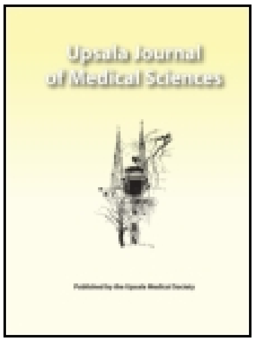

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Physical Working Capacity in Severe Chronic Obstructive Lung Disease

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Physical Working Capacity in Severe Chronic Obstructive Lung Disease

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ABSTRACT

Twenty-five patients (mean age 61±2, range 39–72 years) with severe chronic obstructive lung disease, with a maximum voluntary ventilation (MVV_F), without bronchodilating spray, ≤35% of the individually predicted normal value, were classified into two groups: (1) a group who had suffered from at least one period of absolute respiratory insufficiency (R), with 8 men and 6 women, and (2) a comparison (C) group with the corresponding degree of MVV_F limitation but without any period of absolute respiratory insufficiency, with 10 men and 1 woman. The patients were studied in their habitual state by a standard ergometer-bicycle exercise test. The highest performed work load, near maximal (W_{max}), was determined, and also the pulmonary gas exchange, arterial-blood (O_2 and CO_2) gas tensions, lactate concentration and acid-base balance under the conditions of maximum work load.

MVV_F and W_{max} were found to be positively correlated in the R and C groups, but not in the female patients. W_{max} was also correlated to other factors, namely negatively to resting FRC/TLC and RV/TLC, and to V_D/V_T measured under maximum working conditions. Average W_{max} was 189±52 in the male R group and 118±37 kpm/min in the female, and in the male C group 256±40 kpm/min. W_{max} in kpm/min per kg body weight was in the R group 2.63±0.57 and in the C group 4.29±0.65. There was a tendency to lower P_{aO_2} and C_{aO_2} during maximum work and higher heart rate in relation to work load in the R group than in the C group although this was not statistically significant.

INTRODUCTION

Due to the improvement of diagnostic tools, the rate of easily repeated ECG recordings and arterial blood gas analysis has risen and, with the development of intensive care, the number of patients with chronic obstructive lung disease (COLD) brought through periods of absolute respiratory insufficiency has also increased. The disability of these patients in their habitual state, between acute exacerbations, is evaluated mainly by spirometric investigation of the ventilatory capacity and the lung volumes, and arterial blood gas analyses, combined in some cases with gas exchange studies in resting or submaximal working conditions. However, since many patients with severe chronic obstructive lung disease repeatedly reach their maximum physical working capacity in daily life it was considered of interest to study the relationship between ventilatory and physical working capacity. In addition, a study was made on the correlation between maximum work load, on the one hand, and pulmonary gas exchange, acid-base balance, and circulatory and peripheral metabolic factors, on the other hand, in the respective conditions.

Patients with a maximum ventilatory capacity ≤35% of predicted normal values were investigated in their habitual state. Furthermore, a comparison was made between a group of patients with one or several earlier periods of absolute respiratory insufficiency (R group) and another group (C – comparison) with about the same ventilatory impairment but no periods of absolute respiratory insufficiency.

MATERIAL AND METHODS

A description of the material and of the selection of the patients is given by Brundin & Tammivaara-Hilty (1972). The material consisted of 14 (8 male and 6 female) patients with earlier periods of absolute respiratory insufficiency (R group) and of 11 (10 male and one female) comparison patients (C group). The mean, standard error and range of the age, weight and height in the R-group males were 62±2 (50–69) years, 61±4 (48–82) kg and 174±3 (162–186) cm and in the R-group females 64±3 (57–72) years, 53±6 (40–73) kg and 161±1 (158–165) cm. The corresponding values in the C-group males were 59±4 (38–70) years, 62±3 (53–83) kg and 172±2 (162–180) cm and in the only C-group female patient 56 years, 46 kg and 158 cm.

Under the influence of the patients' daily habitual medica-

Table I. *Results of dynamic and static spirometry as mean values, S.E.M. and range in male and female patients in groups R and C without (A) and under (B) the influence of a bronchodilating spray*

Maximal voluntary ventilation (MVV_F) in l/min and as per cent of predicted normal values, forced expiratory one second volume ($FEV_{1.0}$) in litres and as per cent of VC, peak expiratory flow (PEF) in l/min and functional residual capacity (FRC) and residual volume (RV), both in litres and as per cent of predicted normal values. Among the 14 R-group patients the measurements were performed under condition (A) in 8 male patients, under condition (B) in 7 male patients and under both conditions in 6 female patients. Among 11 C-group patients the measurements under both condition (A) and (B) were performed in 10 male patients and 1 female

	R group			C group		
	Males	Females	All	Males	Females	All
MVV_F, l/min						
(A) *M*±S.E.M.	29.0±3.0	23.0±2.9		28.9±3.6	24	
range	19–46	15–32		13–47	—	
(B) *M*±S.E.M.	37.8±4.4	25.0±2.3		37.7±4.1	31	
range	27–60	17–33		21–59	—	
Per cent of pred.						
(A) *M*±S.E.M.	20.9±2.3	23.7±3.4	22.1±1.9	20.4±2.5	23	20.6±2.2
range	13–34	14–34	13–34	10–35	—	10–35
(B) *M*±S.E.M.	27.6±3.5	25.8±2.9	26.8±2.2	26.9±2.7	30	27.2±2.5
range	20–44	16–36	16–44	17–46	—	17–46
VC, litres						
(A) *M*±S.E.M.	2.36±0.20	1.75±0.08		2.69±0.21	2.0	
range	1.6–3.1	1.5–2.1		1.5–3.9	—	
(B) *M*±S.E.M.	2.99±0.24	1.95±0.13		3.10±0.16	2.1	
range	2.3–4.3	1.7–2.5		2.3–3.9	—	
Per cent of pred.						
(A) *M*±S.E.M.	49.3±3.8	57.5±2.9	52.8±2.7	56.2±4.7	65	58.6±2.7
range	32–63	47–68	32–68	33–85	—	33–85
(B) *M*±S.E.M.	61.9±4.4	64.2±4.5	62.9±3.0	65.0±3.5	68	64.7±3.8
range	49–81	53–81	49–81	52–85	—	52–85
$FEV_{1.0}$, litres						
(A) *M*±S.E.M.	0.80±0.09	0.65±0.06		0.84±0.09	0.8	
range	0.5–1.4	0.5–0.8		0.4–1.3	—	
(B) *M*±S.E.M.	0.97±0.09	0.73±0.05		1.01±0.08	0.9	
range	0.7–1.3	0.6–0.9		0.6–1.5	—	
$FEV_{1.0}$/VC, per cent						
(A) *M*±S.E.M.	34.0±3.1	37.5±3.1	35.5±2.2	31.3±2.4	43	38.3±2.7
range	24–47	31–50	24–50	18–43	—	18–43
(B) *M*±S.E.M.	32.6±2.0	38.7±2.4	35.4±1.7	32.9±2.1	43	39.3±2.1
range	28–42	33–49	28–49	22–45	—	22–45
PEF, l/min						
(A) *M*±S.E.M.	133.1±17.9	101.7±16.5		136.5±14.4	135	
range	70–200	70–175		70–240	—	
(B) *M*±S.E.M.	170.0±17.7	120.8±16.7		153.0±14.0	130	
range	115–230	80–190		90–250	—	
FRC, litres						
(A) *M*±S.E.M.	5.69±0.48	3.77±0.27		5.72±0.39	3.8	
range	3.8–8.1	3.0–4.6		4.3–7.9	—	
Per cent of pred.						
(A) *M*±S.E.M.	128.6±10.4	155.7±13.7	140.2±8.8	137.3±11.0	146	138.1±10.0
range	95–184	103–200	95–200	100–211	—	100–211
RV, litres						
(A) *M*±S.E.M.	4.84±0.42	3.12±0.26		4.69±0.41	3.2	
range	3.4–6.6	2.5–4.0		3.0–6.7	—	
Per cent of pred.						
(A) *M*±S.E.M.	189.3±14.8	213.0±18.3	199.4±11.6	190.9±16.0	246	195.9±15.3
range	136–254	179–271	136–271	130–291	—	130–291

tion the static lung volumes were measured before and the dynamic ventilatory capacity both before and 10 min after a bronchodilating spray, orciprenaline (Alupent®) was, given as described by Bäcklund & Tammivaara-Hilty (1972), among others. Usually the static and dynamic spirometry followed one another on the same day, but longer resting intervals than usual were allowed. However, in the most dyspnoeic patient (R4) the two types of spirometry (but without a bronchodilating spray) had to be performed on two separate days. One or several repetitions of the same test were not always performed, if the patient was severely dyspnoeic and the first test was considered to be optimal, as otherwise the full scheme of different ventilatory tests could not have been completed. The values obtained were compared with the normal values reported by Berglund et al. (1963), Birath et al. (1963) and Grimby & Söderholm (1963) for persons up to 68 years. The spirometric investigations in the different groups of patients are presented in Table I.

The measurement of the physical working capacity (W_{max}, kpm/min) in the sitting posture was performed according to Sjöstrand (1947) and Wahlund (1948), on an electrically braked bicycle ergometer (Holmgren & Mattsson 1954). W_{max} was estimated according to Strandell (1964) as the highest work load performed (or calculated to be performed) for 6 min, but not always in a circulatory steady state, however. W_{max} has also been expressed per body weight (kpm/min·kg). The work test was mostly terminated because of dyspnoea, experienced by the patient as very severe and sometimes combined with a sensation of sternal oppression and verified also by the clinical observation of the author. Another reason for discontinuation was a combination of severe dyspnoea and pronounced fatigue. The latter could be confirmed as a relevant reason for discontinuation either by means of a repeated test, if there was any suspicion that the patients had not co-operated well enough, or by circulatory or metabolic findings. In none of the patients was the test terminated because of typical angina pectoris, though in several of the patients the oppression associated with the dyspnoea might well have been explained as an unspecific symptom of coronary insufficiency. During the work test the pulmonary gas exchange was measured by the Douglas bag technique with simultaneous arterial blood sampling for analysis of the arterial blood gas tensions, acid-base balance, haemoglobin, haematocrit and lactate, and calculations were made, as described by Bäcklund & Tammivaara-Hilty (1972). Systematic duplicate estimations of the pulmonary gas exchange under maximum working conditions were not performed, mainly out of consideration for the patients and because of an increasing risk of cardiac complication if maximum work tests had been repeated several times on the same day. A comparison, made between two different pulmonary gas exchange studies on the same work load (50–100% of maximum), showed probably significant but small differences only between the alveolar ventilation ($\dot{V}_A$, l/min), arterial oxygen (P_{aO_2}, mmHg) and carbon dioxide (P_{aCO_2}, mmHg) tension (Tammivaara-Hilty, to be published). The breathing reserve index (BRI, per cent) was calculated as $100 \times (MVV - \dot{V}_E)/MVV$, as described by Linderholm (1967) among others, when $\dot{V}_E$ (l BTPS/min) was minute ventilation in maximum working conditions.

STATISTICS

Standardized statistical formulae were used and the calculations were performed with a desk computer (Olivetti Programma). Unless otherwise stated the mean values, S.E.M. and range are given. Student's t-test was used to test significance: $p \geq 0.05$ non-significant (NS), $p \leq 0.05$ probably significant, $p \leq 0.01$ significant and $p \leq 0.001$ highly significant.

RESULTS

The physical working capacity (W_{max}, kpm/min and W_{max}/body weight, kpm/min·kg) and the breathing reserve index (BRI, per cent) are presented in Table II for different groups, comprising a total of 22 patients, in whom gas collection could be made under maximum working conditions. No statistically significant differences were found between the different groups, but there was a tendency ($p < 0.10$) to a lower W_{max}, in kpm/min, in the female than the male patients and a tendency to a lower W_{max}, both in kpm/min and in kpm/min·kg, in the R- than the C-group patients.

BRI without bronchodilatation (A), calculated from $\dot{V}_E$ and MVV_F, was probably significantly higher ($p < 0.05$) in the R than the C group and the same tendency ($p < 0.10$) was seen between the R- and C-group male patients. BRI with bronchodilatation (B), calculated from $\dot{V}_E$ and MVV_F, showed a tendency ($p < 0.10$) to a higher value in the R rather than in the C group, and in the R-group male rather than in the female patients, but was probably significantly higher in the R- than the C-group male patients ($p < 0.05$). When $\dot{V}_E$ measurement in maximum working conditions was unsuccessful, BRI values in submaximum conditions, were as follows (at rest, sitting): in patient R7 34% (A) and 41% (B), in R12 50% (A) and 54% (B), and in C3 at 200 kpm/min 5% (A) and 34% (B). The work loads 130, 100 and 400 kpm/min were terminated after 2 min 20 sec, 3 min, and 3 min, respectively, by these patients. In patient R4, in whom no work test could be performed because of severe dyspnoea even at rest, the BRI at rest sitting was 34% (A).

Table II. *Physical working capacity (W_{max}), both in kpm/min and per body weight in kpm/min·kg, and the breathing reserve index (BRI) in per cent, as mean values, S.E.M. and range in different groups*

M = male, F = female

		W_{max}		BRI (%)	
		kpm/min	kpm/min·kg	(A)	(B)
RM	$M\pm$S.E.M.	189.4±52.4	3.06±0.89	18.7±9.4	38.0±5.3
	Range	0–450	0–7.89	−5−57	16–54
	Number	8	8	6	6
RF	$M\pm$S.E.M.	117.5±37.1	2.06±0.60	9.5±11.1	19.6±7.0
	Range	25–200	0.53–4.26	−18–41	1–42
	Number	6	6	5	5
RM+F	$M\pm$S.E.M.	158.6±34.2	2.63±0.57	14.5±7.0	29.6±5.0
	Range	0–450	0–7.89	−18–57	1–54
	Number	14	14	11	11
CM	$M\pm$S.E.M.	255.8±40.1	4.28±0.72	−15.8±14.0	15.8±7.5
	Range	50–400	0.79–7.09	−109–45	−30–53
	Number	10	10	9	9
CF		200	4.40	−19	8
CM+F	$M\pm$S.E.M.	250.7±36.6	4.29±0.65	−16.1±12.5	15.0±6.8
	Range	50–400	0.79–7.09	−109–45	−30–53
	Number	11	11	10	10
R+CM	$M\pm$S.E.M.	226.3±32.2	3.74±0.56	−2.0±10.0	24.7±5.7
	Range	0–450	0–7.89	−109–57	−30–54
	Number	18	18	15	15
R+CF	$M\pm$S.E.M.	129.3±33.5	2.40±0.61	4.8±10.2	17.7±6.0
	Range	25–200	0.53–4.40	−19–41	1–42
	Number	7	7	6	6

The regression equations between maximal voluntary ventilation (MVV_F, l BTPS/min) and W_{max} (kpm/min) are presented in Table III separately for different groups and the two sexes; equations referring to MVV_F measured both without (A) and under (B) the influence of a bronchodilating spray are given. The correlations are significant for R- and C-group male patients, highly significant for all male patients and non-significant for R-group female and all female patients. The intercept is lower in the R- than the C-group male patient regression equations, but the difference between the groups diminishes with increasing maximum ventilatory capacity.

As the range in age and body size among both the present male and female patients was large, the

Table III. *The regression equations between the maximal voluntary ventilation* (MVV_F, l/min) *as independent variable and physical working capacity* (W_{max}, kpm/min) *as dependent variable in different groups*

r = correlation coefficient, n = number of patients, M = male, F = female

RM	(A)	$W_{max} = -269.8 + 15.8 \times MVV_F$	(S.D. 69.1),	$r = 0.90$	$n = 8$
	(B)	$W_{max} = -207.3 + 11.1 \times MVV_F$	(S.D. 49.3),	$r = 0.94$	$n = 7$
CM	(A)	$W_{max} = -13.6 + 9.3 \times MVV_F$	(S.D. 71.0),	$r = 0.85$	$n = 10$
	(B)	$W_{max} = -47.1 + 8.0 \times MVV_F$	(S.D. 77.2),	$r = 0.82$	$n = 10$
RF	(A)	$W_{max} = 89.2 + 1.2 \times MVV_F$	(S.D. 101.0),	$r = 0.10$	$n = 6$
	(B)	$W_{max} = 40.0 + 3.1 \times MVV_F$	(S.D. 99.6),	$r = 0.19$	$n = 6$
M	(A)	$W_{max} = -98.6 + 11.2 \times MVV_F$	(S.D. 80.7),	$r = 0.82$	$n = 18$
	(B)	$W_{max} = -105.1 + 9.1 \times MVV_F$	(S.D. 69.3),	$r = 0.85$	$n = 17$
F	(A)	$W_{max} = -3.3 + 7.4 \times MVV_F$	(S.D. 75.5),	$r = 0.50$	$n = 7$
	(B)	$W_{max} = 4.1 + 4.8 \times MVV_F$	(S.D. 92.3),	$r = 0.31$	$n = 7$

Table IV. *Regression equations between maximal voluntary ventilation* (MVV_F, *per cent of pred. normal values) as independent variable and physical working capacity* (W_{max}/*body weight, kpm/min·kg) as dependent variable in different groups*

r = correlation coefficient, n = number of patients, M = male, F = female

RM	(A)	$W_{max} = -4.70 + 0.37 \times MVV_F$ (S.D. 0.80), $r = 0.96$	$n = 8$
	(B)	$W_{max} = -2.79 + 0.23 \times MVV_F$ (S.D. 1.15), $r = 0.90$	$n = 7$
RF	(A)	$W_{max} = 1.88 + 0.01 \times MVV_F$ (S.D. 1.64), $r = 0.04$	$n = 6$
	(B)	$W_{max} = 1.51 + 0.02 \times MVV_F$ (S.D. 1.63), $r = 0.11$	$n = 6$
CM	(A)	$W_{max} = -0.27 + 0.22 \times MVV_F$ (S.D. 1.57), $r = 0.76$	$n = 10$
	(B)	$W_{max} = -0.63 + 0.18 \times MVV_F$ (S.D. 1.74), $r = 0.70$	$n = 10$
R	(A)	$W_{max} = -0.74 + 0.15 \times MVV_F$ (S.D. 1.89), $r = 0.52$	$n = 14$
	(B)	$W_{max} = -1.67 + 0.17 \times MVV_F$ (S.D. 1.62), $r = 0.66$	$n = 13$
C	(A)	$W_{max} = -0.27 + 0.22 \times MVV_F$ (S.D. 1.46), $r = 0.76$	$n = 11$
	(B)	$W_{max} = -0.62 + 0.18 \times MVV_F$ (S.D. 1.64), $r = 0.69$	$n = 11$
All	(A)	$W_{max} = -0.27 + 0.17 \times MVV_F$ (S.D. 1.94), $r = 0.54$	$n = 25$
	(B)	$W_{max} = -1.25 + 0.18 \times MVV_F$ (S.D. 1.71), $r = 0.64$	$n = 24$
M	(A)	$W_{max} = -1.86 + 0.27 \times MVV_F$ (S.D. 1.50), $r = 0.80$	$n = 18$
	(B)	$W_{max} = -1.48 + 0.20 \times MVV_F$ (S.D. 1.53), $r = 0.76$	$n = 17$
F	(A)	$W_{max} = 2.31 + 0.004 \times MVV_F$ (S.D. 1.76), $r = 0.02$	$n = 7$
	(B)	$W_{max} = -1.14 + 0.05 \times MVV_F$ (S.D. 1.72), $r = 0.21$	$n = 7$

effect of these factors on the relationship was eliminated by giving the MVV_F values as a percentage of predicted normal values and W_{max} per kg body weight. The regression equations are given in Table IV. The correlation between the ventilatory capacity and physical working capacity was better in the R- than in the C-group male patients, but even lower in the R-group female and all female patients. The physical working capacity in relation to maximum ventilatory capacity was better in the C- than in the R-group patients. The reason did not seem to be a greater increase of ventilation in relation to work load or oxygen uptake in maximum working conditions, as the BRI, at least in the R-group male patients, was higher than in the C-group patients (Table II). Besides, though there was a large inter-individual variation in $\dot{V}_E/\dot{V}_{O_2}$ under maximum working conditions, there was no significant difference between the groups: the mean ± S.E.M. and range in 12 R-group patients was 34.5 ± 2.6 (26.5–53.6) and in 10 C-group patients 35.4 ± 2.2 (23.8–44.4). There was a tendency ($p < 0.10$) to lower PEF values at rest in the R group (105 ± 18 l/min) than in the C group (119 ± 26 l/min) on the work test day though the PEF values measured on the previous day at the end of the dynamic spirometries showed no significant differences between the two groups either without or under the influence of a bronchodilating spray. The higher mean PEF values in the R and C groups on the day of spirometry, shown in Table I, may be noted. Fig. 1 presents the individual differences between MVV (without regard to the breathing frequency used), measured without and under the influence of a bronchodilating spray, and the highest measured $\dot{V}_E$, alveolar ventilation ($\dot{V}_A$, l BTPS/min) and oxygen uptake ($\dot{V}_{O_2}$, l STPD/min) values with the respective maximum work loads. The regression equation between the maximum work load (kpm/min) and $\dot{V}_E$ under the same conditions for 16 male patients was: $\dot{V}_E = 14.57 + 0.05 \times$ maximum load (S.D. 5.39), $r = 0.82$, and for 6 female patients: $\dot{V}_E = 16.32 + 0.03 \times$ maximum load (S.D. 4.22), $r = 0.58$. $\dot{V}_E$ at a maximum work load exceeded the MVV (A) values in 3 R-group and in 8 C-group patients, and the MVV (B) values in none of the R-group and in 2 of the C-group patients (C9 at 400 and C10 at 250 kpm/min).

The regression equation between the maximum work load and $\dot{V}_A$ under the same conditions was: $\dot{V}_A = 4.08 + 0.03 \times$ maximum load (S.D. 2.52), $r = 0.88$ for the male patients, and $\dot{V}_A = 5.35 + 0.30 \times$ maximum load (S.D. 2.02), $r = 0.79$ for the female patients.

The corresponding regression equations between the maximum work load and oxygen uptake were: $\dot{V}_{O_2} = 0.3312 + 0.0019 \times$ maximum load (S.D. 0.0932), $r = 0.95$ for the male, and $\dot{V}_{O_2} = 0.4687 + 0.00135 \times$ maximum load (S.D. 0.0366), $r = 0.95$ for the female

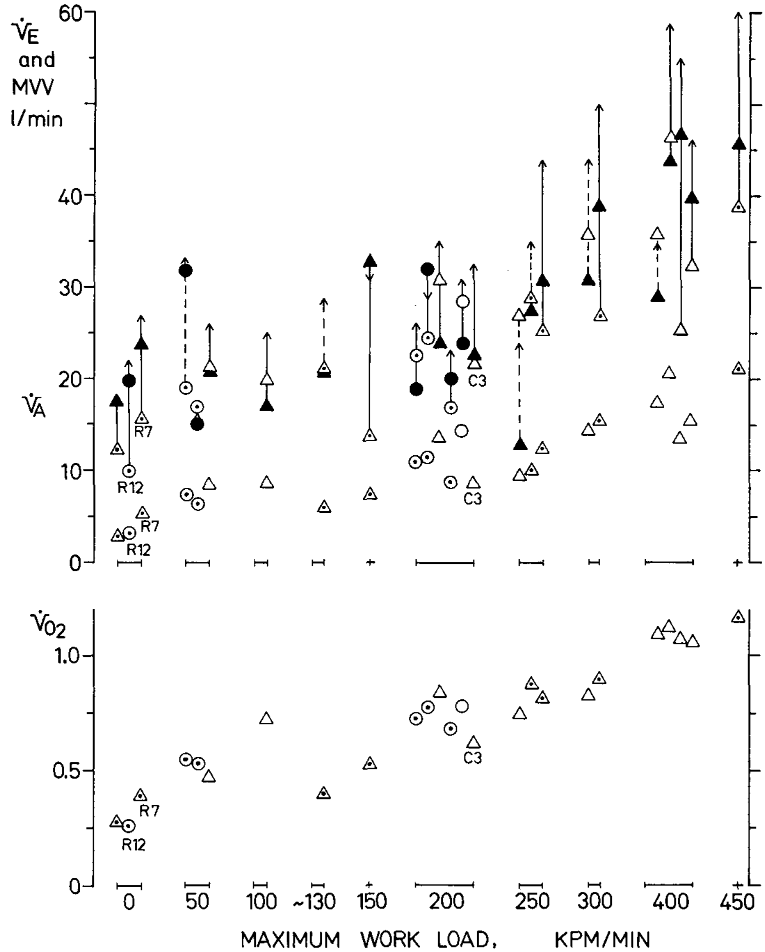

Fig. 1. Highest measured minute ventilation ($\dot{V}_E$, l BTPS/min), alveolar ventilation ($\dot{V}_A$, l BTPS/min) and oxygen uptake ($\dot{V}_{O_2}$, l STPD/min) in each patient at the respective maximum work loads (kpm/min), except in patients R7, R12 and C3 where they are given for submaximum conditions, in relation to maximal voluntary ventilation (MVV, l BTPS/min) without (● female and ▲ male patients) and 10 min after (→) a bronchodilating spray in R- and C-group patients. Explanations: MVV was the highest value without regard to the breathing frequency. ---- = work load terminated before 6 min. $\dot{V}_E$, $\dot{V}_A$ and $\dot{V}_{O_2}$ in the R group are indicated dy ⊙ in the female and by ◬ in the male patients and in the C group by ○ in the female and by △ in the male patients.

patients. In a total of 22 patients the maximum $\dot{V}_O$ in male patients was 0.785 ± 0.114 in the R and 0.889 ± 0.073 l/min in the C group ($p > 0.20$); in the female patients 0.650 ± 0.049 l/min in the R and 0.775 l/min in the C group ($p > 0.20$).

The breathing frequency (f), the physiological dead space (V_D, ml BTPS) and the ratio between V_D and tidal volume (V_T, ml BTPS) $= V_D/V_T$ are presented in Fig. 2 as change from resting conditions in the sitting posture to conditions with the respective maximum work loads. There were no statistically significant differences in f at the maximum work load between the R and C groups nor between male and female patients, and neither was there any significant increase of V_D with increasing maximum work load; but there was a correlation between maximum work load and decrease of V_D/V_T from resting to the respective working conditions in the male patients ($p < 0.025$) and a tendency to the same type of change in the females ($p < 0.20$). There was also a negative significant correlation between the maximum work load and V_D/V_T, under the respective

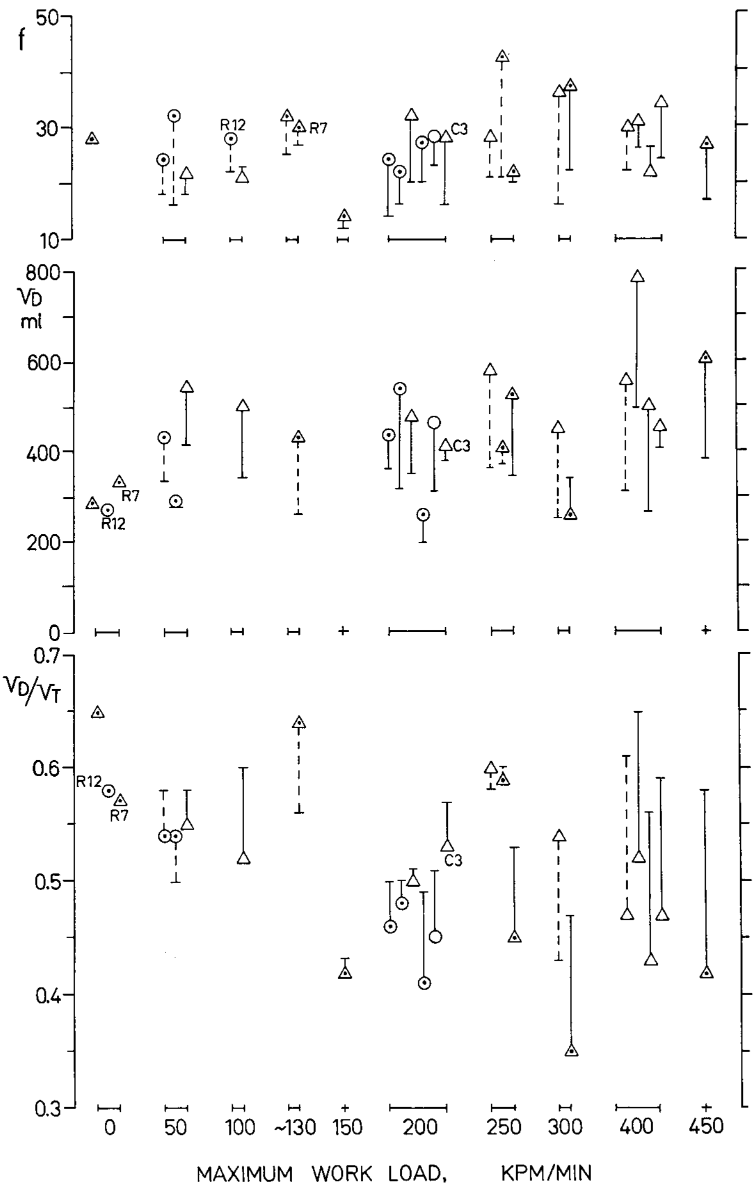

Fig. 2. Physiological dead space (V_D, ml BTPS) and physiological dead space-tidal volume (V_T, ml BTPS) ratio (V_D/V_T) in each patient at rest (⊢) and at the respective maximum work loads, except in patients R 7, R 12 and C 3 where they are given for submaximum conditions in R- and C-group patients. Symbols are as in Fig. 1.

conditions, both in the male ($r = -0.55$) and in the female ($r = -0.90$) patients. However, 3 patients (R6, R11 and C5) showed an increasing V_D/V_T ratio in connection with tachypnoea from rest to maximum work load and one (C10) from a submaximum to the maximum work load, which in all these patients was interrupted earlier than at 5 min. In all of them $\dot{V}_E$ exceeded the MVV (A) values obtained the day before and in 2 patients (R11 and C10) it reached and exceeded even the MVV (B) values. Patient R2 was able to continue with the maximum load of 250 kpm/min for 5 min with a practically unchanged high V_D/V_T ratio, and tachypnoea.

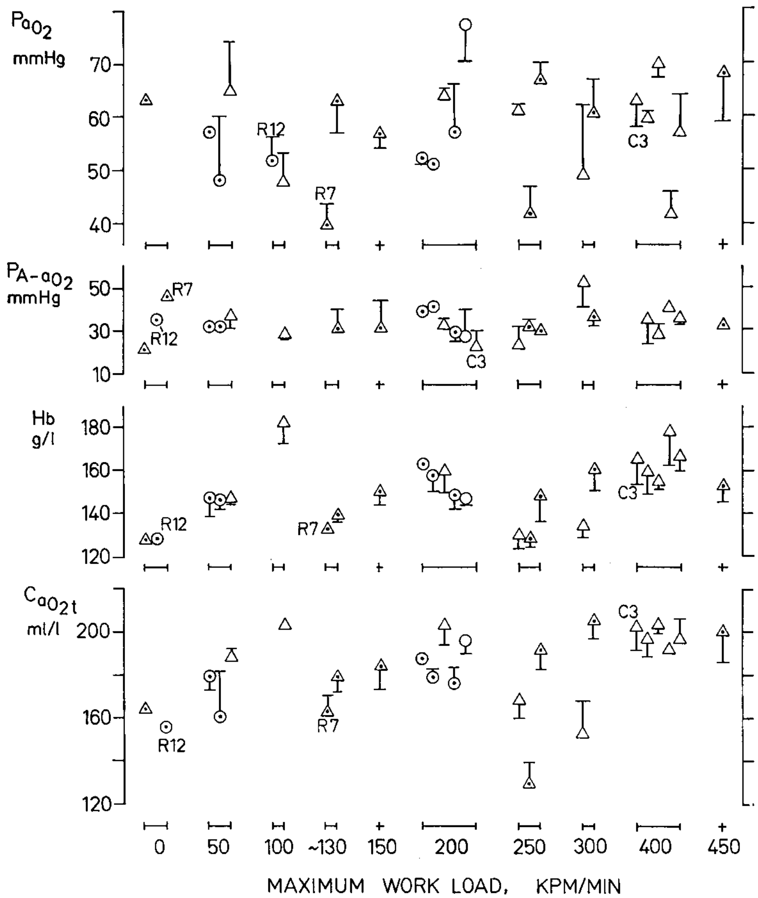

Fig. 3. Arterial oxygen tension (Pa_{O_2}, mmHg), alveolo-arterial oxygen tension difference ($PA{-}a_{O_2}$, mmHg), haemoglobin (Hb, g/l) and arterial oxygen content (Ca_{O_2t}, ml/l) in each patient at rest (⊢) and at the respective maximum work loads (kpm/min), except $PA{-}a_{O_2}$ in patients R 7, R 12 and C3 and Hb in R 12 where it is given for submaximum conditions, in R- and C-group patients. Symbols are as in Fig 1.

The correlation (Fig. 5) between the lowest FRC/TLC and RV/TLC ratios and V_D/V_T under maximum working conditions, in 22 patients (R 7, R 12 and C3 not included) can be expressed by the following equations: $V_D/V_T = -0.287+1.084 \times$ FRC/TLC (S.D. 0.053), $r=0.74$ and $V_D/V_T=0.079+0.696\times$ RV/TLC (S.D. 0.058), $r=0.67$.

The arterial oxygen tension (Pa_{O_2}, mmHg), alveolo-arterial oxygen tension difference ($PA{-}a_{O_2}$, mmHg), haemoglobin (Hb, g/l) and total arterial oxygen content (Ca_{O_2t}, ml/l) at rest and at the maximum work load are presented in Fig. 3. There was no significant relationship between these variables and the maximum work load. The Pa_{O_2} under maximum working conditions was 55.6 ± 2.3 (42–67) mmHg in the R group and 59.6 ± 3.1 (42–77) mmHg(NS) in the C group. At the maximum work load the Ca_{O_2t} in the R group was 177.6 ± 19.8 (130.3–205.8) and in the C group 191.0 ± 16.8 (153.4–203.7) ml/l ($p<0.10$) and at rest in the sitting posture in the R group 175.1 ± 14.6 (139.6–197.0) and in the C group 189.9 ± 14.1 (159.8–206.1) ml/l ($p<0.02$). The difference was also probably significant ($p<0.05$) between the male patients in the R and C groups at rest: R group 173.3 ± 17.0 (139.6–186.2) and C group 189.9 ± 14.9 (168.9–206.1). In some patients (R2, R7, R11 and C5) marked hypoxaemia, seen either already at rest or appearing during exercise, might be one of the reasons for tachypnoea and hyperventilation. In 2 patients (maximum work

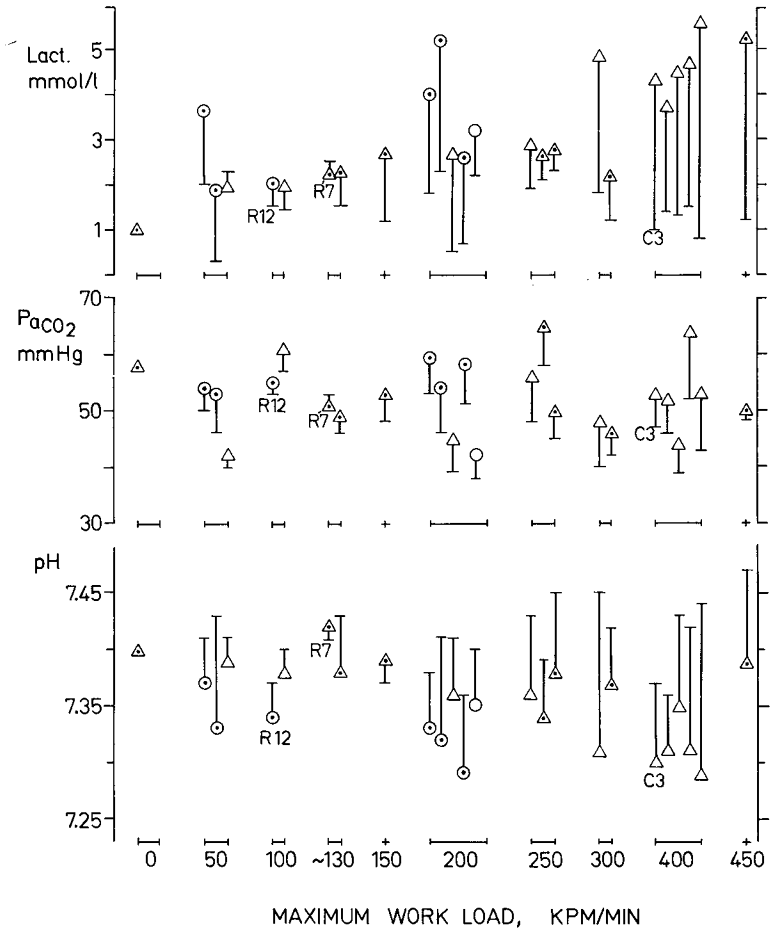

Fig. 4. Arterial lactate (Lact., mmol/l), carbon dioxide tension ($P_{a_{CO_2}}$, mmHg) and pH in each patient at rest (⊢) and at the respective maximum work loads in R- and C-group patients. Symbols are as in Fig 1.; for arterial lactate, the highest value, either during or 2–3 min after work, was chosen.

load in C2 400 and in C6 100 kpm/min) with haemoglobin values over 170 g/l, probably because of arterial hypoxaemia, the ventilatory reactions and pressure in the pulmonary circulation were different (Tammivaara-Hilty, to be published) despite an approximately similar carbon dioxide retention under maximum working conditions (64 and 61 mmHg).

In Fig. 4 the arterial lactate concentration (Lact., mmol/l), carbon dioxide tension ($P_{a_{CO_2}}$, mmHg) and pH values at rest and at the maximum work load or 2–3 min after (highest value chosen) are presented for each patient. The Lact. increased with the maximum work load in the 18 male ($r=0.80$) but less in the female ($r=0.48$) patients. The highest Lact. in the male patients was 3.4 ± 0.4 mmol/l and in the female patients 3.2 ± 0.5 mmol/l. The highest Lact. in the female patients (3.2 ± 0.5 mmol/l) was not significantly higher than in male patients (2.6 ± 0.4 mmol/l) of the R group. However, among the male patients there was a tendency ($p<0.10$) to higher Lact. in the C group (4.0 ± 0.6 mmol/l). The larger number of C-group males among the higher maximum work loads is worthy of note. At the maximum work load $P_{a_{CO_2}}$ was 53.9 ± 1.3 in the R group and 50.9 ± 5.1 mmHg in the C group (difference NS). Among the female patients $P_{a_{CO_2}}$ was lowest at the maximum work load in the only C-group female patient. In none of the groups was any significant correlation found between maximum work load and $P_{a_{CO_2}}$ at the respective loads. However, among 17 male

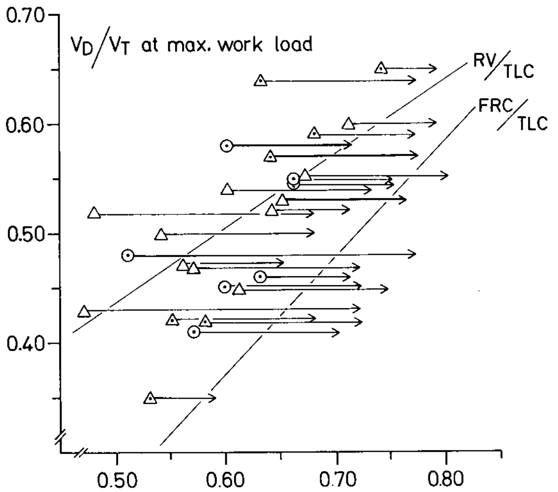

Fig. 5. The relationship between the lowest functional residual (FRC/TLC) and residual (RV/TLC) ratio at spirometry and the physiological dead space-tidal volume ratio (V_D/V_T) in maximum, or in R7, R12 and C3 sub-maximum working conditions (thick lines). The symbols for the R- and C-group female and male patients are as in Fig. 1 between RV/TLC and V_D/V_T and $\rightarrow$ = FRC/TLC in relation to V_D/V_T.

patients a positive correlation was noted between maximum work load and increase in Pa_{CO_2} from rest in the sitting posture to maximum load ($r=0.49$). This was not the case among the female patients.

The pH at maximum work load was 7.36 in the R group and 7.34 ± 0.01 in the C group (NS). In the R-group female patients (7.33 ± 0.01) and in the C-group male patients (7.34 ± 0.01) this was significantly lower ($p<0.005$) than in the R-group male patients (7.38). The difference was due to higher lactate and lower standard HCO_3^- concentration in the C-group male patients.

Fig. 6 presents the heart rate (*a*) at rest in the supine posture and (*b*) at rest and during exercise at the maximum work load in the sitting posture, in relation to oxygen uptake. Though 10 out of 14 R-group and 1 out of 11 C-group patients had digitalis, there were more patients with a high heart rate among the R-group patients. (All patients had sinus rhythm.) There was no significant difference in heart rate between the R and the C group either at rest or at the maximum work load (supine 90 ± 5 in the R and 84 ± 4 in the C group, sitting at rest 99 ± 5 in the R and 94 ± 4 in the C group and at maximum work load 127 ± 6 in the R and 121 ± 6 in the C group), but as there were more patients with low maximum oxygen uptake in the R group than in the C group the heart rate in relation to maximum oxygen uptake was higher in the R than in the C group.

As described in detail by Brundin & Tammivaara-Hilty (1972), patients R5, R6, R16 and C5 had had earlier or had at the time of the investigation ECG changes at rest which were interpreted as myocardial ischaemia. During the present work test C5 showed distinct ECG signs of coronary insufficiency but in patients R5, R8, R11, and C6 this was uncertain as they were taking digitalis. In patients R12 and R16 the origin of their marked ST-T changes already at rest was unclear because of digitalis. Patients R2, R7 and C11 had supraventricular arrhythmia (SVES) both at rest and during work and in patients R7, R13 and C6 monotopic ventricular ectopic beats appeared during work.

DISCUSSION

The present investigations demanded good co-operation and motivation to achieve a maximal performance; these were considered very satisfactory in the present severely disabled patients. Fluctuations and reversible components in airway obstruction gave rise to some variation in the results, however. In this

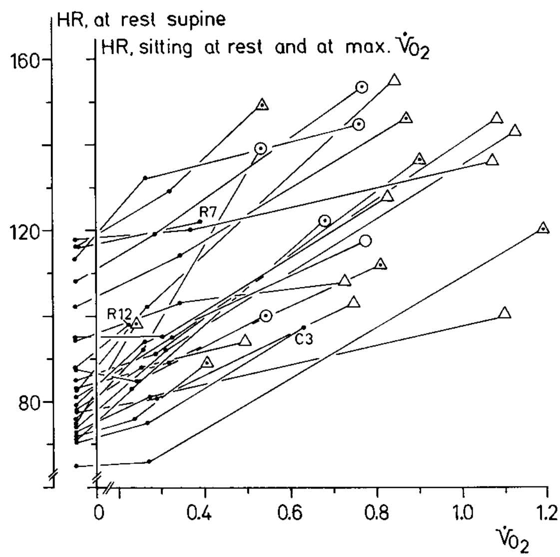

Fig. 6. Heart rate at rest supine, and at rest and at maximal physical exercise in the sitting posture, in relation to oxygen uptake ($\dot{V}_{O_2}$, l STPD/min) in R- and C-group patients. In patients R7 and 12 the highest $\dot{V}_{O_2}$ could be measured only at rest and in C3 at 200 kpm/min. Symbols for R- and C-group female and male patients are as in Fig. 1.

material the MVV values were considered to give a better picture of the dynamic ventilatory function than $FEV_{1.0}$, as MVV depends to a greater extent on the function of the respiratory muscles and as the actually achieved MVV values were compared with $\dot{V}_E$ in maximum working conditions. The correlations between $FEV_{1.0}$ and MVV_F both without and under the influence of a bronchodilating spray (A, $r=0.89$ and B, $r=0.86$) were highly significant (Brundin & Tammivaara-Hilty, 1972). Helium spirometry is known to give lower FRC and RV volumes than body plethysmography because of "air trapping" in patients with uneven intrapulmonary gas distribution. Significant correlations between V_D/V_T, measured in maximum working conditions, and FRC/TLC were, however, found in this material.

The measurements of the physical working capacity might have been influenced by the dead space of the ventilatory valve and the unusual test situation in that the patients have difficulty in communicating with the investigators. Most of the patients were, however, familiar with the work test, and as all patients were investigated in the same manner, the comparison between the patients should not have been influenced by these factors. In two of the patients (R6 and R11) the ventilatory valve caused such distress, probably because of the increase in dead space, that work loads which with the valve had to be terminated after 4 and 3 min, respectively, could be continued without a valve for 11.5 min (with a lower breathing frequency) in the first patient and for 30 min (with the same breathing frequency) in the second patient. In some of the most disabled patients W_{max} might have been somewhat better if the increase in work load had been more gradual. With one exception (C6) the loads chosen were, however, the lowest possible. When the gas exchange was measured at exercise breaking point, the steady state conditions were not fulfilled, but despite methodological errors the measurements were considered valid enough from a clinical point of view and to correspond better to the true maximum working conditions than measurements made in submaximum conditions. Further, it would not have been possible, for practical reasons, to arrange a test situation in working conditions on an ergometer bicycle where steady state conditions in the more severely ill patients would have been fulfilled. The use of Bohr's formula, with the approximation that $P_{A_{CO_2}}=P_{a_{CO_2}}$, causes larger methodological errors in patients with uneven pulmonary gas distribution than in normal persons. Duplicate estimations of W_{max} and gas exchange under the respective conditions were, however, not considered possible in our patients, in view of the unnecessary distress that would be caused, the increased risk of cardiac complications if the test had been repeated on the same day and the increased risk of arterial complications if the catheter had been left in place until the next day. The duplicate estimations at two separate exercise tests, mentioned under Methods, showed no other significant differences than lower $P_{A_{O_2}}$ and $P_{a_{O_2}}$ and higher $P_{a_{CO_2}}$ values at the first test situation with gas collection 3–6 min from the start of the exercise than at the second test with gas collection 12–15 min from the start. The differences, though significant, were small, however.

The relationship between maximal ventilatory and physical working capacity in chronic obstructive lung disease has been studied by a few authors (Gilbert et al., 1964; Simonsson et al., 1969; Marcus et al., 1970). As all these studies and the present one were combined with gas exchange investigation with the Douglas bag technique, they should be comparable. However, the present patients seemed, in general, to have a more severe airway obstruction. As mentioned earlier, breathing through a valve might have had a minor reducing effect on W_{max}. The assumption that airway obstruction, measured by the dynamic spirometric tests, is one of the most important factors in limiting the physical working capacity in patients with MVV $\leq 35\%$ of predicted normal values, was supported by the correlation found between MVV and W_{max}. A significant correlation has also been shown by Simonsson et al. between $FEV_{1.0}$ and "maximum work load" in chronic bronchitis patients, in whom FEV % was reduced to at least 1 S.D. below the predicted normal values. Neither in theirs nor in the present material was any significant correlation found between FEV% and physical working capacity, as the VC was also reduced. Even the small reversible airway obstruction components, which in less severe lung disease would be considered unimportant, seemed to increase the ventilation during exercise.

Dynamic ventilatory function was, however, obviously not the only limiting factor of the physical working capacity. Also FRC/TLC and RV/TLC, when TLC was calculated from VC measurements with bronchodilatation, were negatively correlated to the physical working capacity in kpm/min·kg and therefore may have played a role. These residual volume ratios were also measured in maximal working conditions. In the female patients, in whom no relationship between the ventilatory capacity and physical working capacity, either in absolute or relative values, could be found, an even closer relationship was found than in the male patients between maximum work load and V_D/V_T ratio under the respective conditions and between maximum work load and change in V_D/V_T ratio from rest to work. However, in a few male patients an increasing V_D/V_T ratio from submaximum to maximum working conditions was seen at the same time as the spirometric MVV values were exceeded and the dyspnoea caused tachypnoea, which led to a further increase in dead space ventilation, insufficient alveolar ventilation and consequent termination of the work test. As the V_D/V_T in these patients was not measured in steady state, the result has to be regarded with some reservation. Increasing V_D/V_T ratios in maximum steady state working conditions were, however, also observed by Jones (1966) in some patients, both with emphysema and chronic bronchitis.

Another factor responsible for the difference in the physical working capacity between the R and C groups was a combination of lower arterial oxygen tension, lower arterial oxygen capacity and higher heart rate in relation to maximum oxygen uptake in the R group, though in maximum working conditions none of these variables alone was significantly different from that of the C group. When the R-group male and female patients are compared, the male patients seem to be metabolically better compensated and peripherally less anaerobic in maximal working conditions than the female patients. This difference may be due to an inadequate cardiac output or to peripheral muscular and circulatory factors due to the sedentary life resulting from the severe respiratory disease. In a few patients coronary insufficiency and insufficient left ventricular function with increased filling pressures (measured as pulmonary capillary venous pressure; Tammivaara-Hilty, to be published) might both indirectly, by stimulating the ventilation, and directly, via an insufficient cardiac output, have limited the physical working capacity.

Marcus et al. (1970) considered that in emphysema with low elastic recoil it is the diffusing capacity and not the ventilatory capacity that limits the physical working capacity, because of the reduced pulmonary capillary bed. The diffusing capacity could not be measured in all the present patients nor was it possible to divide the patients into groups with pure emphysema and pure chronic bronchitis, as did Jones and Marcus et al., but the same tendency was found as was noted by these authors: patients with mainly emphysema had a lower diffusing capacity than those with mainly chronic bronchitis. However, it seems that in the present patients the ventilatory capacity and the dead space ventilation were the main limiting factors, though the minute ventilation, because of some reversibility in airway obstruction or change in breathing pattern, may have exceeded the spirometric MVV values.

Though the ventilatory and physical working capacity in these patients were significantly correlated, one measurement should not be used for predicting the other in the individual patient, as the influence of other factors, e.g. lung volumes and gas exchange during work, may vary.

As most of these patients are over middle-age and are smokers, they might well also have coronary sclerosis and relative coronary insufficiency or cardiac insufficiency from myocardial ischaemia during periods of absolute respiratory insufficiency with hypoxaemia. Therefore, if there is a need to know the degree of physical incapacity of the individual patient, a work test is indicated. If the same precautions are undertaken as in cardiac patients, i.e. examination of the case history, continuous clinical supervision with ECG registration for detection of ST-T changes and arrhythmia, and blood pressure measurements, the risk in performing near maximum work tests even in patients with a combination of severe chronic obstructive lung disease and cardiac disease is thought to be sufficiently low to be warranted in view of the information obtained. In this material there were no complications.

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