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## THE EFFECT OF EXERCISE ON MEAN LEFT VENTRICULAR EJECTION RATE IN MAN \*

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The cardiac response to exercise has long been utilized as a means of characterizing normal and abnormal ventricular performance. Nonetheless, the normal behavior of stroke volume during stress has remained controversial. Early studies demonstrated that normal humans generally effect a rise in stroke volume with exercise (1-3)—a response not shared by the failing ventricle (4). More recently, Rushmer has challenged this view and has maintained that “stroke volume increases but little during exertion, and rarely exceeds recumbent control levels” (5, 6). Furthermore, it has become apparent that the training of the individual, the position of exercise, and the severity of the stress itself influence the stroke volume response (6-8). Mild exercise, performed in the supine position, has proved to be a useful stress test in many catheterization laboratories. When done in this fashion, it is generally associated with mild and inconstant increases in stroke volume by the normal heart.

Further insight into the stroke volume behavior may be gained by inspection of the direct determinants of the stroke volume itself. Cardiac stroke volume may be considered as the product of the mean systolic ejection rate (MSER) and the duration of systole. In this manner the dynamic contractile effort is conditioned by time. Thus for a given period of ejection, the volume of blood delivered by the heart will be determined by the rate of fiber shortening and the initial chamber volume from which fiber shortening takes place.

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The present study seeks to examine the effect of exercise on a readily determined parameter of cardiac ejection, the mean systolic ejection rate. Studies were carried out in normal human subjects, in patients with left ventricular failure, and in patients with valvular heart disease.

### MATERIALS AND METHODS

Rest and exercise studies were performed on 64 subjects. A control group composed of 26 subjects included 18 normal individuals and 8 patients with mild heart disease. This latter group included 5 patients with mild mitral stenosis (valve area greater than 2.5 cm<sup>2</sup>), 1 with patent ductus arteriosus (pulmonary-systemic flow ratio, 1.2/1), 1 with hyperkinetic heart syndrome (9), and 1 with mild pulmonary hypertension of unknown etiology (pulmonary arterial pressure, 34/18 mm Hg). The failure group comprised 15 cases and consisted of 7 patients with arteriosclerotic heart disease, 2 with hypertensive heart disease, 3 with left ventricular failure of unknown etiology, and 1 each with myocarditis, patent ductus arteriosus, and coarctation of the aorta. All patients in this group had in common clinical evidence of left ventricular failure and pulmonary capillary pressures of greater than 12 mm Hg at rest, or greater than 17 mm Hg during exercise, or both. No cases of aortic valve disease were included in this group. A third group of 11 patients had severe mitral stenosis (valve area less than 1.2 cm<sup>2</sup>) without evidence of left ventricular failure. A small group of 6 patients with pure aortic stenosis *without* left ventricular failure, as judged from pulmonary capillary pressures of less than 12 mm Hg at rest and during exercise, was also studied. Six near-normal individuals were studied before and after the intravenous administration of atropine (1.0 to 1.4 mg) and have been previously reported in part (10); 3 had functional systolic murmurs, 1 had a diastolic murmur of aortic insufficiency without major change in blood pressure, 1 had mitral stenosis, and 1 had mild mitral insufficiency.

Right heart catheterization was performed in all patients. Cardiac output was measured by the direct Fick method, and brachial artery and pulmonary capillary pressures were recorded by means of a Statham P-23D strain gauge on a Sanborn direct recorder at paper speeds of 25 to 50 mm per second. Heart rate, pressure, and

systolic ejection period per beat were measured on the brachial artery pressure pulse, recorded simultaneously with cardiac output. Respiration was not controlled, but the duration of systole rarely varied by more than 0.01 second during phasic respiration. Multiple measurements of the systolic ejection period were made, and the average value over at least two respiratory cycles was derived. In those cases with atrial fibrillation the average was derived from a minimum of 12 complexes. Those cases in which the systolic ejection period was not clearly defined on the arterial pressure pulse were excluded from the study. On five occasions pullbacks from the ascending aorta to the brachial artery revealed no measurable difference in the duration of the systolic ejection period. Regardless of this consideration all measurements of the systolic ejection period were made under identical conditions, and each patient served as his own control. Stroke volume was calculated by dividing the cardiac output by the heart rate. In the absence of atrial fibrillation, the standard error of the stroke volume in our laboratory is 9 per cent. Effective MSER was derived as the effective stroke volume per  $m^2$  divided by systolic ejection period, and is expressed as cubic centimeters per second of systole per  $m^2$ . For the expression *total* MSER, total stroke volume is substituted for effective stroke volume.

All measurements were made between the third and fifth minutes of supine leg-raising exercise sufficient to raise total body oxygen consumption two- to threefold over the resting value. Rest observations were made 15 minutes after the stress period.

In 4 patients with aortic insufficiency and congestive heart failure, not included in the above-mentioned group, total as well as effective stroke volumes were determined. In each instance aortic regurgitant data were derived hydraulically from necropsy material (11). In 2 of these, the aortic regurgitant valve area was measured cinematically with the heart on a McMillan pump. In the other 2 with fixed, heavily calcified aortic leaflets, the valve area was planimeted directly at necropsy. These data were utilized to back-calculate regurgitant and total stroke volumes during the rest and exercise studies (11) and thus, *total* as well as effective MSER was derived.

## RESULTS

## 1. Normal and failing left ventricles

The rest and exercise data for control and failure groups are shown in Tables I and II. During exercise total body oxygen consumption rose from 142 to 326 cc per minute (155 per cent) in the control group and from 154 to 341 cc per minute (122 per cent) in the failure group. Heart rate increased from 85 to 117 (38 per cent) in the controls and from 83 to 108 (35 per cent) in the failure cases. Effective stroke volume increased an average of 16 per cent in the nonfailing hearts and fell by an average of 2 per cent in the failure group, while the systolic ejection period fell by

TABLE I  
Control group

Subjects		Heart rate		Stroke volume		Systolic ejection period		Mean systolic ejection rate		Left ventric. syst. mean press.		Total body O <sub>2</sub> consump.				
Age	Sex	BSA	Rest	Exer.	Rest	Exer.	Rest	Exer.	Rest	Exer.	Rest	Exer.	Rest	Exer.		
<i>yr</i> s		<i>m</i> <sup>2</sup>	<i>beats/min</i>		<i>cc/beat/m</i> <sup>2</sup>		<i>sec/beat</i>		<i>cc/sec/m</i> <sup>2</sup>		<i>mm Hg</i>		<i>cc/min/m</i> <sup>2</sup>			
1	RM	42	f	1.68	90	134	45	43	0.24	0.20	186	218	112	138	142	324
2	TM	45	m	1.82	111	150	30	37	0.20	0.20	151	187	137	163	149	400
3	JC	28	f	1.28	82	97	55	76	0.27	0.28	205	271	88	88	168	252
4	PR	27	f	1.50	70	78	51	52	0.29	0.28	175	186	115	128	169	302
5	BH	32	f	1.40	92	120	44	51	0.27	0.28	164	184	91	123	114	282
6	RL	53	m	1.65	91	118	41	52	0.28	0.26	145	198	93	110	137	355
7	PA	29	f	1.58	68	104	34	38	0.27	0.25	124	152	86	100	96	260
8	CL	37	f	1.27	74	86	51	64	0.30	0.26	171	248	98	110	134	279
9	JL	43	m	2.05	104	134	21	23	0.22	0.20	94	115	120	144	120	279
10	RF	18	m	1.96	57	72	48	72	0.30	0.27	160	268	93	99	119	288
11	DB	18	m	1.78	88	114	45	55	0.24	0.24	190	229	100	120	128	361
12	WB	46	m	1.99	83	92	31	35	0.25	0.25	125	140	104	121	149	277
13	RD	13	m	1.72	83	122	21	38	0.32	0.30	97	126	88	118	172	194
14	RH	36	m	1.88	69	126	39	42	0.30	0.26	128	162	117	147	153	480
15	RHu	37	m	1.89	75	92	49	48	0.24	0.24	203	199	130	130	164	316
16	LK	22	f	2.28	65	138	50	51	0.31	0.22	161	232	108	146	151	615
17	LO	21	f	1.76	102	135	40	45	0.22	0.17	181	267	117	127	170	
18	VP	32	f	1.42	88	108	32	66	0.26	0.26	123	254	106	130	138	317
19	AR	16	f	1.50	109	164	37	34	0.23	0.18	161	189	120	140	147	368
20	JT	23	f	1.43	105	140	45	45	0.22	0.18	204	250	105	125	149	334
21	MM	31	f	1.65	90	120	48	59	0.29	0.26	167	227	96	105	111	347
22	RM	57	m	1.54	90	120	53	48	0.26	0.22	203	218	88	115	171	410
23	JC	40	f	1.52	83	122	44	45	0.28	0.24	155	186	63	85	145	323
24	YA	40	f	1.62	70	100	56	56	0.30	0.28	185	201	126	116	111	314
25	WP	17	m	2.04	68	80	50	69	0.26	0.27	190	256	128	135	171	282
26	FD	60	f	1.60	100	170	17	24	0.21	0.17	81	141	135	175	114	312
Average		33		1.69	85	117	41	48	0.26	0.24	159	204	106	125	142	326
Standard deviation	±				5	14	15	16	0.018	0.021	39	52	16	11	22	78

TABLE II  
Congestive heart failure group

Subjects	Age	Sex	BSA	Heart rate		Stroke volume		Systolic ejection period		Mean systolic ejection rate		Left ventric. syst. mean press.		Total body O <sub>2</sub> consump.	
				Rest	Exer.	Rest	Exer.	Rest	Exer.	Rest	Exer.	Rest	Exer.	Rest	Exer.
1	WY	52	m	1.58	120	34	0.21	162	143	173	275				
2	MN	45	f	2.00	140	26	0.24	109	120	127	377				
3	HA	56	m	1.89	84	26	0.32	82	90	120	342				
4	RF	41	m	1.62	90	19	0.25	77	106	130	248				
5	VS	58	f	1.77	82	23	0.24	91	108	127	270				
6	MB	30	f	1.57	64	39	0.26	150	99	122	351				
7	EH	57	f	1.59	63	46	0.30	153	108	146	326				
8	TK	44	f	1.67	103	40	0.24	167	129	153	319				
9	TP	39	f	1.50	91	111	0.33	335	97	131	147	346			
10	EW	41	f	1.71	77	30	0.27	120	103	142	370				
11	JY	25	m	2.06	67	44	0.27	162	129	155	383				
12	JYO	40	m	2.11	65	39	0.19	205	93	95	163	380			
13	PR	50	f	1.60	84	44	0.30	147	105	125	159	339			
14	WS	39	m	1.80	71	57	0.24	238	90	114	178	332			
15	ED	47	m	1.78	75	49	0.30	163	182	235	158	341	±42		
Average±SD				1.75	83±15	41±21	0.27±0.39	155±64	114±24	141±31	154±16	341±42			

9 and 7 per cent in the two groups, respectively. Pulmonary-capillary pressures rose from 6 to 9 mm Hg in the controls and from 18 to 32 in the failure cases.

In Figure 1, rest and exercise mean systolic ejection rates, in cubic centimeters per second per m<sup>2</sup>, are individually plotted for all patients in the control and failure groups. The effective MSER rose during exercise in 25 of the 26 control subjects (average rise, 28 per cent). In the failure group, on the other hand, effective MSER did not rise significantly. In the majority, little change was found and in no instance did MSER differ by more than ± 11 per cent of the resting value. The group differences are significant (p < 0.001).

Figures 2 and 3 demonstrate the magnitude and direction of change of the two measured parameters that enter into the mean systolic ejection rate calculation. In these quadratic graphs, percentile changes in stroke volume and in systolic ejection period are shown for each subject in the two groups. Deviation from the 45° line to the left and upward indicates a rise in MSER. In the controls (Figure 2) the largest rises in stroke volume were associated with the greatest increases in MSER.

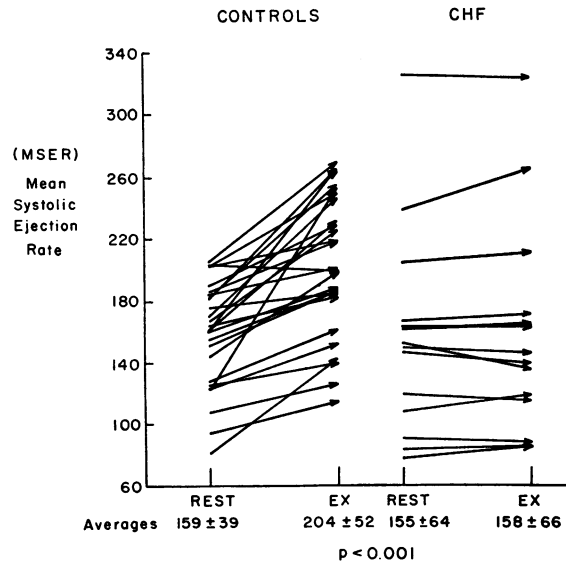


FIG. 1. MEAN SYSTOLIC EJECTION RATES IN CUBIC CENTIMETERS PER SECOND OF SYSTOLE PER M<sup>2</sup>, AT REST AND DURING EXERCISE IN CONTROLS AND IN PATIENTS WITH CONGESTIVE HEART FAILURE (CHF). An overlap in values of three subjects is seen at the ejection rate of 162 to 167 cc per second.

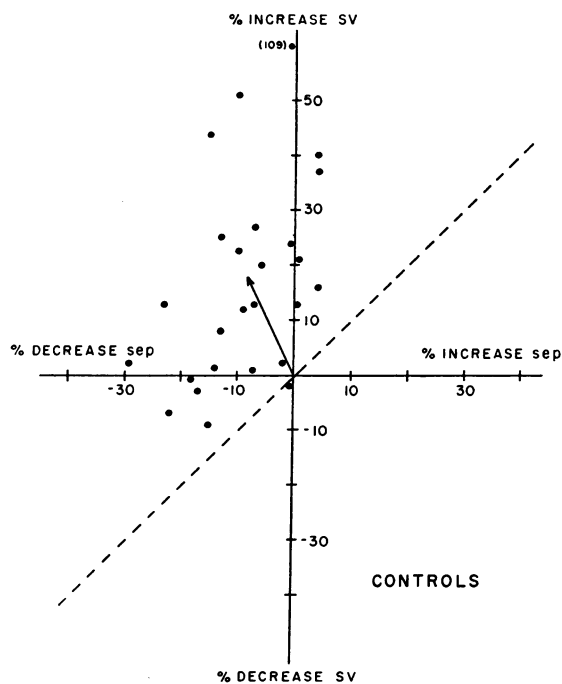


FIG. 2. PERCENTILE CHANGES IN STROKE VOLUME (SV) ON THE ORDINATE AND IN SYSTOLIC EJECTION PERIOD (sep) ON THE ABSCISSA ARE PLOTTED FOR ALL PATIENTS IN THE CONTROL GROUP. The solid arrow represents the mean vector for the group. Deviation from the 45° interrupted line in a leftward and upward direction indicates a rise in mean systolic ejection rate; (109) represents a point off the chart.

Nine of the 26 control subjects (35 per cent) did *not* show a significant rise in stroke volume on effort. In eight of these nine subjects, however, systolic ejection period decreased out of proportion to stroke volume, indicating that MSER *increased* as with the other control subjects. When this smaller group of nine cases, with no change or with a fall in stroke volume, is compared with the failure series, the difference in mean systolic ejection rate response is still significant, with a  $p$  value of  $< 0.001$ .

In general, when changes in stroke volume occurred in the heart failure group there was an associated parallel change in systolic ejection period. Thus, little change in mean systolic ejection rate occurred, regardless of change in stroke volume (Figure 3). Two failure patients showed a rise in MSER as great as 10 per cent. In one of these, effective stroke volume was inordinately low and the percentile rise in ejection rate reflected an absolute increment in stroke index of 3 cc

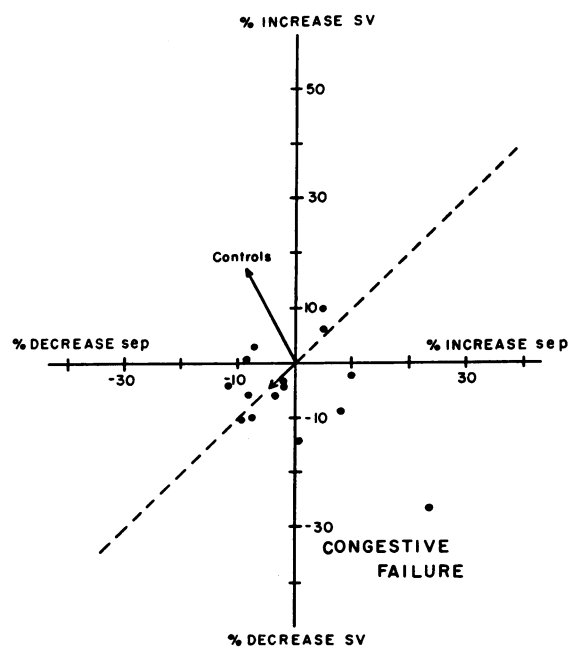


FIG. 3. PERCENTILE CHANGES IN STROKE VOLUME (SV) AND SYSTOLIC EJECTION PERIOD (sep) DURING EXERCISE IN CONGESTIVE HEART FAILURE PATIENTS. See legend for Figure 2.

with no change in systolic ejection period, obviously approaching methodologic accuracy.

The influence of the magnitude of the heart rate response on the MSER is examined in Figure 4.

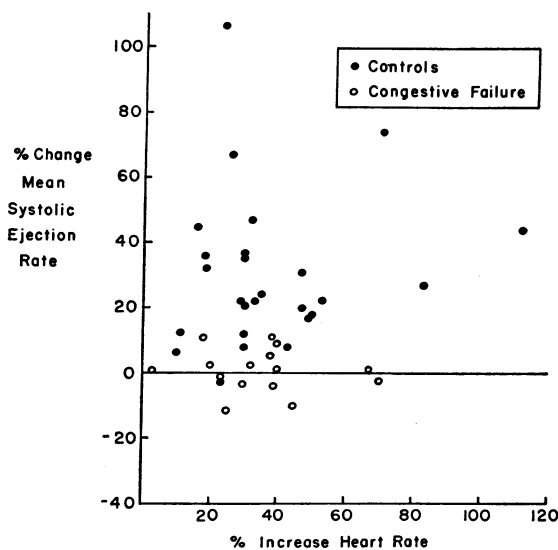


FIG. 4. PER CENT INCREASE IN HEART RATE DURING EXERCISE IS PLOTTED AGAINST THE PER CENT CHANGE IN MEAN SYSTOLIC EJECTION RATE. Note that no relationship is apparent.

TABLE III  
Miscellaneous subject groups

Subjects		BSA	Heart rate		Stroke volume		Systolic ejection period		Mean systolic ejection rate		Left vent. syst. mean press.		Total body O <sub>2</sub> consump.			
Age	Sex		Rest	Exer.	Rest	Exer.	Rest	Exer.	Rest	Exer.	Rest	Exer.	Rest	Exer.		
		m <sup>2</sup>	beats/min		cc/beat/m <sup>2</sup>		sec/beat		cc/sec/m <sup>2</sup>		mm Hg		cc/min/m <sup>2</sup>			
<b>Mitral stenosis</b>																
1	AT	25	m	2.06	78	120	45	37	0.28	0.23	160	163	94	133	153	455
2	BK	23	f	1.35	72	140	50	34	0.29	0.23	173	148	78	85	148	298
3	JF	37	m	1.88	91	141	23	22	0.21	0.19	109	118	104	112	154	402
4	EL	57	f	1.47	103	120	25	30	0.20	0.20	126	150	95	138	143	322
5	AH	47	m	1.84	107	130	24	26	0.18	0.17	136	158	96	116	163	290
6	EM	58	f	1.62	102	126	21	17	0.20	0.22	105	79	87	131	154	286
7	HN	47	f	1.72	76	97	25	34	0.30	0.29	83	118	111	118	99	288
8	GR	30	f	1.40	106	147	20	20	0.27	0.19	74	106	101	114	153	291
9	NS	55	f	1.74	100	128	28	35	0.24	0.23	117	152	170	195	127	331
10	GT	31	m	1.72	76	112	26	34	0.22	0.20	119	172	107	112	124	434
11	HM	39	f	1.40	91	143	27	22	0.26	0.20	104	111	108	136	130	305
Average		41		1.65	91	128	28	29	0.24	0.21	120	136	105	126	142	237
Standard deviation ±					10	7	11	8	0.028	0.021	36	40	13	18	19	63
<b>Aortic stenosis</b>																
1	WD	42	m	1.90	84	120	38	29	0.39	0.34	98	87			151	378
2	ED	50	m	1.76	68	90	39	38	0.31	0.29	124	130	246	258	134	233
3	CD	22	m	2.20	77	80	54	50	0.34	0.34	158	149	329	215	161	213
4	SP	45	m	1.94	79	91	44	46	0.32	0.34	139	137	168	183	183	315
5	BH	54	m	1.58	86	95	30	35	0.28	0.27	109	129	207	276	122	273
6	FM	45	f	1.43	70	86	34	31	0.32	0.30	106	106	167	169	127	294
Average		43		1.80	77	94	41	39	0.33	0.31	124	124	203	220	146	284
Standard deviation ±					6	6	14	14	0.018	0.013	41	37	21	26	23	59
<b>Atropine</b>																
1	ES	29	f	1.50	63	96*	47	29*	0.34	0.30*	206	147*	92	94*		
2	DM	24	m	2.08	62	87*	30	20*	0.36	0.34*	85	58*	110	115*		
3	LT	21	m	1.75	82	100*	33	23*	0.31	0.30*	106	77*	105	98*		
4	SP	42	m	1.95	62	90*	25	15*	0.36	0.32*	69	47*	120	118*		
5	DH	21	f	1.57	80	108*	33	27*	0.32	0.28*	103	99*	115	110*		
6	BK	31	f	1.72	70	102*	26	19*	0.34	0.29*	75	65*	108	107*		
Average		28		1.76	70	97	32	22	0.34	0.30	94	71	108	107		
Standard deviation ±					4	6	4	5	0.02	0.019	3	19	7	10		

\* Atropine.

It is apparent that there is no relationship, in either the control or failure cases, between the degree of tachysystole and the change in effective mean systolic ejection rate induced by effort. Further information with regard to the effect of tachycardia alone on the MSER was obtained in six patients given intravenous atropine (Table III). Atropine produced an average rise in heart rate of 39 per cent, a fall in stroke volume of 31 per cent, and a decrease in systolic ejection period of 9 per cent. In each instance the MSER fell (average decrease, 24 per cent). Thus, tachysystole alone, as produced by atropine, is associated with a decrease rather than with a rise in the mean rate of left ventricular ejection.

## 2. Mechanical obstruction to blood flow

In an effort to compare the effect of mechanical obstruction to blood flow with that of primary

myocardial failure, two groups of subjects with valvular stenosis were studied (Table III).

**Mitral stenosis.** While stroke volume rose in only five of the eleven subjects during effort, mean systolic ejection rate increased in nine (average rise, 13 per cent). Of the two subjects in whom mean systolic ejection rate did not increase, one was in marked right ventricular failure. The difference in MSER response between the mitral stenosis group and the congestive failure group is significant ( $p = 0.03$ ).

**Aortic stenosis.** Only two of the six subjects in this category effected a rise in mean systolic ejection rate with effort, despite the absence of elevated left ventricular diastolic pressures. The average MSER for this group did not change with exercise.

A single patient with classical constrictive pericarditis demonstrated a 32 per cent rise in MSER during similar effort.

TABLE IV  
Change of effective mean systolic ejection rate (MSER) and total MSER in patients with aortic regurgitation \*

Patient:		1	2	3	4
Effective stroke volume, cc/beat	R	31	41	59	50
	E	36	37	42	40
Total stroke volume, † cc/beat	R	68	145	110	77
	E	68	79	73	66
Systolic ejection period, sec/beat	R	0.28	0.23	0.32	0.35
	E	0.28	0.18	0.28	0.32
Effective MSER, cc/sec	R	111	178	184	143
	E	127	206	150	125
Change, %		+14	+16	-18	-12
Total MSER, cc/sec	R	243	630	344	220
	E	243	440	261	206
Change, %		0	-30	-24	-6

\* R = rest; E = exercise.

† Includes aortic regurgitant plus effective stroke volume.

### 3. Valvular regurgitation

Since valvular regurgitation can affect the mean systolic ejection rate calculation, an effort was made to assess the changes in total mean systolic ejection rate in selected patients with aortic insufficiency during exercise. In four patients with aortic insufficiency and left ventricular failure, aortic regurgitant data, derived hydraulically from necropsy material in each case (vide supra), were

used to back-calculate total as well as effective stroke volumes and mean systolic ejection rates during the rest and exercise studies (Table IV). Two of these cases demonstrated an increase in effective (or "forward flow") MSER during effort (Figure 5). However, as regurgitant stroke volume decreased more than effective stroke volume during exercise, total MSER fell in one case and remained unchanged in the other. In the remaining two cases, both total and effective MSER fell during the exercise period. Thus, as aortic regurgitant stroke volume generally decreases on effort with a decrease in diastolic filling period per beat and insignificant changes in aortic valve diastolic gradient, the abnormal MSER response to effort in congestive failure becomes apparent, particularly when total rather than effective ejection rates are examined. It is clear how effective cardiac output can rise in aortic insufficiency without a change in cardiac contractility, simply by the mechanical reduction in regurgitation.

### DISCUSSION

The present studies indicate that under conditions of stress, the nonfailing human left ventricle predictably effects a rise in mean systolic ejection rate, irrespective of changes in stroke volume. The failing left ventricle, however, with comparable physical stress, appears unable to increase its mean rate of ejection. Every attempt was made in these studies to standardize the stress sustained by both groups of patients. Total body oxygen consumption was similar in the control and failure groups. This similarity, however, is more apparent than real, for as Huckabee and Judson (12) have shown, congestive failure patients subjected to mild exercise demonstrate an average anaerobic metabolic rate of 30 per cent that of the total metabolic rate, while in normal subjects this figure is negligible (5 per cent). This suggests somewhat greater total body stress in the failure as compared with the control subjects. A comparable rise, however, in pressure time per minute<sup>1</sup> indicated that cardiac stress was similar in both the control and failure groups (1,130 and 1,270 mm Hg-second per minute, respectively).

Similarly, while the increment in heart rate

<sup>1</sup> Product of heart rate, systolic ejection period per beat, and left ventricular systolic mean pressure.

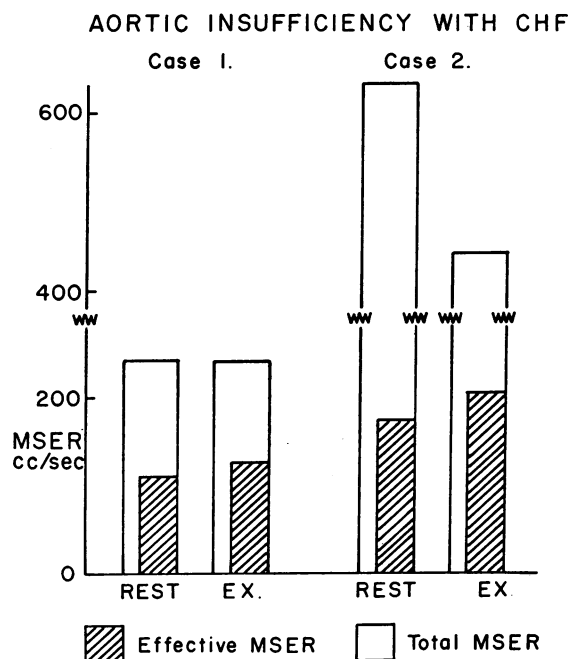


FIG. 5. AORTIC INSUFFICIENCY AND CONGESTIVE HEART FAILURE (CHF). MSER = mean systolic ejection rate. The effective and total MSER's during exercise are shown for Patients 1 and 2 of Table IV. See text.

attending exercise was an average of 7 beats per minute greater in the control series, no relationship between individual changes in mean systolic ejection rate and heart response was found. This was true of both control and failure groups. Indeed, vagolytic tachycardia in resting subjects was uniformly associated with a fall in both stroke volume and mean ejection rate. In the electrically paced human heart a similar decrease in stroke volume was demonstrated with increasing rate by Warner and Lewis, although they did not measure ejection rates (13). Therefore, the normal mean systolic ejection rate response to stress does not reflect changes in cycle length alone.

The problem of valvular regurgitation warrants comment. True changes in mean systolic ejection rate can be derived only when changes in the total stroke volume of the ventricle are known. In the case of aortic insufficiency, the hydraulic determinants of backflow (regurgitant flow period and aortic valve diastolic gradient) are easily measured. Thus, irrespective of regurgitant stroke volume, percentile changes in regurgitation during exercise may be calculated with accuracy (11). When the regurgitant aortic valve area is known, as in the cases reported herein after necropsy, absolute changes in regurgitant stroke volume and total mean systolic ejection rates may then be derived.

As defined in the expression, mean systolic ejection rate reflects only an average rate of flow and provides no information concerning the instantaneous rate of ejection. Aortic root velocity has been studied in the normal subject by several investigators (14-16) and, in general, maximal velocity is attained early in systole and is maintained throughout the greater portion of the ejection period. A small number of failure cases studied by Barnett, Greenfield and Fox exhibited lower velocity levels which were poorly sustained (17). In both instances the shape of the velocity curves was such that a derived mean velocity does not introduce gross misinterpretations, as would occur if the curves were asymmetrical or had large negative complexes. Since only relatively small changes in aortic cross-sectional area occur during the cardiac cycle, the instantaneous ejection rate curve should have the same general contour as that of the velocity curve. In similar

fashion, therefore, gross misinterpretation of left ventricular ejection rate is not likely to be introduced by the mean systolic ejection rate calculation.

The mean systolic ejection rate characterizes only one aspect of cardiac contractility. If one defines the contractile effort as the rate of fiber shortening per unit of outflow pressure (left ventricular systolic mean pressure) (18), it is possible to describe contractility if the following are known: 1) mean systolic ejection rate, 2) left ventricular systolic mean pressure, 3) diastolic volume. While true changes in diastolic volume are not known, some insight into gross directional changes may be inferred from changes in left ventricular diastolic filling pressures and stroke volumes. The failure group exhibited a large increase in left ventricular filling pressure at a time when the average stroke volume fell slightly. Despite the fact that these dilated, hypertrophied ventricles function on the steep portion of the ventricular compliance curve (19), it is reasonable to assume that the mean radius of the ventricular chamber increased to some degree during exercise. A distended ventricle need diminish its total mass proportionately less than a nondistended one to maintain a given stroke volume. It follows that if a fiber shortens the same distance in the same period of time, but from an initially larger volume, stroke volume and mean systolic ejection rate necessarily increase. However, as neither stroke volume nor mean systolic ejection rate increased, fiber-shortening distance must have decreased on exercise. This could represent either a reduced rate of fiber shortening or a considerable curtailment of the duration of ventricular ejection with essentially unchanged contraction velocity (fiber-shortening rate). Our data show small reductions in both systolic ejection period and stroke volume in left ventricular failure during exercise. Hence, while it is likely that fiber-shortening rate decreased in these hearts during stress, this cannot be stated with certainty from the information available.

In the control group in whom left ventricular filling pressures rose slightly, if at all, and stroke volume increased in the majority, changes in mean radius of the left ventricular chamber are less predictable. Unless exercise end-diastolic volume increased markedly over resting values, the uni-



form rise in mean systolic ejection rate during exercise would indicate a rise in fiber-shortening rate. In any event, fiber-shortening rate should be greater in these nonfailing hearts than in the failing ventricles. Rushmer, Smith and Franklin have shown that both diastolic and systolic cardiac diameters are reduced in the normal, exercising dog (20). If these observations are representative of the behavior of the normal exercising human heart, then an absolute increase in fiber-shortening distance and contraction velocity occurs in normal man during stress.

Fiber shortening is not the sole measure of contractility, since the contractile effort may be manifest as either fiber shortening, wall tension, or both. Left ventricular systolic mean pressure rose an average of 19 mm Hg (+ 18 per cent) in the control series and 27 mm Hg (+ 24 per cent) in the failure cases during exercise, and the pressure time index increments in the two groups differed by less than 12 per cent (*vide supra*). Consequently, the ability of the failing heart to generate pressure on effort is not impaired. In addition, when one considers the added wall tension imposed on these hearts through dilatation (by virtue of the law of Laplace), it appears that the dilated, failing ventricle is forced to function in a more nearly isometric fashion during stress.

One patient with clinically severe left ventricular failure (not included in the above group) was studied after phlebotomy and found to have normal pulmonary-capillary pressures at rest and during exercise. Mean systolic ejection rate at this time rose normally (+ 20 per cent) during effort. This preliminary observation supports the concept that excessive rise in wall tension owing to dilatation precludes a normal response of the mean systolic ejection rate during stress. Conversely, with sufficient reduction in mean chamber size and, therefore, in wall tension, the normal mean systolic ejection rate response *may* be restored. It is of interest that abnormal changes in mean systolic ejection rate were also noted in the aortic stenosis group without left ventricular failure. Here again the contractile effort of the ventricle is diverted from fiber shortening to tension development. These observations are consistent with studies by Hill (21) of the force-velocity curves for isolated skeletal muscle strips

in which velocity of shortening decreased as the force was increased.

Obstructive mitral disease, on the other hand, did not qualitatively alter the mean systolic ejection rate response of the normal ventricle to stress. The normal and unburdened left ventricle in mitral stenosis responds normally to the stimulus of exercise, even though the initial chamber volume is limited by the inflow restrictions of obstructive mitral disease. The rise in mean systolic ejection rate in the mitral stenosis group, however, was considerably less than that of the controls (Table I), but did resemble those nine control patients in whom stroke volume did not rise with exercise.

The possible influence of right ventricular failure on left ventricular ejection rate is as yet unknown, and studies are currently in progress to shed light on both this and the reversibility of the fixed mean systolic ejection rate of the stressed, failing ventricle.

#### SUMMARY

The effect of exercise on the mean rate of left ventricular ejection was studied in 64 subjects with normal and abnormal left ventricular function. The exercising, nonfailing left ventricle consistently exhibited a rise in effective mean systolic ejection rate, with or without an increase in stroke volume. The failing ventricle, on the other hand, did not increase its rate of ejection during stress. When changes in *total* systolic ejection rate were examined, this defect in fiber shortening could also be demonstrated in the failing hearts of aortic insufficiency subjects. Obstructive mitral disease did not qualitatively alter the normal response of the left ventricle. Aortic stenosis patients without left ventricular failure, however, were generally unable to effect a rise in mean systolic ejection rate on effort. It is suggested that excessive rise in muscle wall tension during stress imposed by virtue of dilatation in congestive failure, and by systolic hypertension in aortic stenosis (through the force-velocity relationship), precludes the normal rise in mean systolic ejection rate.

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