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Haemodynamics during maximal exercise after coronary bypass surgery

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SUMMARY Fifty patients underwent an objective measurement of physical working capacity by means of a multistage test of maximally tolerated exertion before and after coronary bypass surgery; 29 patients also had haemodynamic measurements during maximal exercise before and after coronary bypass surgery. The patients were divided into 3 groups according to the degree of revascularisation: adequate (n = 20), partial (n = 17), or none (n = 13).

Adequate revascularisation induces a large increase in physical working capacity because of an increased maximal heart rate and maximal cardiac output; stroke volume during maximal exercise and ejection fraction at rest were not modified, suggesting no major changes in left ventricular function. After unsuccessful coronary bypass surgery, the physical working capacity was unchanged despite an increased maximal heart rate; maximal cardiac output was unchanged and stroke volume during maximal exercise was significantly lower. These undesirable results are often associated with perioperative myocardial infarction and are attended by a decreased ejection fraction at rest; these data suggest an impaired left ventricular function after unsuccessful coronary bypass surgery. The results of partial revascularisation are intermediate but appear to be determined by the incidence of partial graft failure which is also often associated with perioperative myocardial infarction.

From individual changes in data collected during maximal exercise testing, it is often impossible to predict the degree of revascularisation.

Aortocoronary bypass surgery improves or relieves angina pectoris in 60 to 90 per cent of the patients (Ross, 1975). These figures are most often based on a purely clinical evaluation and only a few reports include objective assessment of the physical working capacity, that is pre- and postoperative maximal exercise tests (Bartel *et al.*, 1973; Guiney *et al.*, 1973; Lapin *et al.*, 1973; Balcon *et al.*, 1974; Knoebel *et al.*, 1974; Frick *et al.*, 1975; Merrill *et al.*, 1975; Siegel and Loop, 1976).

The effects of coronary bypass surgery on the haemodynamic response to exercise largely remain to be established since the few available studies include only data collected during mild exercise (Rutherford *et al.*, 1972; Campeau *et al.*, 1974; Barry *et al.*, 1976) or they do not enable one to relate the observed changes to the graft status (McDonough *et al.*, 1974).

The purposes of the present study were to correlate the changes in physical working capacity after coronary bypass surgery with the degree of revascularisation and to determine the haemodynamic modifications underlying these changes. It involved direct measurement of the physical working capacity by maximal exercise testing together with selective coronary arteriography and left ventriculography before and 3 months after coronary bypass surgery. A wide subset of patients (29/50) also had haemodynamic measurements during maximally tolerated exertion before and after coronary bypass surgery.

Subjects

Fifty patients (46 men and 4 women) were included in this study. They underwent a coronary bypass surgical procedure for the treatment of severe angina pectoris refractory to medical treatment. Before operation, they had no clinical signs of heart failure and their preoperative ejection fraction was above 50 per cent. Eleven patients had electrocardiographic signs of healed myocardial infarction before

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operation. The study group was selected from 252 operated patients who had undergone an objective assessment of graft status 3 months after operation. From these 252 patients, 103 had preoperative exercise studies and these exercise studies were repeated 3 months after operation in only 50 patients who constitute the material of the present study. The major reasons for not repeating the exercise studies 3 months after operation in 53 patients were the excellent subjective results which were considered by the referring physician as sufficient evidence for surgical success. Patients with doubtful or poor subjective results are, therefore, over-represented; this accounts for the low graft patency rate (62%) observed in the present group, contrasting with the 79 per cent patency rate observed in our total group of 252 patients (up to November 1976).

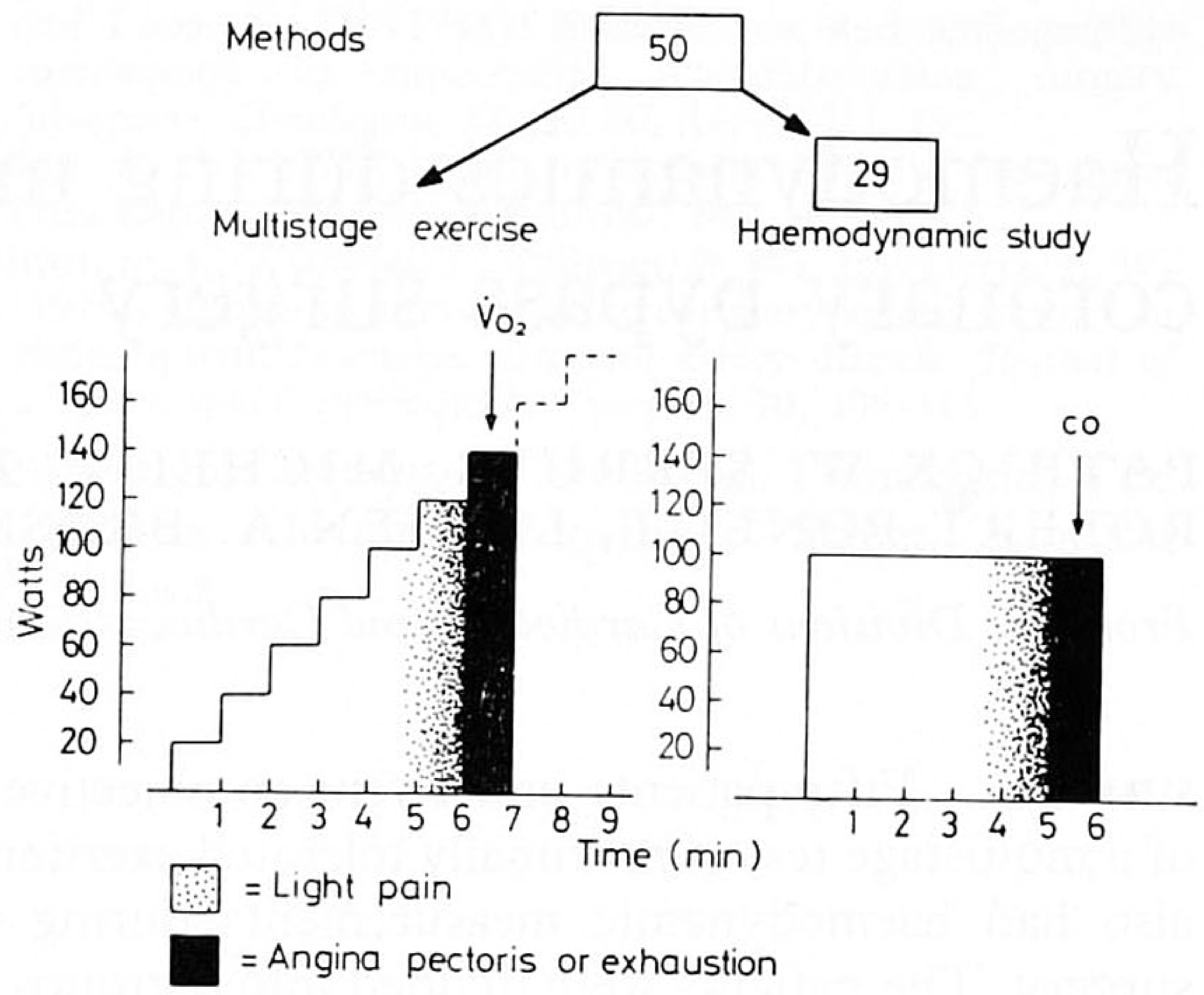

Fig. 1 *Procedure of the study.*

Methods

The methods for maximal exercise testing were as previously reported (Rousseau *et al.*, 1973; Detry *et al.*, 1975). Briefly, a few days before the pre- and postoperative arteriographic study all patients performed a multistage uninterrupted test of maximal exercise on a bicycle ergometer in order to measure their physical working capacity, that is the oxygen consumption at maximally tolerated exercise ($\dot{V}_{O_2}SL$ $\dot{V}_{O_2}$ max) and the maximal heart rate (HR). The initial workload was 20 watts for 1 minute and the intensity of the exercise was then increased every minute by 20 watts: the exercise test was continued until typical angina pectoris developed or until subjective exhaustion. The electrocardiogram was recorded on paper at 1 minute intervals and it was visually analysed; the horizontal or downsloping depression of the ST segment was measured at the J point with the intersection of the PR interval with the QRS as zero voltage reference. The methods for collecting expiratory gases and measuring oxygen consumption were previously reported (Detry *et al.*, 1972). Beta-blocking agents were discontinued at least 48 hours before the exercise test and no patient was on digitalis therapy. The results of this non-invasive exercise test were used to select the workloads to be used during the haemodynamic study (Fig. 1).

The procedure for the preoperative haemodynamic study in 26 patients included haemodynamic measurements during exercise-induced angina pectoris; the workload corresponding to the anginal level was selected so as to precipitate angina pectoris after 4 to 5 minutes. In 3 additional patients, angina pectoris could not be precipitated by exercise before operation and the maximal workload was interrupted for dyspnoea and fatigue. Depending on the results of the exercise test, the postoperative maximal workload used for the haemodynamic study was either lower, the same, or greater than the preoperative one; it induced angina pectoris in 6 patients and corresponded to subjective exhaustion without angina pectoris in the remaining 23 patients.

The cardiac output was measured in the sitting position during the last minute of the maximal workload using the Fick principle. The catheters were introduced percutaneously as described previously, and the blood oxygen content was measured with the Lex-O_2-CON analyser (Clerbaux *et al.*, 1973). The pressure-rate product was calculated as the product of heart rate and mean brachial artery pressure.

Coronary arteriography was performed by the femoral route using the method of Bourassa (Lesperance *et al.*, 1970). The coronary arteriograms and the selective injections of the grafts were always preceded by left ventricular ventriculography in the right

Table 1 *Clinical and angiographic data*

	Revascularisation		
	Adequate (*n* = 20)	*Partial* (*n* = 17)	*No* (*n* = 13)
Age	50	50	48
Number of diseased vessels	2·0	2·5	2·3
Number of grafts	28	28	18
Status of the graft:			
Patent	28	18	—
Occluded	—	10	18
Myocardial infarction (ECG):			
Preop	7	2	2
Postop	7	7	8

anterior oblique position. The films were reviewed independently by 2 separate investigators. The coronary lesions and status of the grafts were scored according to the recommendations of the American Heart Association (Austen *et al.*, 1975). The left ventricular ejection fraction was calculated using the area-length method: postectopic beats were disregarded.

The patients received 74 saphenous vein grafts; 27 patients had a single graft, 22 a double graft, and 1 a triple graft. The patients have been divided in 3 groups according to the degree of revascularisation which was determined as follows (Table 1).

Adequate revascularisation (group 1; n = 20; 28 grafts): all artery with stenoses ≥ 50 per cent were successfully grafted. Ten patients with a complete obstruction of 1 (n = 9) or 2 (n = 1) coronary artery are included in this group; the distal portion of these obstructed arteries was not visualised at preoperative arteriography, and endarterectomy was never attempted.

Partial revascularisation (group 2; n = 17; 28 grafts): partial graft failure (n = 10; 20 grafts) or some stenotic coronary lesions not bypassed because of the poor condition of the distal artery (n = 7; 8 grafts).

No revascularisation (group 3; n = 13; 18 grafts): total graft failure.

Evidence of peri- or postoperative myocardial infarction was based only on the development of new pathological Q waves (Assad-Morell *et al.*, 1975).

Statistical analysis of the data was done using the paired t test of Student.

Informed consent was obtained from each patient and no complications occurred as a result of the experimental procedure.

Results

By definition, the patency rate was 100 per cent in group 1 and 0 per cent in group 3; in group 2, 64 per cent of the grafts were patent after operation (Table 1). After coronary bypass surgery, postoperative myocardial infarctions were never observed in group 1 but they were present in 46 per cent (6/13) of the patients of group 3 and in 29 per cent (5/17) of the patients of group 2; all patients of group 2 with postoperative myocardial infarction had partial graft failure. From these 11 postoperative myocardial infarctions, 9 were in the myocardial zone supplied by a grafted artery (8 occluded grafts and 1 patent graft) and 2 were in a myocardial zone supplied by a diseased ungrafted artery.

All individual data are listed in Table 2 which also presents for each group and subgroup the mean values of the data collected during maximal exercise testing. The changes in physical working capacity are clearly related to the degree of revascularisation since physical working capacity increased by 47 per cent in group 1, 23 per cent in group 2, and was not significantly modified in group 3; similar increases in the maximal heart rate were, however, noted in the 3 groups. After coronary bypass surgery, angina pectoris at maximal exercise disappeared in 83 and 87 per cent of the patients of group 1 and 2 but 58 per cent of the patients of group 3 were no longer limited by angina after unsuccessful surgery. Electrocardiographic signs of myocardial ischaemia during maximal exercise were significantly reduced in groups 1 and 2 and unmodified in group 3. Finally, the ejection fraction measured at rest was significantly lower after surgery in group 3.

Haemodynamic data at the maximal exercise level are available in 3 subsets of patients whose changes in $\dot{V}_{O_2}$ max, maximal heart rate, angina pectoris, and ejection fraction were similar to those observed in the 3 groups of patients (Table 2). The 50 per cent greater $\dot{V}_{O_2}$ max in group 1 resulted from significant increases in maximal heart rate (+ 28%) and maximal cardiac output (+ 35%) without modification of the stroke volume during maximal exercise; simultaneously, the pressure-rate product increased by 43 per cent while the $(AV)O_2$ difference reached normal maximal values. The data collected in the 10 patients of group 1 with an ungrafted occluded coronary artery were similar to those obtained in the other patients of group 1. In group 3, the unchanged $\dot{V}_{O_2}$ max was attended by a slight decrease in the maximal cardiac output despite a 15 per cent increase in maximal heart rate; the stroke volume during maximal exercise was 18 per cent lower after operation in this group while the ejection fraction was 12 per cent lower. Intermediate changes were noted in group 2.

From the individual changes in stroke volume during maximal exercise (Fig. 2) it is apparent that the most striking decreases in stroke volume were observed in patients with a postoperative myocardial infarct. After coronary bypass surgery, in group 3, the stroke volume was 22 per cent lower (from 90 to 70 ml) in the 4 patients with postoperative myocardial infarction and 15 per cent lower (from 81 to 69 ml) in the 5 patients without electrocardiographic signs of postoperative myocardial infarction.

Since graft failure and incidence of postoperative myocardial infarction appear to determine the changes in physical working capacity, the 17 patients in group 2 have been further subdivided into 2 smaller groups: those with incomplete surgery and

Table 2 *Individual data*

No.		*Sex*	*Age*	*Myocardial infarction (ECG)*	*Coronary arteriography* LM	*LAD*	*Circ.*	*RCA*	*Ejection fraction (%)*
Group 1: Adequate revascularisation									
1	Pre	M	48	—	—	90	—	—	88
	Post			—	—	P_o	—	—	94
2	Pre	M	62	—	—	90	90	100	69
	Post			—	—	P_o	P_o	—	59
3	Pre	M	31	Inf.	—	—	100	90	50
	Post			Inf.	—	—	—	P_o	41
4	Pre	M	51	—	—	—	—	75	78
	Post			—	—	—	—	P_o	65
5	Pre	M	45	Inf.	—	90	75	100	62
	Post			Inf.	—	P_o	P_o	—	72
6	Pre	M	47	Inf.	—	90	—	100	51
	Post			Inf.	—	P_o	—	—	57
7	Pre	M	51	—	—	90	—	—	64
	Post			—	—	P_o	—	—	76
8	Pre	M	47	Inf.	—	90	—	100	51
	Post			Inf.	—	P_o	—	—	60
9	Pre	M	60	—	—	75	90	90	70
	Post			—	—	P_o	P_o	P_o	79
10	Pre	F	43	—	—	—	—	90	76
	Post			—	—	—	—	P_o	79
11	Pre	M	46	—	—	90	—	100	65
	Post			—	—	P_o	—	—	66
Mean 1-11	Pre		48						66
	Post								68
	%								+ 4
	P								NS
12	Pre	M	51	Inf.	—	75	75	100	61
	Post			Inf.	—	P_o	P_o	—	58
13	Pre	M	65	—	—	75	90	100	82
	Post			—	—	P_o	P_p	—	61
14	Pre	M	44	—	—	90	75	100	62
	Post			—	—	P_p	P_o	—	63
15	Pre	M	48	—	—	90	—	—	76
	Post			—	—	P_o	—	—	68
16	Pre	M	51	Inf.	—	90	100	100	58
	Post			Inf.	—	P_p	—	—	53
17	Pre	M	46	—	—	90	—	—	60
	Post			—	—	P_o	—	—	66
18	Pre	F	52	—	—	50	—	—	87
	Post			—	—	P_p	—	—	87
19	Pre	M	49	Inf.	—	90	—	90	57
	Post			Inf.	—	P_o	—	P_o	71
20	Pre	M	54	—	—	—	—	70	63
	Post			—	—	—	—	P_o	50
Mean 1-20	Pre		50						66
	Post								66
	%								—
	P								NS
Group 2: Partial revascularisation									
21	Pre	M	55	—	90	75	75	100	77
	Post			—	—	O_p	P_p	—	50
22	Pre	M	41	—	90	—	75	50	58
	Post			Lat.	—	P_o	O_o	—	54
23	Pre	M	53	Inf.	—	90	—	50	87
	Post			Inf.	—	P_o	—	—	87
24	Pre	M	63	Inf.	—	75	100	75	66
	Post			Inf.	—	P_p	—	O_p	66
25	Pre	M	51	—	—	90	—	75	70
	Post			—	—	P_p	—	—	77
26	Pre	M	46	—	—	90	—	50	59
	Post			—	—	P_o	—	—	70
27	Pre	M	44	—	90	90	90	—	60
	Post			Inf.	—	P_p	O_o	—	44
28	Pre	M	53	—	—	75	—	90	58
	Post			Inf.	—	P_p	—	O_o	41
29	Pre	M	39	—	—	90	—	50	74
	Post			—	—	P_p	—	—	80
Mean 21-29	Pre		49						68
	Post								63
	%								−7
	P								NS

Workload (watts)	Angina	Data during maximally tolerated exercise: ST depression (mm)	$\dot{V}O_2$ (l/min)	HR (beats/min)	SV (ml/beat)	CO (l/min)	HR × $\overline{BP}$ (mmHg/min^{-2})	$\overline{P_{AP}}$ (mmHg)
100	Yes	−2·5	1·35	126	75	9·4	176	40
170	No	—	2·06	158	80	12·6	265	30
40	Yes	—	0·72	85	89	7·6	82	24
120	No	−3·0	1·39	147	73	10·7	194	31
160	Yes	—	2·07	176	79	14·0	246	48
160	No	—	1·79	175	65	11·7	226	40
150	No	−1·0	1·75	148	80	11·8	178	24
150	No	−0·5	1·76	124	110	13·7	145	27
50	Yes	−2·0	0·89	101	76	7·7	109	27
150	No	—	1·82	160	88	14·1	230	30
90	Yes	−2·0	1·10	132	58	7·6	211	52
150	No	—	1·80	162	72	11·7	143	33
70	Yes	−1·5	1·11	134	79	10·6	204	28
130	No	−2·2	1·54	168	80	13·4	228	33
75	Yes	−1·0	1·01	114	66	7·5	128	39
125	Yes	−1·2	1·88	166	76	12·7	229	34
20	Yes	−4·5	0·38	96	78	7·5	155	22
170	No	—	1·84	177	78	13·9	276	40
100	Yes	−1·0	1·24	138	72	10·0	163	24
100	No	−0·7	1·27	157	74	11·6	195	27
75	Yes	−1·5	1·03	126	72	9·0	164	30
140	No	−1·5	1·83	163	67	11·9	248	34
84	10	−1·5	1·15	125	75	9·3	155	32
142	1	−0·8	1·73	160	78	12·6	221	33
+69	−90	−47	+50	+28	+4	+35	+43	—
0·005	—	NS	0·005	0·005	NS	0·005	0·01	NS
140	Yes	−3·0	1·60	130				
160	No	—	1·80	180				
100	Yes	−2·0	1·20	103				
160	No	—	1·80	142				
100	Yes	−2·5	1·30	155				
220	No	—	2·40	175				
100	Yes	−2·0	1·09	118				
220	No	−2·2	2·46	185				
140	Yes	−1·0	1·40	120				
160	No	−2·0	1·30	165				
110	Yes	−2·5	1·30	147				
185	No	−1·2	1·78	150				
120	Yes	−2·0	0·95	160				
90	Yes	−1·5	0·94	155				
100	Yes	−3·0	1·06	120				
200	No	−2·5	2·07	152				
160	No	−1·5	1·39	160				
160	No	−1·0	1·77	180				
100	18	−1·8	1·20	129				
156	3	−1·0	1·77	162				
+56	83	−44	+47	+25				
0·001	—	0·05	0·001	0·001				
50	Yes	−5·0	0·92	112	63	7·1	126	38
90	Yes	−3·0	1·23	142	70	9·9	171	37
100	Yes	−3·5	1·36	130	81	10·5	182	58
200	No	—	2·42	178	84	14·9	256	48
100	Yes	−2·0	1·29	151	63	9·6	211	35
150	No	−0·5	1·84	164	83	13·7	236	32
150	Yes	−4·5	1·94	152	84	12·7	195	50
150	No	—	1·89	162	92	14·9	209	21
75	Yes	—	0·93	68	97	6·6	79	40
170	No	−1·0	2·04	155	88	13·6	205	38
50	Yes	−2·2	1·10	118	86	10·2	149	48
175	No	—	2·38	176	77	13·5	211	35
100	Yes	−3·0	1·24	141	65	9·2	180	42
50	Yes	−1·0	0·79	152	37	5·6	188	46
100	Yes	—	1·29	108	95	10·3	134	29
160	No	—	1·47	168	58	9·7	215	37
180	No	—	2·29	179	92	16·5	226	25
180	No	—	2·34	180	91	16·4	220	30
101	8	−2·2	1·37	129	81	10·3	166	41
147	2	−0·6	1·82	164	76	12·5	220	36
+46	75	−73	+33	+27	−6	+21	+33	−12
0·05	—	0·02	NS*	0·01	NS	NS*	0·01	NS

Table 2 *Individual data—continued*

No.		*Sex*	*Age*	*Myocardial infarction (ECG)*	*Coronary arteriography* *LM*	*LAD*	*Circ.*	*RCA*	*Ejection fraction (%)*
30	Pre	M	53	—	—	90	50	75	66
	Post			—	—	O_o	—	P_o	74
31	Pre	M	49	—	—	90	75	100	70
	Post			—	—	O_p	—	P_p	65
32	Pre	M	42	—	—	90	75	90	59
	Post			Inf.	—	O_p	—	P_o	52
33	Pre	M	44	—	—	90	90	—	76
	Post			—	—	P_o	—	—	72
34	Pre	M	64	—	75	75	—	90	77
	Post			AS	—	O_p	—	P_o	50
35	Pre	M	54	—	—	90	90	50	77
	Post			—	—	P_o	O_p	—	80
36	Pre	M	50	—	—	—	75	90	73
	Post			—	—	—	—	P_o	83
37	Pre	M	49	—	—	90	75	75	79
	Post			—	—	P_o	—	P_o	67
Mean 21-37	Pre		50						70
	Post								65
	%								−6
	P								NS
Group 3: No revascularisation									
38	Pre	M	45	—	—	50	75	75	72
	Post			—	—	O_o	—	O_p	63
39	Pre	M	52	—	75	75	—	75	53
	Post			—	—	O_o	O_o	—	49
40	Pre	M	39	Inf.	—	90	50	100	57
	Post			Inf.	—	O_o	—	—	44
41	Pre	F	61	—	—	90	90	100	79
	Post			—	—	O_o	—	—	63
42	Pre	M	39	Inf.	—	50	75	100	66
	Post			Inf.	—	O_o	—	—	74
43	Pre	M	53	—	—	75	75	100	72
	Post			Inf.	—	O_p	O_p	—	48
44	Pre	M	47	—	—	90	—	—	76
	Post			Ant.	—	O_p	—	—	80
45	Pre	M	47	—	—	90	—	—	87
	Post			AS	—	O_o	—	—	89
46	Pre	M	48	—	—	90	—	—	84
	Post			AS	—	O_o	—	—	60
Mean 38-46	Pre		48						72
	Post								64
	%								−12
	P								NS*
47	Pre	F	39	—	50	75	—	—	67
	Post			—	—	O_o	—	—	77
48	Pre	M	48	—	—	90	—	—	79
	Post			Ant.	—	O_o	—	—	44
49	Pre	M	58	—	—	50	90	90	61
	Post			—	—	—	O_p	O_o	64
50	Pre	M	48	—	—	90	75	75	85
	Post			Ant.	—	O_o	—	O_p	66
Mean 38-50	Pre		48						72
	Post								63
	%								−12
	P								0·05

Abbreviations: M, male; F, female; Inf., inferior; Ant., anterior; AS, anteroseptal; Lat., lateral; LM, left main coronary artery; LAD, left anterio descending artery; Circ., circumflex artery; RCA, right coronary artery; P, patent graft; O, occluded graft; P_o, O_o, occlusion of the proximal stenosis P_p, O_p, patency of the proximal stenosis; $\dot{V}O_2$, oxygen consumption; HR, heart rate; SV, stroke volume; CO, cardiac output; $\overline{BP}$, mean brachial arter pressure; $\overline{P_{AP}}$, mean pulmonary artery pressure; NS*, $0{\cdot}05 < P < 0{\cdot}10$.

Workload	*Angina*	*Data during maximally tolerated exercise*						
(watts)		*ST depression* *(mm)*	$\dot{V}O_2$ *(l/min)*	*HR* *(beats/min)*	*SV* *(ml/beat)*	*CO* *(l/min)*	$HR \times \overline{BP}$ *(mmHg/min^{-2})*	$\overline{P_{AP}}$ *(mmHg)*
65	Yes	−1·0	1·89	168				
55	No	—	1·74	170				
60	Yes	−4·0	1·64	136				
20	No	−4·0	2·02	175				
25	Yes	−0·7	1·29	133				
40	No	−2·0	1·50	170				
60	Yes	−6·0	1·85	153				
60	No	−0·5	2·74	180				
45	Yes	−2·0	1·47	115				
55	No	−1·7	1·52	138				
55	Yes	−2·7	1·84	180				
85	No	−1·5	1·93	170				
80	No	−2·5	1·90	145				
85	No	—	1·97	175				
20	Yes	−3·0	1·34	130				
60	No	−3·5	1·64	180				
24	15	−2·5	1·50	136				
64	2	−1·1	1·85	167				
+32	87	−56	+23	+22				
0·005	—	0·01	0·01	0·001				
50	Yes	−2·0	2·24	140	110	15·4	179	23
00	Yes	−2·0	1·53	140	85	11·9	213	36
00	Yes	−2·5	1·63	158	75	11·9	202	30
00	Yes	−3·5	1·49	179	59	10·6	240	26
00	Yes	—	1·26	138	68	9·3	185	24
00	No	−1·0	1·36	110	65	7·2	152	32
50	Yes	−3·0	0·89	108	63	6·8	97	24
75	Yes	−1·5	1·09	144	59	8·5	115	27
50	No	−1·0	2·51	168	88	14·7	242	37
50	No	—	2·29	178	80	14·3	263	36
00	Yes	−2·0	1·07	120	66	7·9	163	54
50	No	—	1·49	163	50	8·1	196	59
00	Yes	−2·0	1·51	120	113	13·6	122	23
90	No	—	2·18	167	84	14·0	240	30
20	Yes	+2·0	1·43	132	85	11·2	158	30
50	No	+2·0	2·11	168	78	13·2	242	24
70	Yes	−1·5	2·06	158	98	15·6	177	30
70	No	—	2·05	184	74	13·7	217	31
16	8	−1·7	1·62	138	85	11·8	169	31
32	3	−0·7	1·73	159	70	11·3	209	34
+14	62	−59	+7	+15	−18	−4	+24	+10
NS	—	NS	NS	0·05	0·005	NS	0·02	NS
20	Yes	−1·0	1·00	132				
40	No	—	1·28	145				
30	Yes	−1·0	0·99	94				
20	Yes	−2·0	1·17	142				
75	Yes	−7·0	2·14	150				
90	No	−8·0	2·16	163				
00	Yes	−2·2	1·10	92				
40	Yes	−2·7	1·14	128				
16	12	−1·8	1·52	131				
36	5	−1·4	1·64	154				
+17	58	−19	+8	+18				
NS*	—	NS	NS	0·005				

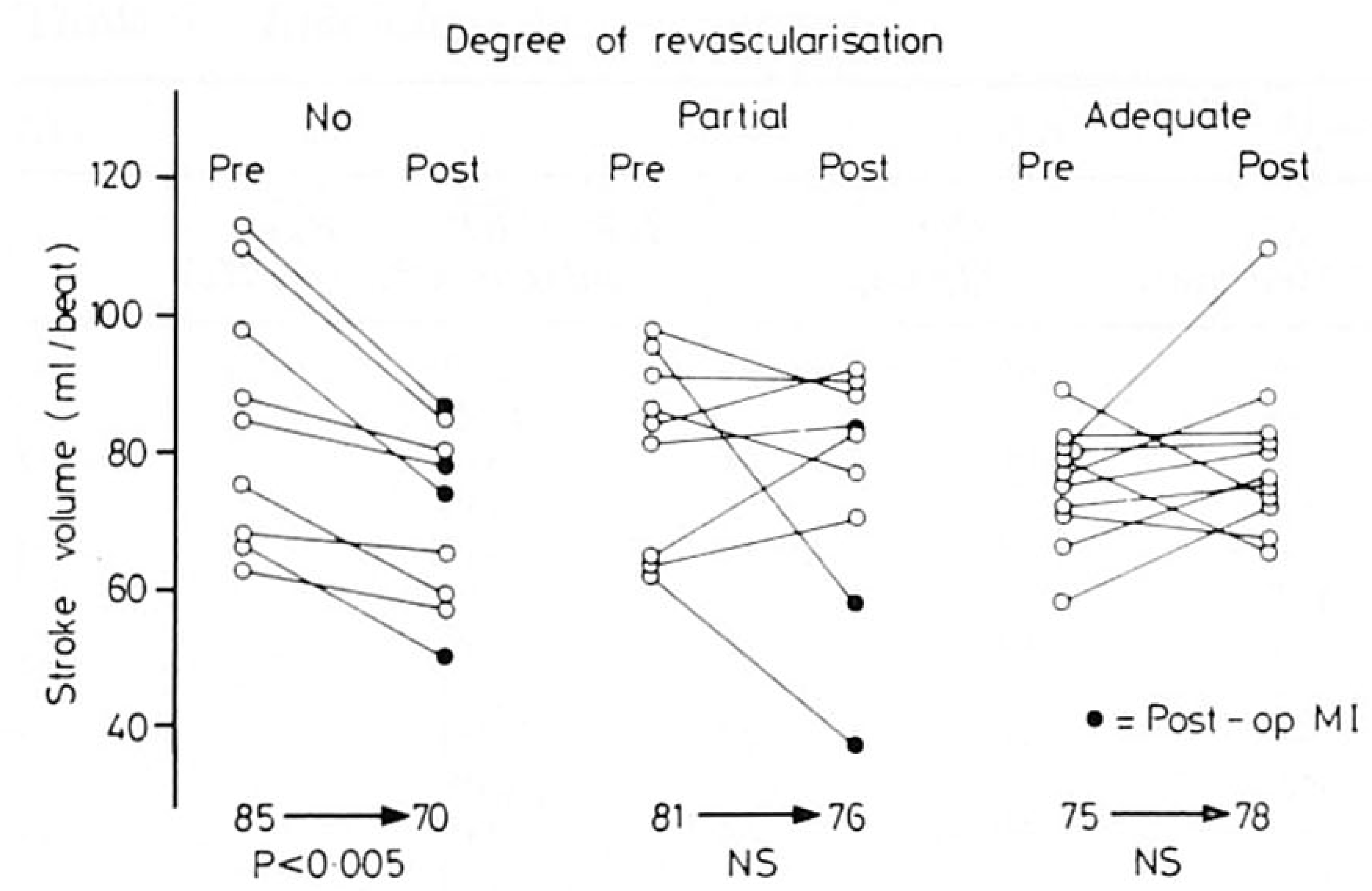

Fig. 2 *Individual changes in stroke volume during maximally tolerated exercise after coronary bypass surgery.*

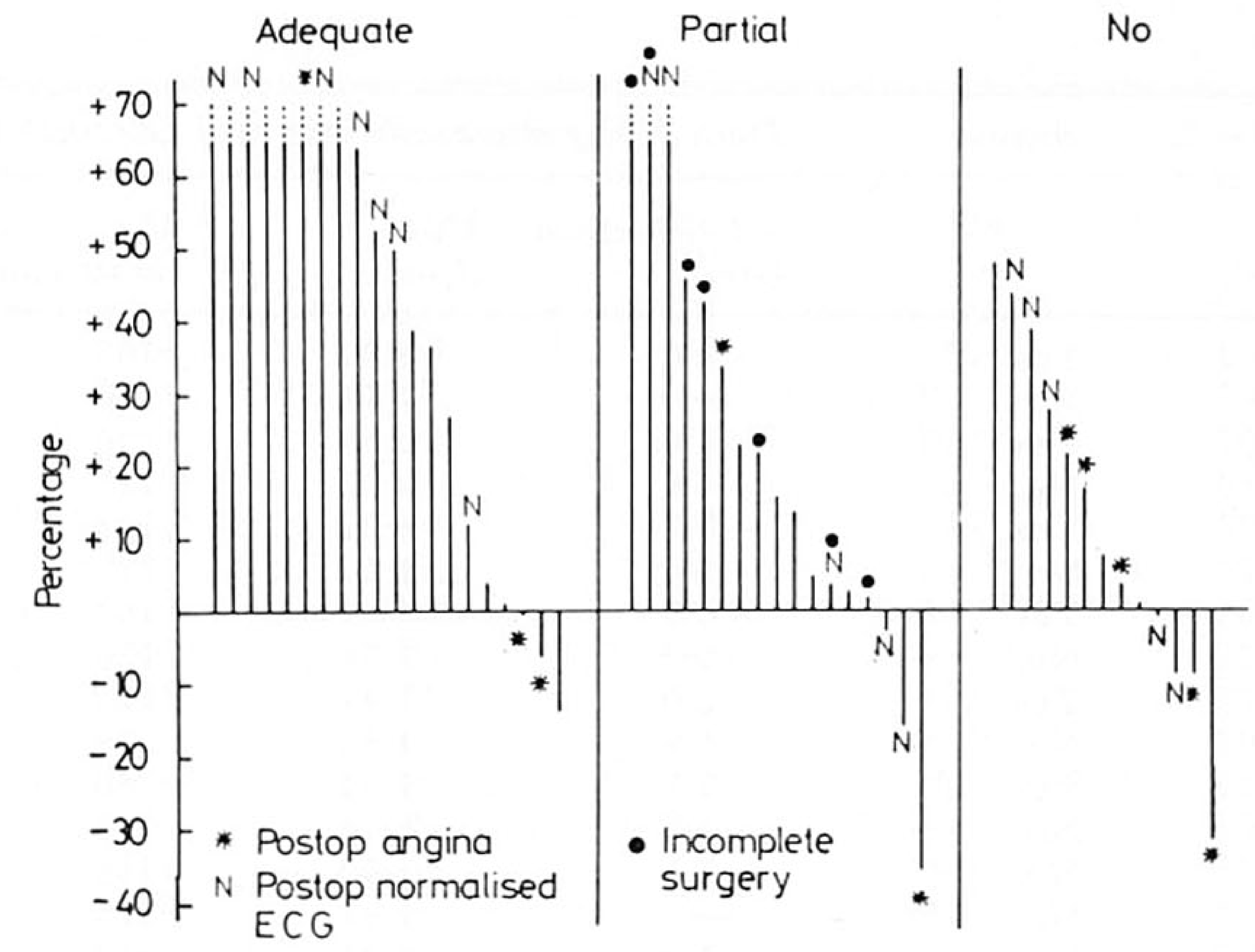

Fig. 3 *Individual changes in physical working capacity ($\dot{V}O_2$ max or $\dot{V}O_2SL$) after coronary bypass surgery.*

those with partial graft failure (Table 3). Though the number of patients in each subgroup is small, these data suggest that the effects of partial graft failure are similar to those of total graft failure while the results of incomplete surgery look similar to those of adequate revascularisation.

From the individual changes in physical working capacity, it was not easy to predict the degree of revascularisation (Fig. 3); all 14 patients with a 50 per cent or larger increase in $\dot{V}O_2$ max had adequate (11) or partial (3) revascularisation, while among the 19 patients with less than a 10 per cent increase in $\dot{V}O_2$ max, 12 had adequate or partial revascularisation and 7 had no revascularisation. Allowing for the complete normalisation of the exertional electrocardiogram and the persistence of exertional angina pectoris we could not give a better prediction of the degree of revascularisation. The overlap between the groups was still more pronounced when individual changes in maximal heart rate were considered (Fig. 4).

Table 3 *Changes after coronary bypass surgery in the patients with partial revascularisation*

	Incomplete revascularisation (*n* = 7)	*Partial graft failure* (*n* = 16)
Grafts: patent	8	10
occluded	—	10
VO_2 'max or SL'	+40%†	+11%
HR max	+28%†	+18%†
Postop angina	0/7	2/10
Postop MI	0/7	5/10
Ejection fraction	+3%	−14%
SV max*	—	−12%
CO max*	+34%	+11%
HR × BP max*	+31%	+34%†

*: 4 patients with incomplete revascularisation and 5 patients with partial graft failure.
†: P < 0·05; all other changes are not significant.

Discussion

The patients have been subdivided into 3 groups according to the degree of revascularisation which has been considered as adequate, partial, or none. This subdivision does not affect the data collected in the patients with adequate or no revascularisation; among the patients with adequate revascularisation, the presence in 10 patients of an ungrafted occluded artery did not influence the surgical results. As will be discussed below, the group with partial revascularisation is not homogeneous since patients with incomplete surgery appear to differ from those with partial graft failure. The subdivision into 3 groups is entirely based on postoperative data and the latter account for slight differences in the preoperative condition of the patients; those with adequate revascularisation had a slightly less severe

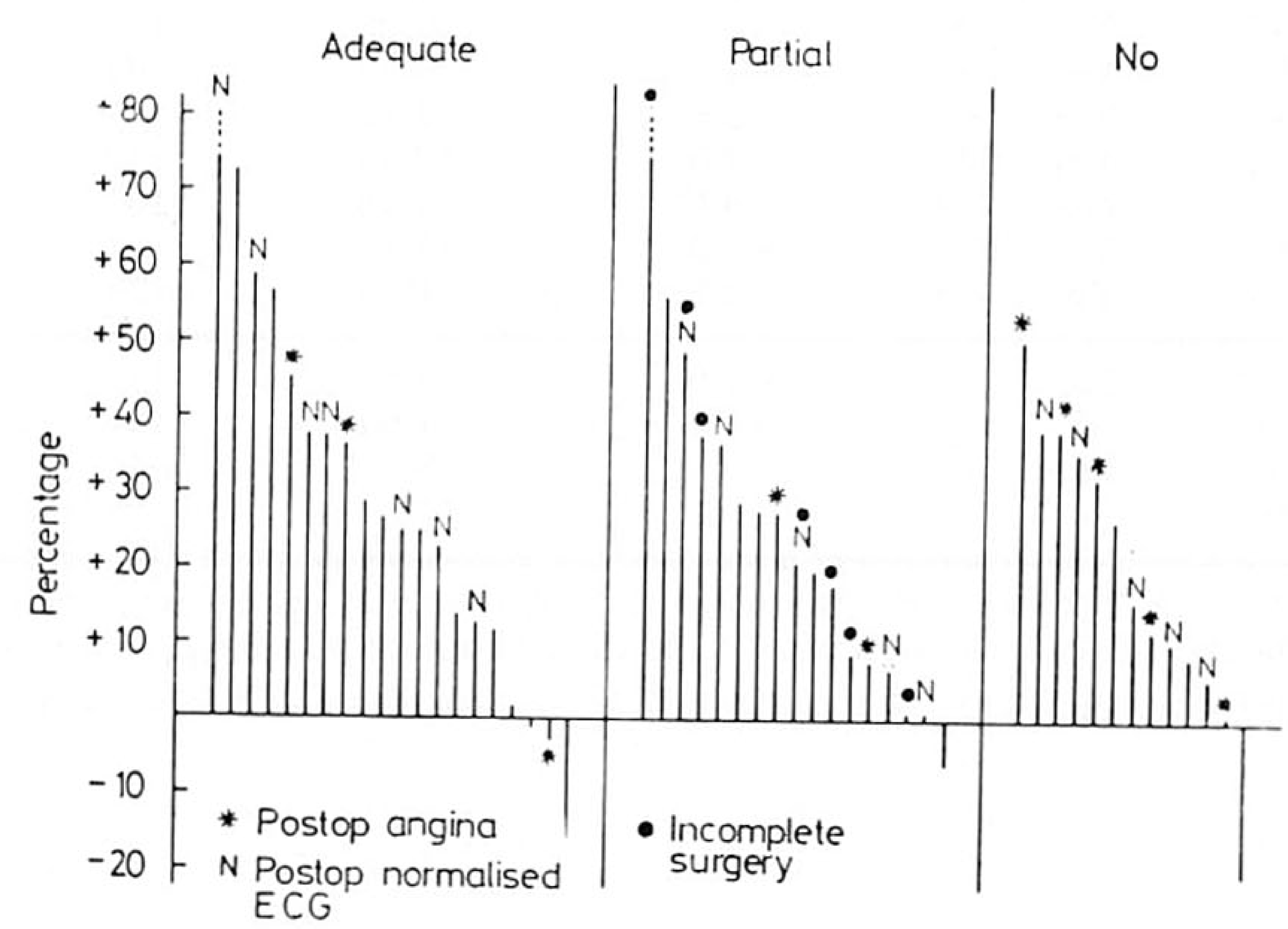

Fig. 4 *Individual changes in maximal heart rate after coronary bypass surgery.*

coronary heart disease and preoperative myocardial infarctions were more frequent in this group.

The graft patency rate noted in the present group of patients is very low (62%) and contrasts with the overall patency rate observed in our own institution (79%). The low patency rate reported here should, therefore, not be interpreted as resulting from poor surgical techniques since it is entirely the result of the mode of selection of the patients: many patients with good surgical results and patent grafts could not be included since they had no postoperative exercise studies.

Haemodynamic data were not collected in all 50 patients but the changes in physical working capacity, maximal heart rate, exertional angina pectoris, and resting ejection fraction measured in the 3 subsets of patients who underwent haemodynamic studies are practically identical to those observed in the 3 groups of patients: these haemodynamic data provide the information required to understand the mechanisms underlying the changes observed after coronary bypass surgery.

As previously observed, adequate revascularisation results in a spectacular improvement of the physical working capacity, with disappearance of exertional angina pectoris in most patients (Bartel *et al.*, 1973; Lapin *et al.*, 1973; Balcon *et al.*, 1974; Knoebel *et al.*, 1974; Siegel and Loop, 1976); the electrocardiographic abnormalities during exercise are significantly reduced but the electrocardiogram is rarely completely normal, suggesting some residual myocardial ischaemia. These effects are the result of the partial or complete relief of myocardial ischaemia which allows the patients to reach their predicted maximal heart rate without angina pectoris. The higher postoperative $\dot{V}_{O_2}$ max is the result of both an increased maximal cardiac output and an expanded $(AV)O_2$ difference during maximal exercise; the stroke volume and the mean pulmonary arterial pressure during maximal exercise are not significantly modified, nor are the ejection fraction and the LVEDP at rest. McDonough *et al.* (1974) reported a lower maximal stroke volume after coronary bypass surgery but they did not mention the status of the grafts. Our data suggest no major changes in the left ventricular function, which was not unexpected since before operation all patients had resting ejection fractions above 50 per cent; an improved left ventricular function at rest and during exercise has been observed in several patients after successful coronary bypass surgery, but, from the available published reports, there is no systematic trend toward significant and persistent improvement (Bourassa, 1973; Campeau *et al.*, 1974; Hamby *et al.*, 1974; Hammermeister *et al.*, 1974; Levine *et al.*, 1975; Ross, 1975; Barry *et al.*, 1976). Electrocardiographic signs of postoperative myocardial infarction were never observed after adequate revascularisation, which is possibly related to the high incidence of preoperative myocardial infarction in this group; the incidence of postoperative myocardial infarction is indeed less in those patients with preoperative myocardial infarction (Assad-Morell *et al.*, 1975).

In contrast, physical working capacity was unchanged after unsuccessful operation (Bartel *et al.*, 1973; Lapin *et al.*, 1973; Balcon *et al.*, 1974) despite a significant increase in maximal heart rate and the disappearance of exertional angina pectoris in 58 per cent of the patients; the electrocardiographic signs of myocardial ischaemia during maximal exercise were not significantly modified in these patients. The unchanged $\dot{V}_{O_2}$ max or $\dot{V}_{O_2}$SL observed after operation in these patients is related to an unchanged maximal cardiac output; the latter is entirely caused by a significant decrease in stroke volume during maximal exercise. This lower stroke volume during maximal exercise together with the significantly decreased ejection fraction at rest strongly suggest an impaired left ventricular function after unsuccessful surgery; interestingly, the LVEDP at rest was not modified in these patients after operation (Rutherford *et al.*, 1972).

A major factor responsible for these undesirable results appears to be the occurrence of perioperative myocardial infarction which was observed in 46 per cent (6/13) of the patients with no revascularisation and in 50 per cent (5/10) of the patients with partial revascularisation resulting from partial graft failure. Perioperative myocardial infarction was most often observed in the myocardial zone supplied by a grafted artery (9/11) and frequently associated with failure of the graft (8/11). These observations made on a limited number of patients suggest a close relation between graft failure and perioperative myocardial infarction but other studies, on larger populations, have clearly indicated that perioperative myocardial infarctions were frequently observed in the absence of graft failure (Assad-Morell *et al.*, 1975; Morton *et al.*, 1975; Sternberg *et al.*, 1975). The patients who had no electrocardiographic evidence of perioperative myocardial infarction had similar results; this is possibly because of the incidence of 'electrocardiographic silent' myocardial necrosis; both anatomical (Assad-Morell *et al.*, 1975) and isotope (Platt *et al.*, 1976) studies have indicated a high incidence of perioperative myocardial infarcts which were not detected by the routine 12 electrocardiograms lead. The incidence of total graft failure was clearly associated with a lower stroke volume during maximal exercise and a lower ejection fraction at rest (Bourassa *et al.*, 1972; Sternberg *et al.*, 1975; Barry *et al.*, 1976). These data indicate that though unsuccessful surgery often alleviates angina pectoris and does not reduce physical working capacity, the net result of total graft failure is often a significant impairment of the left ventricular function; the prognostic implications of this situation deserve further studies, but a worsened prognosis would not be surprising (Brewer *et al.*, 1972; Bruschke *et al.*, 1973; Schrank *et al.*, 1974).

The effects of partial revascularisation on the physical working capacity are intermediate (Knoebel *et al.*, 1974) and in our patients they appear to depend essentially on the presence or the absence of graft failure. When all grafts are patent but some significant lesions have not been bypassed, the results are close to those of adequate revascularisation, and perioperative myocardial infarctions have never been observed. On the other hand, the incidence of perioperative myocardial infarction is high in our patients with partial graft failure; the results are similar to those observed in the group with total graft failure, and similar signs of impaired left ventricular function are observed. These data are of practical importance since partial graft failure is not infrequent.

Several authors have reported that postoperative maximal exercise testing was a valuable method in the assessment of the results of coronary surgery (Bartel *et al.*, 1973; Guiney *et al.*, 1973; Lapin *et al.*, 1973; Balcon *et al.*, 1974; Merrill *et al.*, 1975); though the latter is true when groups of patients are considered, our data indicate that, in a given patient, it is often impossible to predict the degree of revascularisation from maximal exercise testing data because of the overlap between the groups. This is because of the frequent disappearance of angina pectoris after unsuccessful surgery and because of the increased maximal heart rate and maximal pressure-rate product observed in our patients with total graft failure; our findings which are similar to those recently reported by Siegel and Loop (1976) are in disagreement with previous studies indicating a good agreement between the changes in maximal heart rate or maximal pressure-rate product and graft patency (Lapin *et al.*, 1973; Merrill *et al.*, 1975). The reasons for these discrepancies are unclear.

We conclude from this study that in patients with normal preoperative ejection fraction, adequate revascularisation causes a significant improvement in physical working capacity; the left ventricular function does not appear to be modified and the observed improvement results from the prevention of angina pectoris which allows the patients to reach their predicted normal maximal heart rate. When all grafts are occluded, the physical working capacity is not significantly modified though the maximal heart rate is increased; the latter results from a lower stroke volume and ejection fraction which are likely to reflect an impaired left ventricular function and are often associated with perioperative myocardial infarction. The effect of partial revascularisation appears to be determined by the occurrence of partial graft failure. Individual changes in maximal exercise testing responses do not allow reliable predictions about the degree of surgical revascularisation.

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