of 4–10 minutes duration; a high value is a selection criterion for some tasks and in a population is evidence for high customary activity and hence physical fitness. It is measured during progressive exercise up to the point when oxygen uptake reaches a plateau.[1] An alternative end point is when cardiac frequency attains the predicted maximum[2]; this presupposes that the reference value for maximal cardiac frequency applies to the study population but it may not. The measurement procedure requires a high level of motivation, causes distress to some subjects, entails medical and electrocardiographic surveillance, and occasionally precipitates myocardial ischaemia or cardiac arrest.[3] Indirect estimation of $\dot{n}O_2$ max appears preferable; however, the method should be reproducible and the result equivalent to that obtained by direct measurement. The $\dot{n}O_2$ max is usually predicted by extrapolating the relation of cardiac frequency on oxygen uptake for progressive submaximal exercise up to the predicted maximal cardiac frequency, but the accuracy of prediction is poor.[2] Greater accuracy is achieved using blood lactic acid concentration[4-6]; however, the requisite blood sampling is not always practicable. In a pilot study prediction from submaximal exercise, cardiac frequency, fat free mass, and vital capacity showed promise,[7] but it was less satisfactory when applied to another population.[8] After the lead given by Issekutz and other workers,[9-11] we explored predicting $\dot{n}O_2$ max from oxygen uptake at a respiratory exchange ratio of unity.[12] The present paper applies the method to shipyard workers; the relation contains appropriate components and the estimated $\dot{n}O_2$ max is related to activity and age in a manner consistent with other studies. The method provides an accurate way of estimating $\dot{n}O_2$ max from the results of a submaximal exercise test in working populations.

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Methods

The subjects were 345 shipyard workers (welders, caulker burners, and other tradesmen) aged 23–47 who volunteered for the study which was approved by the local ethical committee. The study arose from an investigation into the long term effects of fumes from welding and caulker burning. To this end the subject underwent an assessment of lung function, the Medical Research Council Questionnaire on Respiratory Symptoms was completed, and additional questions asked about chest pain and habitual activity: the latter were used to rate activity outside working hours on a four point scale (table 1). The questionnaire was used to identify men with wheeze or chronic bronchitis and smokers or ex-smokers. Fat free mass and body fat as a percentage of body mass were estimated by the method of Durnin and Womersley[13] from body mass and skinfold thickness measured with Harpenden skin calipers (Holtain). Details are given elsewhere.[14]

Exercise was preceded by measuring blood pressure and 12 lead electrocardiography (ECG). This information and the questionnaire were used to screen out subjects for whom the test was inappropriate. The exercise was performed on a Siemens ergomed cycle ergometer at a pedal frequency of 60 a minute. The ECG lead CM5[15] was recorded and scrutinised during the test. A mouthpiece and low resistance valve box of deadspace 0·05 l were used. Ventilation minute volume was recorded using a rotating vane anemometer with microprocessor output (Morgan); this was calibrated before each period of exercise using a procedure which was itself checked by an independent method. The back pressure to ventilation was less than 2 mm H_2O at a flow rate of 85 l/min. Mixed expired gas was sampled for analysis using a Morgan paramagnetic meter for oxygen and infrared analyser for carbon dioxide; the analysers' calibrations were checked before each session. A microcomputer and printer (Morgan) displayed the raw measurements together with oxygen uptake, carbon dioxide output, and respiratory exchange ratio each half minute during exercise. Subsequently graphs were printed relating the ventilation, cardiac frequency, and respiratory exchange ratio to oxygen uptake and the tidal volume to ventilation.

Table 1 *Score for habitual activity outside working hours*

Score	*Strenuous activities a week**	*Cycling to work (miles)*	*Comment*
1	None	0	Sedentary
2	1–2	<2	Some activity
3	3–4	2–5	Above average
4	>4	>5	Very active

*Competitive sports; other activities as appropriate.

The intermediate results were used (i) for quality control during exercise, (ii) to determine if exercise should be stopped prematurely, and (iii) for deriving by interpolation the ventilation and cardiac frequency at an oxygen uptake of 45 mmol/min (1·0 l/min, $\dot{V}_E45$, fC_{45} respectively) and the oxygen uptake at a respiratory exchange ratio of unity ($\dot{n}O_2$ at $R_{1\cdot0}$). Interpolation was performed by the least squares method over the range where the data appeared linear. The anaerobic threshold was obtained by inspection of the relation of ventilation on uptake of oxygen.[8]

The subject rested on the ergometer for two minutes, pedalled at zero load for one minute, and then worked with increasing intensity (15W increments) until respiratory exchange ratio just exceeded unity. After a 20 minute rest the exercise was restarted at a rate 20W below that previously attained; the increments were 20W a minute up to the maximum the subject was prepared to tolerate. Exercise was terminated by the operator in the event of systolic hypertension (200 mm Hg) or electrocardiographic abnormality (ST depression > 2 mm, three consecutive ventricular ectopic beats or seven such beats in one minute) or when the subject could go no further. The highest recorded oxygen uptake was accepted as maximal if it differed from that for the previous minute by less than 4 mmol/min or the maximal cardiac frequency was not less than 10/min below the reference value or both.[2] The reference value was also used as an endpoint in the prediction of $\dot{n}O_2$ max by extrapolation of the relation of cardiac frequency on oxygen uptake obtained during the first period of exercise up to $R_{1\cdot0}$.

Results were analysed using an IBM 370 computer and the Statistical Package for the Social Sciences of the University of Michigan.[16] The methods included Student's paired *t* test and linear multiple regression analysis. For the latter the variables were added one at a time, starting with that which most reduced the variance. The precision of the estimation of the dependent variable was expressed in terms of its standard error (SEE) or as the goodness of fit of the regression equation, in terms of R^2, the proportion of variation explained by the independent variables. The 5% level of probability was accepted as significant.

Results

DESCRIPTION OF SUBJECTS

Questionnaires, lung function tests, and anthropometry were applied to 345 men. Of these, 45 then declined exercise and four were considered to be unsuitable on account of hypertension (diastolic pressure > 110 mm Hg) or previous myocardial infarction. A total of 296 men performed the progressive exercise test; 261 completed it by attaining $R_{1\cdot0}$, 25 gave

Table 2 *Subject participation in the progressive and maximal exercise tests*

	Outcome of initial scrutiny		*Outcome of progressive exercise test*		*Subsequent progress of men who attained $R_{1\cdot0}$*	
Entry 345	Refusals	45	Attained $R_{1\cdot0}$	261	No further exercise	32
	Rejects	4	Attained $\dot{n}O_2$45	25	Attained $\dot{n}O_2$ max	81
	Exercised	296	Others	10	Attained fCmax	75
					Stopped exercise prematurely	73

up or developed ECG changes before this endpoint but reached an oxygen uptake of 45 mmol/min, and the 10 other men provided no usable information. Of the men who attained $R_{1\cdot0}$, 32 were stopped at this point, 81 attained a plateau of oxygen uptake, 75 achieved their maximal cardiac frequency as defined, and 73 gave up before this endpoint was reached (table 2). In total, 52 men did not attempt one or other exercise test, 56 exerted insufficient effort, six had skeletal problems, 49 had ECG abnormalities at rest or on exercise, two suffered from hypertension, and in 24 only incomplete information was obtained. Mean results by age group for the subjects who attained $R_{1\cdot0}$ are given in table 3.

RESULTS FOR MAXIMAL EXERCISE

The mean $\dot{n}O_2$ max for the 81 men who achieved a plateau of oxygen uptake was 127·4 mmol/min; this was significantly less than that predicted by the extrapolation method. The maximal cardiac frequency (fC max) was also lower than predicted (table 4). For these men $\dot{n}O_2$ max was described by a multiple regression on $\dot{n}O_2$ at $R_{1\cdot0}$, forced vital capacity, fC_{45}, age, fat free mass, stature, the occurrence of regular wheeze, and a history of previous pneumonia (the latter two scored as present or absent) (SEE 10·4 mmol/min, R^2 0·76). The equation was used to estimate $\dot{n}O_2$ max in the 75 men who attained a maximal cardiac frequency (defined) but not a plateau of oxygen uptake. For these subjects the maximal cardiac frequencies were similar to those in the other group (table 4) and the observed $\dot{n}O_2$ max (134·9 mmol/min) did not differ significantly from the estimate (133·8 mmol/min). The results for the two groups of men were pooled for the definitive analysis.

DESCRIPTION OF $\dot{n}O_2$ MAX IN TERMS OF OTHER VARIABLES

$\dot{n}O_2$ Max was described by a multiple regression equation with age, fat free mass, activity score, and current smoking as the independent variables (SEE 17·3 mmol/min, R^2 0·42). When prediction was based on oxygen uptake at a respiratory exchange ratio of unity, the SEE was 14·1 mmol/min. It was reduced to 12·1 mmol/min (R^2 0·67) by also including in the equation fat free mass and either %fat or forced vital

Table 3 *Mean results by age groups*

	*Age groups (years)**			
	25–29	*30–34*	*35–39*	*40–47*
No (but see table 2)	76	54	50	80
Age (yr)	27·0	31·8	37·2	43·1
Stature (m)	1·73	1·75	1·74	1·73
Body mass (BM) (kg)	73·5	78·9	77·5	77·4
Fat (%)	16·3	19·9	20·4	22·4
Fat free mass (FFM) (kg)	61·3	62·7	61·5	59·3
Activity score	1·85	1·60	1·56	1·45
Lung function:				
Forced expiratory volume (FEV_1) (l)	4·10	4·13	3·93	3·57
Forced vital capacity (FVC) (l)	5·30	5·38	5·25	4·93
Submaximal exercise:				
Ventilation ($\dot{V}_E$45) (l/min)	22·7	23·0	23·3	24·2
Cardiac frequency (fC_{45}) (min^{-1})	104·6	105·3	106·1	108·5
Tidal volume (Vt_{30}) (l)	1·62	1·64	1·73	1·59
$\dot{n}O_2$ at anaerobic threshold (mmol/min)	79·4	76·0	73·6	71·2
$\dot{n}O_2$ at $R_{1\cdot0}$ (mmol/min)	98·4	96·1	95·4	86·8
Maximal exercise:				
$\dot{n}O_2$ max (direct or estimated) (mmol/min)	131·2	124·8	127·1	117·5
$\dot{n}O_2$ max (St, BM) (mmol/min)	140·6	137·4	121·6	118·9
$\dot{n}O_2$ max (St, FFM) (mmol/min)	138·9	140·9	121·6	119·2
$\dot{n}O_2$ max (St, BM)/BM (mmol/min/kg)	1·92	1·74	1·56	1·52
$\dot{n}O_2$ max (St, FFM)/FFM (mmol/min/kg)	2·28	2·23	1·96	2·01

*One subject was aged 23 so his results do not appear in the table.
St, standardised to mean BM or FFM using equations 1 and 2 in text.

Table 4 *Observed and predicted fC max, observed ṅO_2 max, and ṅO_2 max predicted by extrapolation for subjects who attained a plateau of oxygen uptake during the maximal exercise test (n = 81)*

	Mean	*SD*	*Range*
fC Max (min^{-1}):*			
Observed	182·0†	8·38	163–202
Predicted	187·7	4·10	180–193
ṅO_2 Max (mmol/min):			
Observed	127·4†	20·6	88–184
Extrapolated	139·8	30·6	84–260

*The corresponding mean values for 75 subjects who met the cardiac frequency criterion for ṅO_2 max were 181 and 188 a minute.
†Significantly different from predicted $p < 0·05$.

capacity (table 5). Adding forced expiratory volume, current smoking, whether or not the subject had discontinued smoking, and age slightly but significantly improved the description. ṅO_2 Max was significantly correlated with body mass and fat free mass; the linear relations were:

ṅO_2 max = 0·58 body mass (kg) + 88·9 (SEE 21·7) mmol/min (equation 1)

ṅO_2 max = 1·56 fat free mass (kg) + 34·9 (SEE 20·0) mmol/min (equation 2)

The proportionalities ṅO_2 max/body mass and ṅO_2/FFM were negatively correlated with body mass. ṅO_2 Max could also be described with similar precision in terms of body mass to the power of 0·31.

DESCRIPTION OF INDICES OBTAINED DURING SUBMAXIMAL EXERCISE

Oxygen uptake at a respiratory exchange ratio of unity (ṅO_2 at $R_{1·0}$, mean value 93·8 mmol/min) was correlated with anaerobic threshold (mean value 75·1 mmol/min, r = 0·70). It was related to activity score, smoking, and fat free mass. After allowing for these variables ex-smokers with a history of wheeze had a below average ṅO_2 at $R_{1·0}$ and men with chronic bronchitis an above average value. Cardiac frequency at an oxygen uptake of 45 mmol/min (fC_{45}) was negatively correlated with the activity score, fat free mass, and forced vital capacity; it was higher by nine beats a minute in subjects who gave a history of pleurisy compared with those who did not. The respiratory exchange ratio at an oxygen uptake of 45 mmol/min was positively correlated with exercise ventilation ($\dot{V}_E45$ and Vt_{30}) and with fC_{45} standardised for fat free mass: it was higher in men who worked as caulker burners compared with other occupational groups.

Discussion

MAXIMAL OXYGEN UPTAKE

Information on exercise capacity is used as a guide to suitability for heavy work, particularly at pre-employment examination, after illness or injury, and when the work is performed infrequently; the relevant occupations include professional sport, membership of rescue and fire brigades, the armed forces, police, deep sea divers, and occupations entailing heavy work. The exercise capacity is also used to assess the physical fitness of occupational and other populations and hence the possible need for changes in lifestyle or recreational facilities. For persons who are fit and highly motivated the maximal oxygen uptake, which is a measure of exercise capacity, can usually be measured without difficulty. In other circumstances the direct measurement is frequently unacceptable. It is also inefficient since in the present instance, despite some initial selection, there was a high dropout rate from both medical and psychological causes (respectively 16% and 31%); these aspects are considered below. The maximal exercise test starts with submaximal exercise, however, and the submaximal results may be used to estimate the exercise capacity instead of or before making the direct measurement.

ESTIMATION OF MAXIMAL OXYGEN UPTAKE: USE OF ṅO_2 MAX AT $R_{1·0}$

The widely used extrapolation procedure for predicting ṅO_2 max from cardiac frequency is unreliable because both the relation between cardiac frequency and oxygen uptake is not rectilinear[17] and the Scandinavian reference values for maximal cardiac frequency do not apply to all subjects. In the present instance they overestimated the measured fC max by 2·7% (table 4). Rectilinear extrapolation to the predicted maximal cardiac frequency overestimated the measured ṅO_2 max by 9·6%, indicating that the shape of the ṅO_2/fC relation also contributed to the discrepancy.

Estimation based on cardiac frequency at a single oxygen uptake was previously found to be unsatisfactory for predicting ṅO_2 max though it could be used to predict the Harvard pack index.[18] Prediction of

Table 5 *Linear regression equations for estimating ṅO_2 max (n = 156, $\bar{x}$ = 130·6, mmol/min)*

A Without exercise	*B Including exercise*
Coefficient terms:	
1·43 FFM (kg)	0·626 ṅO_2 at $R_{1·0}$ (mmol/min)*
−0·95 Age (yr)	0·78 FFM (kg)
6·31 Activity (1–4)	−0·86 Fat (%)
−8·06 Sm (yes/no)	−0·29 fC45 (min^{-1})
Constant 69·5	70·1
SEE 17·3 (mmol/min)	12·1 (mmol/min)
R^2† 0·42	0·67

*Without other variables ṅO_2 max = 0·78 ṅO_2 at $R_{1·0}$ + 54·8 (SEE 14·1, R^2 0·61).
†Proportion of variance explained by regression.

$\dot{n}O_2$ max was improved by including fat free mass and forced vital capacity in the prediction equation.[7] Substitution of stroke volume for fat free mass and fC_{45} further improved the accuracy of prediction[8] but the measurement entailed rebreathing which was disagreeable and difficult for some subjects. The alternative use of anaerobic threshold, estimated indirectly from the relation of ventilation on oxygen uptake, did not have this disadvantage but the estimation procedure was subject to observer error.[19] Use of the oxygen uptake at a respiratory exchange ratio of unity has the advantages of being at least as good a predictor of $\dot{n}O_2$ max as the other variables, of being readily estimated, and having an acceptable reproducibility—in one instance 5%.[8] Because it was correlated with anaerobic threshold, $\dot{n}O_2$ at $R_{1\cdot0}$ also provided an estimate of capacity for prolonged work. In the present study the index was obtained on 76% of the initial population which represented 88% of the men who were prepared to exercise. Both the proportion in this category and the number who persevered to attain $R_{1\cdot0}$ would have been increased if the men had had a material interest in the result. In addition, of those who were stopped on account of electrocardiographic abnormality, the great majority performed successfully when the test was repeated a few weeks later. This suggested that the immediate cause was apprehension and was reversible. The number of such abnormalities and the proportion which resulted from ischaemic heart disease increased with age[20] but over the present age range the test up to $R_{1\cdot0}$ appeared to strike the right balance between, on the one hand, adequate intensity of effort and, on the other, safety, acceptability, and technical complexity. The precision of prediction (SEE approximately 12 mmol/min depending on which variables were included) was not bettered by any of the alternatives that have been tried to date.

INTERPRETATION OF $\dot{n}O_2$ MAX

$\dot{n}O_2$ Max is interpreted with respect to the reference value, the energy requirements of the occupation,[21] and the cause of any limitation on medical grounds. The reference value may be the previous result for the particular subject or the average result for a person having similar attributes. The reference variables should then be available without recourse to exercise. Arising from the present study the best combination was age, fat free mass, activity category, and smoking (table 5, equation A). The partial regression coefficients on age and activity category were similar to those found by Jones *et al*[22] and the overall results were also similar. The inclusion of smoking, however, seemed to the present authors to be appropriate. In addition, fat free mass was a more relevant reference variable than stature and body mass used by the Canadian workers since body mass included body fat which did not contribute to exercise capacity. Body mass was also correlated with stature, hence the reference variables were not independent and this could have reduced the validity of the reference equation. The variability about the present equation (R^2 0·42) was similar to that for most indices of lung function ($R^2 \simeq$ 0·4–0·5) so like them should have a wide range of applications.

For purposes of comparison between subjects the $\dot{n}O_2$ max is usually expressed per unit of body mass or fat free mass. For the present subjects, however, $\dot{n}O_2$ max/kg was negatively correlated with mass. This was due to the relation between the variables not being a proportionality but a linear regression with a significant constant term. On this account $\dot{n}O_2$ max/kg was not a valid index[23 24]; the $\dot{n}O_2$ at a standard mass could be used (table 3) or the $\dot{n}O_2$ max expressed per unit of body muscle—for example, thigh muscle width or total body potassium, both of which bear a proportional relation to $\dot{n}O_2$ max.[7]

The estimated $\dot{n}O_2$ max provides an index of physical condition in subjects capable of exercising up to a respiratory exchange ratio of unity. It also indicates what the exercise capacity would be, given favourable circumstances. Nevertheless, the aerobic capacity could still be limited by medical conditions; the commonest condition is ischaemic heart disease which is commonly looked for by stress electrocardiography at a workload equivalent to 80% of $\dot{n}O_2$ max. This work rate is not much greater than that needed to attain $R_{1\cdot0}$ (on average 73% of $\dot{n}O_2$ max) so the two procedures could readily be combined.

The $\dot{n}O_2$ max estimated from submaximal data is likely to be most useful in relation to employment. It might also be used to investigate factors that underlie exercise capacity other than those which contribute to the estimate. For this application the number of reference variables should be minimal, hence forced expiratory volume, age, smoking history, and score for habitual activity were omitted from the equation despite their contributing significantly to the description of $\dot{n}O_2$ max. In addition, in order to validate the use of estimated $\dot{n}O_2$ max the analysis was also performed using the measured $\dot{n}O_2$ max as a dependent variable. The contributions of habitual activity and age were rated equally by both methods. Current smoking was identified as reducing the measured $\dot{n}O_2$ max by on average 6%. It did not apparently contribute to estimated $\dot{n}O_2$ max but reduced by 8·6% the $\dot{n}O_2$ at $R_{1\cdot0}$ which was one of the constituents of the prediction equation. Adverse effects of previous pleurisy and of respiratory symptoms sufficient for the subject to abandon smoking were also identified in the component terms but not in the $\dot{n}O_2$ max estimated from them. Thus for assessing the physiological determinants of physical fitness the $\dot{n}O_2$ at $R_{1\cdot0}$ and other component terms in the equation were informative in their own right and could be used as indices in population studies. The $\dot{n}O_2$ at $R_{1\cdot0}$ should probably not be used in relation to claims for compension since, if the subject hyperventilated, an artificially low value might be obtained. But with hyperventilation the directly measured $\dot{n}O_2$ max would not be reliable either.[25]

In conclusion reference values for $\dot{n}O_2$ max in working men have been obtained. The estimation of $\dot{n}O_2$ max from the results of a submaximal exercise test and related variables has been shown to be valid for shipyard workers aged 23 to 47. The test is safer, less stressful, more acceptable, and completed by a higher proportion of subjects than direct measurement and has a place in assessing work capacity in relation to occupation. For comparison between individuals of different size the results should be expressed at a standard body mass or fat free mass and not per kg. Factors that contribute to $\dot{n}O_2$ max may be investigated through their effects on the components of the prediction equation. Estimated $\dot{n}O_2$ max may be misleading in the presence of disease processes or psychological conditions which affect the capacity for exercise. Its use in population studies has still to be evaluated.

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