Recovery from exercise at varying work loads¹ *Time course of responses of heart rate and systolic intervals*

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The time course of the recovery period was characterised by non-invasive measurements after 4-minute bicycle exercise at 3 separate (50W, 100W, and 150W) work loads in 10 volunteers in whom the peak responses during exercise of heart rate and systolic time intervals were consistent with previous investigations of comparable subjects. Most responses started immediately to return toward resting control values. Despite rapidly falling post-exercise heart rates, left ventricular ejection times fell further from their exercise nadirs for the first 5 to 15 seconds of recovery (depending on load) probably because of diminished stroke volume caused by venous pooling and, probably also, by continued rapid ejection rate. The stroke volume change was indicated by a concomitant precipitous fall in ejection time index, which then stabilised in tandem with the subsequently normal (i.e. discordant) left ventricular ejection time-heart rate relation. For the first 30 seconds, heart rate fell from load-related exercise peaks, but at equal slopes of change for all loads; thereafter, rates of return toward resting control were strictly load-related. Changes in pre-ejection period were determined by changes in isovolumic contraction time; the degree of return toward control of pre-ejection period and isovolumic contraction time from their exercise nadirs was load-dependent throughout recovery; load-dependent differences in their rate of return were pronounced in the first 30 seconds. The rates of change in the ejection time index and in the ratio pre-ejection period/left ventricular ejection time (PEP/LVET) were virtually independent of load throughout most of recovery.

Polygraphic recording of systolic time intervals (STI) has been successfully applied during upright exercise (Miller *et al.*, 1970; Pigott *et al.*, 1971; Lindquist *et al.*, 1973; Lance and Spodick, 1975; Xenakis *et al.*, 1975). The uniform response patterns and the directional results, which parallel their invasively measured physiological correlates (Lindquist *et al.*, 1973; Lance and Spodick, 1975), showed that these non-invasive techniques were an appropriate means for determining cardiac responses during actual exercise performance. Various invasive techniques, both in anaesthetised animals and in human subjects, have shown that the heart rate, blood pressure, stroke volume, left ventricular end-diastolic volume (LVEDV), sympathetic activity, and other variables change rapidly immediately after stopping exercise. Though post-exercise systolic time intervals have been recorded at one

instant or another after exercise (Aronow, 1970; Pouget *et al.*, 1971; McConahay *et al.*, 1972), the time course of changes during the recovery period has not been systematically investigated.

We studied the post-exercise recovery period after graded dynamic upright exercise. The purpose of this investigation was to characterise the changes in cardiac dynamics, as expressed by the systolic time index in healthy young men throughout the first 5 minutes of recovery after submaximal exercise on a bicycle ergometer, and to study the effect of different exercise loads on the time course of recovery.

Methods

(A) SUBJECTS

Ten young healthy male volunteers, ages 23 to 32 (mean 27 years), were studied. They were all normally active but not trained athletes and had a

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normal physical examination, chest x-ray, and 12-lead electrocardiogram before the study.

(B) GENERAL PROCEDURE

Subjects performed upright exercise on a Collins bicycle ergometer at three separate work loads: 50, 100, and 150 watts, respectively, for 4 minutes at a constant pedalling rate of 60 r.p.m. A minimum 15-minute rest period (10 minutes on an easy chair and at least 5 minutes on the ergometer seat) preceded each bout of exercise, and the next exercise was started only after the sitting resting heart rate (on the ergometer) was stabilised for several minutes, as observed by the investigators on the true heart rate meter of a Collins Cardiotachimetric Controller hidden from the subject's view. All were tested in the morning in the post-absorptive state with abstinence from smoking.

(C) RECORDINGS

A simple bipolar sternal electrocardiographic lead (Pigott *et al.*, 1971) was applied. The phonocardiographic microphone was an HP model No. 21051 A/B contact sensor placed in the mesoapical area at a nominal filter frequency of 50 Hz. The right carotid arterial pulsation was recorded through a funnel pick-up of 2.5 cm diameter attached to a pulse transducer (Sanborn microphone model No. 374) with filter cut-offs at 0.15 and 20 Hz. Korotkoff sounds and the right brachial arterial cuff pressure were recorded on a calibrated strip chart using a separate contact microphone and pressure transducer. All recordings were made on an 8-channel Hewlett-Packard optical recorder, No. 568-100 A, at a paper speed of 75 mm per second, with time lines of 40 ms. The signals for these polygrams were viewed constantly on a Sanborn 8-channel oscilloscope model No. 760.

(D) TEST PROCEDURE

A baseline recording was made with the subject sitting on the ergometer for about 10 minutes. The subsequent tracings were recorded at the following periods: continuously during the last 5 seconds of exercise and first 30 seconds of recovery, at 1 minute, 1½ minutes, 2 minutes, 3 minutes, and 5 minutes. A minimum of 10 heart beats was recorded at each of these prescribed periods.

(E) MEASUREMENTS

With the onset of the QRS ('q') of the electrocardiogram as zero time, the following phases of the cardiac cycle were measured as previously described (Pigott *et al.*, 1971; Spodick and Quarry-Pigott, 1973; Lance and Spodick, 1975): electromechanical systole, left ventricular ejection time (LVET),

pre-ejection period (PEP), isovolumic contraction time (IVCT), preisovolumic period (q-Im), pulse transmission time (PTT), and PEP/LVET. All measurements were made to the nearest 5 ms. Heart rate (HR) was calculated from the RR intervals of the electrocardiogram ($RR \text{ in ms}/60\,000 = HR \text{ in beats/min}$). The first 30 seconds (continuous recording) were divided into 6 equal 5-second segments, in each of which all measurements were averaged. At 1 minute and at each designated point thereafter, the mean of 5 heart beats was obtained.

(F) BLINDING PROCEDURE

Calculations of actual systolic time intervals (STI) were made only at the end, when the timings of all the prescribed points in the polygram had been measured and averaged. Plotting of the results was done only when all the measurements and calculations were completed.

(G) STATISTICAL HANDLING

Standard errors (SE) for all measurements and the percentage change from control of the mean values were obtained. Results were plotted in time course graphs, with the first 30-second recovery period divided into 6 equal 5-second segments. The *t* test for paired comparisons was applied to compare the changes between measurements at the 4-minute (4 min) exercise end-point and the following: pre-exercise control (resting); 5 seconds (5s) recovery; 10 seconds (10s) recovery; 30 seconds (30s) recovery; and 5 minutes (300s) recovery.

Results

Mean values, standard deviations, standard errors, significance of differences from 4 minutes exercise ($P \Delta (4 \text{ min})$), and per cent change from resting control ($\% \Delta (C)$) for the principal measurements are summarised in Tables 1 to 5. All measurements are plotted in Fig. 1 to 8.

HEART RATE (HR: Table 1, Fig. 1)

Peak rises in heart rate with exercise were roughly proportional to load, and significant at all exercise levels ($P < 0.001$). The peak mean heart rate attained at 150W was 158 beats/min. The rate of decline during the first minute of recovery was similar, as shown by parallel curves for all loads and, therefore, did not appear to be related to work intensity. After 1 minute, the rate of return of heart rate toward control was faster after the 150W work load. As expected, at a given time the absolute heart rates and absolute degree of return towards resting values were dependent upon the peak exercise heart

Table 1 Time course of heart rate responses

Load		Control	Exercise 4 min	Recovery										
				30s						60s	90s	120s	180s	300s
				5s	10s	15s	20s	25s	30s					
50 Watts	$\bar{X}$	74	110	107	99	92	92	95	85	76	77	77	76	76
	SD	10.78	9.12	11.26	11.26	11.40	9.06	9.86	12.51	10.09	11.96	11.26	9.59	10.36
	SE	3.41	3.04	3.75	3.75	3.80	3.02	3.12	3.96	3.19	3.78	3.56	3.16	3.28
	PΔ(4')	<0.001	=	NS	NS				<0.001					<0.001
	Δ(C)	=	+49	+45	+34	+24	+24	+28	+15	+3	+4	+4	+3	+3
100 Watts	$\bar{X}$	74	131	124	118	112	108	105	102	89	88	87	85	83
	SD	7.58	13.65	15.99	16.59	16.45	16.17	18.78	17.71	14.53	14.62	12.51	13.08	10.16
	SE	2.39	4.32	5.06	5.25	5.20	5.11	5.94	5.60	4.59	4.62	3.95	4.14	3.21
	PΔ(4')	<0.001	=	NS	NS				<0.01					<0.001
	%Δ(C)	=	+77	+68	+59	+51	+46	+42	+38	+20	+19	+18	+15	+12
150 Watts	$\bar{X}$	81.3	157.6	153.4	147.1	142.4	137.4	135.6	131.4	118.4	113.2	110	98.8	97.2
	SD	11.30	12.12	13.24	13.88	16.34	16.62	15.44	16.52	17.28	16.01	16.00	14.17	11.26
	SE	3.57	4.04	4.19	4.39	5.45	5.26	4.88	5.22	5.46	5.06	5.34	4.72	3.76
	PΔ(4')	<0.001	=	NS	NS				<0.01					<0.001
	%Δ(C)	=	+93	+87	+79	+73	+67	+65	+60	+44	+38	+34	+21	+18

Symbols: $\bar{X}$, mean; SD, standard deviation; SE, standard error; $PA(4')$, significance level of difference between indicated measurement and four-minute exercise measurement; $\% \Delta(C)$, per cent difference between indicated measurement and resting control measurement (C).

rates. Though the control value was reached by 1 minute of recovery from the 50W load, heart rates at the end of 5 minutes of recovery from 100W and 150W were still 12 per cent and 18 per cent above their corresponding control values.

Fig. 1 Heart rate: time course of recovery from bicycle ergometer exercise at 50 Watts (dots), 100 Watts (squares), and 150 Watts (triangles). Changes from resting control to peak exercise (fourth minute) measurements shown by dashed lines. Bars=SE.

PULSE TRANSMISSION TIME (PTT: Fig. 2) The mean values of PTT did not change significantly with exercise, though there was a general tendency to be lower in the later recovery period. These results indicated that no statistically significant differences existed between the control value and any of the recovery values.

ELECTROMECHANICAL SYSTOLE (EMS: Fig. 3) Decline on exercise and rise on recovery were proportional to load and identical with the LVET

Fig. 2 Preisovolumic period ($q-I_M$; top) and central pulse transmission time (PTT; bottom): time course of recovery from bicycle ergometer exercise at 50 Watts (dots), 100 Watts (squares), and 150 Watts (triangles). Changes from resting control to peak exercise (fourth minute) measurements shown by dashed lines. Bars=SE.

Table 2 Time course of pre-ejection period responses

Load		Control	Exercise	Recovery										
				30s						60s	90s	120s	180s	300s
				5s	10s	15s	20s	25s	30s					
50 Watts	$\bar{X}$	116	73	77	79	83	87	90	93	101	109	112	115	122
	SD	17.32	10.93	12.27	9.32	10.17	9.17	12.07	12.81	14.50	12.00	14.57	14.37	14.51
	SE	5.48	3.64	3.88	3.10	3.39	2.90	3.82	4.05	4.58	3.79	4.60	3.16	4.59
	$P\Delta(4')$	<0.001	=	NS	NS				<0.01					<0.001
	% $\Delta(C)$	=	-45	-45	-40	-38	-34	-31	-30	-27	-17	-12		+5
100 Watts	$\bar{X}$	124	68	70	71	72	73	76	79	91	97	102	107	115
	SD	12.60	10.13	9.13	8.31	9.40	10.65	13.19	11.59	15.32	16.81	18.41	16.33	17.24
	SE	3.98	3.20	2.89	2.63	2.97	3.37	4.17	3.66	4.84	5.31	5.82	5.16	5.45
	$P\Delta(4')$	<0.001	=	NS	NS				NS					<0.001
	% $\Delta(C)$	=	-45	-44	-43	-42	-41	-39	-36	-25	-22	-18	-14	-7
150 Watts	$\bar{X}$	126	55	60	58	59	60	63	63	70	74	77	87	102
	SD	13.52	8.94	10.08	8.82	8.72	9.78	10.39	10.31	13.10	15.26	17.34	18.74	19.25
	SE	4.28	3.16	3.19	2.79	2.91	3.09	3.29	3.26	4.14	4.83	5.78	6.25	6.42
	$P\Delta(4')$	<0.001	=	NS	NS				NS					<0.001
	% $\Delta(C)$	=	-56	-52	-54	-53	-52	-50	-50	-44	-41	-39	-31	-19

Symbols: $\bar{X}$, mean; SD, standard deviation; SE, standard error; $P\Delta(4')$, significance level of difference between indicated measurement and four-minute exercise measurement; % $\Delta(C)$, per cent difference between indicated measurement and resting control measurement (C)

pattern (Fig. 6). Since LVET constitutes the major portion of EMS, this trend was expected. EMS is the sum of PEP and LVET, which are considered individually.

PRE-EJECTION PERIOD (PEP: Table 2, Fig. 4, and PEP components Q-Im and IVCT: Fig. 2 and 5, respectively)
Pre-ejection period constitutes the sum of the pre-isovolumic period (Q-Im) and isovolumic period

(IVCT). Declines in the Q-Im period on exercise with each load were small (between 15 and 18% from control) and statistically insignificant (Fig. 2). The recovery slopes and absolute values of Q-Im for all loads were nearly the same and within a narrow range of each other during the entire period. On the other hand, there was a significant decrease ($P<0.001$) in the mean IVCT produced by

Fig. 3 Electromechanical systole (EMS): time course of recovery from bicycle ergometer exercise at 50 Watts (dots), 100 Watts (squares), and 150 Watts (triangles). Changes from resting control to peak exercise (fourth minute) measurements shown by dashed lines. Bars=SE.

Fig. 4 Pre-ejection period (PEP): time course of recovery from bicycle ergometer exercise at 50 Watts (dots), 100 Watts (squares), and 150 Watts (triangles). Changes from resting control to peak exercise (fourth minute) measurements shown by dashed lines. Bars=SE.

exercise of all intensities. This decline and the subsequent lag in recovery was proportional to load (Fig. 5). There was hardly any recovery in IVCT at the 150W load during the initial 30-second period (change=7–8 ms only). And though the recovery values of IVCT from 150W exercise rose significantly ($P<0.001$) at 2 and 3 minutes from that at 30 seconds, it was less than 50 per cent complete at 5 minutes, as compared with 100 per cent and 80 per cent for the 50W and 100W loads, respectively.

Since Q-Im showed no significant changes, pre-ejection period (Fig. 4) changed almost entirely because of the very significant changes in its other component, IVCT. Comparison of Fig. 4 with Fig. 5 makes this relation apparent. Thus, pre-ejection period (Table 2) showed no significant recovery up to 30s post-exercise at 100W and 150W but had recovered significantly at 30s after the lowest (50W) load; at 5 minutes (300s) recovery had progressed from its exercise nadir for all loads ($P<0.001$ each), though for the highest (150W) load pre-ejection period was still 19 per cent below control.

LEFT VENTRICULAR EJECTION TIME

(LVET: Table 3, Fig. 6)

Exercise reduced the duration of left ventricular ejection time at all work loads, a trend that was maintained into 10 to 15 seconds of recovery. The

exercise drop in left ventricular ejection time was proportional to work load, being greatest with 150W at the 4-minute end-point ($P<0.001$). Subsequent recovery was also proportionately slower for higher exercise intensities. By 30 seconds left ventricular ejection time rose to near resting control value following 50W exercise, but tended to be lower after the 100W load and much lower after 150W. Between 1 and 5 minutes, the recovery was near complete with the two lower loads. With 150W, however, actual recovery started only after 30 seconds (Fig. 6) and left ventricular ejection time reached near resting value (-4%) only at the 5-minute end-point. There was no significant difference between absolute mean recovery left ventricular ejection time for all 3 loads of exercise at 5 minutes (245, 239, and 226 ms, respectively).

EJECTION TIME INDEX (ETI: Table 4, Fig. 7)

With exercise the ejection time index was highest at the maximum load but near equal for the other two intensities (369 and 367 ms for 50W and 100W, respectively). With the beginning of recovery, ejection time index fell sharply with all loads and this sharp decline continued to 10 or 15 seconds of recovery from all levels of exercise representing a statistically significant change from end-exercise in each case at the 0.001 level. The change, thereafter, was very small during the first 30 seconds. There seemed to be an inverse ordering according to work load at 30 seconds, which was maintained

Fig. 5 Isovolumic contraction time (IVCT): time course of recovery from bicycle ergometer exercise at 50 Watts (dots), 100 Watts (squares), and 150 Watts (triangles). Changes from resting control to peak exercise (fourth minute) measurements shown by dashed lines. Bars=SE.

Fig. 6 Left ventricular ejection time (LVET): time course of recovery from bicycle ergometer exercise at 50 Watts (dots), 100 Watts (squares), and 150 Watts (triangles). Changes from resting control to peak exercise (fourth minute) measurements shown by dashed lines. Bars=SE.

until at least 3 minutes (Fig. 7). After 3 minutes, all curves converged to the 5-minute end-point, at which the mean measurements were within a few milliseconds above control.

PEP/LVET (Table 5, Fig. 8)

This ratio fell significantly ($P < 0.001$) with all degrees of exercise. Statistically, no significant differences existed between absolute values for any load at any time. For each load of exercise, PEP/LVET changed significantly between end-exercise and the 5-minute recovery end-point ($P < 0.001$). The recovery during the first 30 seconds was slow for all loads. However, the recovery after the 50W load was continuous and numerically complete by

3 minutes, whereas with the other two grades of exercise there was relatively less change in this ratio between 5 and 30 seconds. After 90 seconds (1.5 min) the mean values at 100W and 150W steadily recovered in parallel with the 50W slope to within a few milliseconds of their control values at 5 minutes.

Discussion

EXERCISE RESPONSES

Recovery proceeded from exercise-induced changes in systolic time intervals, all of which were in the expected ranges (Pigott *et al.*, 1971; Lance and Spodick, 1975; Xenakis *et al.*, 1975). These in-

Table 3 Time course of left ventricular ejection time responses

Load		Control	Exercise 4 min	Recovery										
				30s						60s	90s	120s	180s	300s
				5s	10s	15s	20s	25s	30s					
50 Watts	$\bar{X}$	246	236	232	225	231	234	239	241	253	250	247	249	245
	SD	18.48	21.02	24.07	22.70	24.99	26.72	24.73	26.11	23.35	25.09	21.43	21.09	22.45
	SE	5.85	7.00	7.81	7.56	8.33	8.90	7.82	8.25	7.39	7.94	6.78	6.67	7.09
	$P\Delta(4')$	NS	=	NS	NS	-6	-5	-2	NS	+3	+2			NS
	$\% \Delta(C)$	=	-4	-6	-9	-6	-5	-2	-2	+3	+2			
100 Watts	$\bar{X}$	243	210	197	197	202	207	211	214	227	231	231	236	239
	SD	16.72	21.09	21.70	24.51	27.08	27.08	28.96	31.70	31.68	27.63	24.40	22.57	17.41
	SE	5.92	6.67	6.86	7.75	8.56	8.56	9.16	10.02	10.02	8.74	7.72	7.14	5.51
	$P\Delta(4')$	<0.001	=	NS	NS	-17	-15	-13	NS	-7	-5	-5	-3	<0.01
	$\% \Delta(C)$	=	-14	-19	-19	-17	-15	-13	-12	-7	-5	-5	-3	-2
150 Watts	$\bar{X}$	235	195	172	168	166	171	172	175	186	194	198	210	226
	SD	19.64	18.15	17.88	18.45	14.76	17.85	17.68	18.38	26.88	26.36	28.50	24.32	19.24
	SE	6.21	6.42	5.65	5.83	4.92	5.65	5.59	5.81	8.50	8.33	9.50	8.10	6.41
	$P\Delta(4')$	<0.001	=	<0.05	<0.05				<0.05					<0.01
	$\% \Delta(C)$	=	-17	-27	-29	-29	-27	-27	-26	-21	-17	-16	-11	-4

Symbols: $\bar{X}$, mean; SD, standard deviation; SE, standard error; $P\Delta(4')$, significance level of difference between indicated measurement and four-minute exercise measurement; % $\Delta(C)$, per cent difference between indicated measurement and resting control measurement (C).

Table 4 Time course of ejection time index responses

Load		Control	Exercise 4 min	Recovery										
				30s						60s	90s	120s	180s	300s
				5s	10s	15s	20s	25s	30s					
50 Watts	$\bar{X}$	335	369	357	344	342	343	344	342	344	342	340	340	336
	SD	8.75	14.06	19.11	11.53	13.08	15.26	14.69	12.57	12.79	12.74	12.41	10.10	11.39
	SE	2.77	3.00	6.37	3.84	4.36	5.09	4.65	3.97	4.04	4.03	3.92	3.19	3.60
	$P\Delta(4')$	<0.001	=	NS	<0.001				<0.001					<0.001
	$\bar{X}$	332	367	346	338	337	336	337	336	333	337	336	339	338
100 Watts	SD	10.24	13.43	17.18	11.86	10.74	11.12	10.21	13.04	15.89	12.51	12.00	8.76	8.12
	SE	3.24	4.25	5.43	3.75	3.40	3.52	3.23	4.12	5.03	3.96	3.80	2.77	2.57
	$P\Delta(4')$	<0.001	=	<0.05	<0.001				<0.001					<0.001
	$\bar{X}$	333	383	356	344	336	335	335	333	328	330	330	329	343
	SD	8.13	12.25	14.00	12.31	9.09	8.65	6.57	8.20	9.06	10.33	14.08	20.51	12.63
150 Watts	SE	2.59	4.33	4.43	3.89	3.03	2.88	2.08	2.59	2.86	3.27	4.69	6.84	4.21
	$P\Delta(4')$	<0.001	=	<0.01	<0.001				<0.001					<0.001

Symbols: $\bar{X}$, mean; SD, standard deviation; SE, standard error; $P\Delta(4')$, significance level of difference between indicated measurement and four-minute exercise measurement; % $\Delta(C)$, per cent difference between indicated measurement and resting control measurement (C).

cluded decreases in pre-ejection period, isovolumic contraction time, left ventricular ejection time, and PEP/LVET, together with an increase in ejection time index. Pulse transmission time showed no significant change.

RESPONSES DURING RECOVERY

Heart rates at the 5-minute recovery end-point in this study were comparable to those reported by

early investigators who were concerned with heart rate responses (Bowen, 1904; Wiggers, 1921; Cotton and Dill, 1935). The initial stages of heart rate recovery were similar at all loads in these normal volunteers, reflecting a comparable state of health and fitness (Robinson *et al.*, 1937; Johnson and Brouha, 1942; Kramer and Lurie, 1964).

The lack of significant change in pulse transmission time during exercise was in agreement with other studies (Pigott *et al.*, 1971; Spodick and Quarry-Pigott, 1973; Lance and Spodick, 1975; Spodick and Lance, 1976) and accounts for the lack of changes during recovery. Elasticity of the arterial wall is considered to be the dominant influence on pulse transmission time (Schimmler,

Fig. 7 Ejection time index (ETI): time course of recovery from bicycle ergometer exercise at 50 Watts (dots), 100 Watts (squares), and 150 Watts (triangles). Changes from resting control to peak exercise (fourth minute) measurements shown by dashed lines. Bars = SE.

Fig. 8 Ratio of PEP to LVET: time course of recovery from bicycle ergometer exercise at 50 Watts (dots), 100 Watts (squares), and 150 Watts (triangles). Changes from resting control to peak exercise (fourth minute) measurements shown by dashed lines. Bars = SE.

Table 5 Time course of PEP/LVET responses

Load		Control	Exercise 4 min	Recovery										
				30s						60s	90s	120s	180s	300s
				5s	10s	15s	20s	25s	30s					
50 Watts	X	47	31	33	34	37	37	38	39	40	43	45	46	50
	SD	7.37	5.96	6.65	6.02	7.18	5.79	6.79	6.62	6.22	6.79	6.57	8.47	8.61
	SE	2.33	1.99	2.10	2.00	2.39	1.93	2.15	2.09	1.97	2.15	2.08	2.68	2.72
	PΔ(4')	<0.001	=	NS	NS				<0.01					<0.001
	%Δ(C)	=	-34	-30	-28	-21	-21	-19	-17	-15	-9	-4	-2	+5
100 Watts	X	51	32	35	36	36	36	36	37	40	40	44	45	48
	SD	6.18	5.08	4.81	5.12	5.68	5.64	6.21	5.92	6.47	7.51	7.51	6.67	7.97
	SE	1.95	1.61	1.52	1.62	1.80	1.78	1.96	1.87	2.05	2.38	2.38	2.11	2.52
	PΔ(4')	<0.001	=	NS	NS				NS					<0.001
	%Δ(C)	=	-37	-31	-29	-29	-29	-29	-27	-22	-22	-14	-12	-6
150 Watts	X	53	28	35	35	36	36	36	35	38	38	39	41	44
	SD	5.39	5.62	6.31	5.42	5.97	6.08	6.54	5.10	7.18	6.90	7.92	7.00	6.64
	SE	1.70	1.99	1.99	1.71	1.99	2.02	2.07	1.61	2.27	2.18	2.64	2.34	2.21
	PΔ(4')	<0.001	=	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01					<0.001
	%Δ(C)	=	-47	-34	-34	-32	-32	-32	-34	-28	-28	-25	-23	-16

Symbols: $\bar{X}$, mean; SD, standard deviation; SE, standard error; $P\Delta(4')$, significance level of difference between indicated measurement and four-minute exercise measurement; % $\Delta(C)$, per cent difference between indicated measurement and resting control measurement (C).

1967), and both acute exercise and recovery seem not to exert a measurable effect on this manifestation of that property.

Pre-ejection period, comprised of isovolumic contraction time and preisovolumic period has an inverse relation with the rate of rise of left ventricular isovolumic pressure (dp/dt) (Martin *et al.*, 1970; Talley *et al.*, 1971). The striking similarity between pre-ejection period and isovolumic contraction time curves, while preisovolumic period changed minimally by comparison, indicates that changes in recovery pre-ejection period, like those of exercise pre-ejection period, were accounted for almost entirely by isovolumic contraction time. The exercise isovolumic contraction time (hence, pre-ejection period) changes are consistent with the normal physiological response of sympathetically induced increased contractile velocity during exercise (Braunwald *et al.*, 1958; Morehouse and Miller, 1963; Lindquist *et al.*, 1973). Some of the exercise change may also be ascribed to increased preload resulting from the Starling effect associated with the early phase of upright exercise (Stafford *et al.*, 1970; Spodick and Quarry-Pigott, 1973). The retarded recovery of isovolumic contraction time at the higher work loads may be accounted for by load-dependent residual adrenergic effects.

Left ventricular ejection time 'paradoxically' declined below its exercise nadir during the first 5 to 15 seconds of the immediate post-exercise period despite the rapid fall in heart rate (Fig. 6). This exaggeration of the exercise response is only apparently paradoxical. The two most important determinants of left ventricular ejection time are stroke volume (direct relation) and systolic ejection rate (inverse relation) (Braunwald *et al.*, 1958; Kramer and Lurie, 1964). Thus, two mechanisms can explain the abnormal (i.e. concordant) trends in left ventricular ejection time and heart rate during early recovery: (1) a sustained effect of the augmented ejection rate achieved during exercise, even with minimal or no change in stroke volume (Braunwald *et al.*, 1958; Wildenthal and Mitchell, 1969); (2) with sudden stopping of exercise, blood vessels in working muscles remain dilated while milking action of the muscles is lost, thus allowing transient peripheral venous pooling. This pooling would diminish venous return and, therefore, also tend to aggravate the exercise-induced fall in stroke volume. This abnormally concordant early post-exercise left ventricular ejection time-heart rate relation is analogous to the relation during the strain phase of the Valsalva manoeuvre, during which left ventricular ejection time falls disproportionately to the increasing heart rate because of the exclusion of blood from the central circulation (Spodick

et al., 1974). The subsequent progressive return of left ventricular ejection time towards resting values reflected resumption of the usual inverse heart rate-stroke volume relation.

Left ventricular ejection time varies inversely with heart rate owing to the rate effect on ventricular filling (Weisdorf and Spodick, 1976). Therefore, nullifying the rate effect on left ventricular ejection time by calculating the ejection time index should disclose the influence of changes in stroke volume (Weissler *et al.*, 1963; Lindquist *et al.*, 1973; Weisdorf and Spodick, 1976). Increase in ejection time index during upright exercise had been expected (Spodick and Quarry-Pigott, 1973). The pronounced decline in ejection time index immediately after stopping exercise indicates the transient stroke volume fall reflected in the early left ventricular ejection time values which were concordant with the heart rate changes. A striking feature was the independence from load of the recovery ejection time index, i.e. a similar rate of decline in ejection time index during initial recovery at all work loads. After this, the relatively flat ejection time index at all loads is consistent with resumption of the usual physiological dependence of stroke volume on heart rate (i.e. filling rate).

Another striking phenomenon was also evident (Fig. 7): the degree of recovery for most of the remaining period was reversed as compared with other values, i.e. there was a tendency to a more rapid recovery (i.e. lower values) at the two higher work loads. After 1 minute the 50W curve continued to approach control level, but the 100W and 150W curves did not and showed a slight tendency to rise. We have no explanation for this trend.

Pre-ejection period/left ventricular ejection time emphasises any reciprocal changes in each of its components; in some studies this ratio has had a high negative correlation with stroke index and ejection fraction (Weissler *et al.*, 1969; Ahmed *et al.*, 1970; Martin *et al.*, 1970). Significant lowering of this ratio during exercise performance is in agreement with previous reports (Pigott *et al.*, 1971; Xenakis *et al.*, 1975; Spodick and Quarry-Pigott, 1973). The rate of return of PEP/LVET towards control level did not appear to be load-related, indicating that all degrees of stress produced proportional effects on pre-ejection period and left ventricular ejection time (Fig. 8).

EFFECTS OF LOAD

The rate of post-exercise recovery in some cardiac intervals was delayed proportional to work load. Heart rate, pre-ejection period, isovolumic contraction time, and left ventricular ejection time changed more slowly after higher exercise levels,

particularly during the first 30 seconds. The level ejection time index after its initial transient drop is consistent with stable stroke volume during this period so that the greater heart rates and shorter isovolumic contraction time and left ventricular ejection time at higher loads appear to reflect the increased contractile velocity resulting from relatively greater inotropic levels. Thus, early load-related slower recovery was consistent with more intense and longer lasting inotropic effects after greater stress rather than increased preload via the Starling effect.

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