Left ventricular dynamics during handgrip¹

I. Amende, H. P. Krayenbuehl, W. Rutishauser, and P. Wirz

From the Cardiovascular Division, Medical Policlinic, University of Zürich, Zürich, Switzerland

The effect of isometric exercise by handgrip on the ejection dynamics of the left ventricle, especially the relation between left ventricular stroke work index and end-diastolic pressure, was studied in 25 patients. In the patients with normal or nearly normal left hearts (group 1), the response to handgrip was characterized by a significant increase of left ventricular stroke work index at an essentially unchanged end-diastolic pressure. In the patients with definitely increased LV end-diastolic pressure at rest (group 3), handgrip led to a significant increase of LV end-diastolic pressure associated with only a small and insignificant increase of stroke work index. This response is indicative of depressed left ventricular function. Patients with volume or pressure loaded or coronary diseased left hearts with normal or only slightly raised LV end-diastolic pressure at rest (group 2) showed a response similar to that of group 1. When comparison of the haemodynamic parameters was carried out at similar heart rates, group 2 elicited 'abnormal' left ventricular function characterized by both a significant increase of LV stroke work index and LV end-diastolic pressure. Whether this latter response represents an early sign of left ventricular depression remains open to question.

Previous studies have shown that isometric exercise by handgrip (Lind and McNicol, 1967; MacDonald *et al.*, 1966; Lind, 1970) is a useful stress test for the detection of ventricular dysfunction and evaluation of haemodynamic abnormalities in patients with cardiovascular diseases (Houston, Atkins, and Blomqvist, 1970; Jacobs *et al.*, 1970; Kivowitz *et al.*, 1970; Mullins *et al.*, 1970). Recently, assessment of left ventricular contractile function from isovolumic pressure measurements has led to the conclusion that the normal left ventricular myocardium responds primarily with an enhancement of the contractile state to an acute load produced by handgrip, and that the diseased myocardium utilizes the Frank-Starling mechanism to generate an increased pressure (Krayenbuehl *et al.*, 1972). This type of haemodynamic evaluation necessitates high-fidelity left ventricular pressure measurements, not available at routine catheterization. Furthermore, the absence of a true isovolumic phase of contraction, for instance in mitral incompetence, may render the evaluation of left ventricular function from pressure measurements alone of questionable significance. It is therefore the purpose of this paper to describe the effects of handgrip on the

ejection dynamics of the left ventricle, especially on the relation between left ventricular stroke work and end-diastolic pressure in patients with and without cardiac dysfunction. In order to facilitate the haemodynamic comparisons, the influence of changes in heart rate was eliminated by right atrial pacing at rates as close as possible to those obtained under handgrip.

Materials and methods

Twenty-five patients (10 women and 15 men) were studied by right and left cardiac catheterization. Premedication consisted of 10 mg chlor-diazepoxide (Librium) given orally one hour before the investigation. According to the result of the diagnostic catheterization performed at rest, the 25 patients were divided into three groups.

Group 1 comprised 6 patients with no or minimal loading of the left ventricle and a left ventricular end-diastolic pressure not exceeding 15 mmHg. There were 3 cases with uncomplicated atrial septal defect, 1 case with pectus excavatum, 1 case with moderate primary pulmonary hypertension, and 1 case with minimal mitral incompetence. This group was considered as having normal left ventricular function.

Group 2 comprised 9 patients. Seven of them had slight to moderate left ventricular volume or

Received 2 September 1971.

¹ This work was supported by a grant of the Swiss National Fund.

pressure load, or coronary heart disease. Left ventricular end-diastolic pressure was normal or only slightly raised (not exceeding 16 mmHg). There were 2 cases with persistent ductus arteriosus, 1 case with small ventricular septal defect, 1 case with slight to moderate mitral incompetence, 1 case with idiopathic hypertrophic subaortic stenosis and mild mitral incompetence, and 2 cases with coronary heart disease documented by selective coronary arteriography. In one of these patients, occlusion of the right coronary artery, 1 cm distal to the ostium, and mild mitral incompetence were present. The other patient showed nearly complete obstruction in the middle part of the right coronary artery. In addition, 2 patients with valvular pulmonary stenosis were included in this group since their left ventricular end-diastolic pressure was slightly raised (16 mmHg).

Group 3 comprised 10 patients with clearly raised left ventricular end-diastolic pressures at rest (19 mmHg or more). There were 3 cases with moderate to severe valvular aortic stenosis and slight aortic incompetence, 1 case with mixed aortic valve stenosis and incompetence, 1 case with moderate mitral incompetence, 1 case with combined aortic and mitral incompetence, 1 case with constrictive pericarditis, 1 case with idiopathic hypertrophic non-obstructive cardiomyopathy, 1 case with a calcified cavernous haemangioma affecting the right atrium, right ventricle, and septum, and 1 case with healed myocardial infarction and minimal mitral incompetence. Coronary arteriography revealed occlusion of the right coronary artery in the distal portion of the vessel.

All patients were in sinus rhythm. In the case in group 3 with combined aortic and mitral incompetence, left bundle-branch block was present.

Catheter localization for handgrip study

Conventional catheters were inserted into the ascending aorta and into the left ventricle by the retrograde and/or the transeptal route. A thermistor probe was advanced to the thoracic aorta. For the quantification of mitral and/or aortic incompetence, a second thermistor probe was positioned into the left atrium or the left ventricle through a transeptal Brockenhough catheter 8.5 F¹. Right atrial pacing was accomplished by a Goetz bipolar electrode catheter 6 F¹.

Calculations Pressure measurements were carried out by external Statham P23Db transducers. Registration was achieved by a multichannel oscillograph (DR/8 Electronics for Medicine) at paper speeds of 25 and 200 mm/sec. From the pressure recordings the following detailed measurements were made: left ventricular peak systolic pressure, left ventricular end-diastolic pressure, systolic aortic pressure, diastolic aortic pressure, and mean aortic pressure.

USCI, Glens Falls, New York.

Cardiac output was estimated by the thermodilution technique as described elsewhere (Krayenbühl, 1969). Briefly, 5 ml ice-cold saline were injected into the left ventricle. Dilution curves were obtained by the thermistor probe positioned in the ascending aorta. The amount of injected cold saline was quantified in a model experiment.

The magnitude of mitral and aortic regurgitation was determined by the thermodilution method (Krayenbühl, 1969). For that purpose, sampling was achieved by equisensitive thermistors placed upstream (i.e. in the left ventricle or in the left atrium) and downstream (i.e. in the descending thoracic aorta) of the incompetent valve, after infusion of 10-ml ice-cold saline into the left ventricle and into the aortic root respectively. The ratio of the areas of the dilution curves represents the regurgitant fraction. From the regurgitant fraction and the forward cardiac output, total left ventricular output was calculated according to Lacy *et al.* (1959). The magnitude of left-to-right shunts was determined from dye dilution curves recorded by earpiece after dye injection into the pulmonary artery using the method of Carter *et al.* (1960). Left ventricular stroke work index in g m/m² was calculated from the formula

$$LVSWI = \frac{SVI \times (MAP - LVEDP) \times 1.36}{100}$$

where SVI = stroke volume index in ml/m²; MAP = mean aortic pressure (mmHg); and LVEDP = left ventricular end-diastolic pressure (mmHg).

It has to be noted that the stroke volume index always represents forward stroke volume index except in aortic incompetence and persistent ductus arteriosus where total left ventricular stroke volume index, i.e. the amount of blood ejected into the aortic root per beat/m², was used to calculate LV stroke work index.

Experimental protocol Handgrip was performed with a balloon dynamometer. The details have been described previously (Krayenbühl *et al.*, 1972).

When the patient had become familiar with the handgrip test, a control run at rest was carried out. The patient was then requested to squeeze the dynamometer for 3 minutes. Between the second and third minute of compression, an experimental run was recorded. In 15 out of the 25 patients, right atrial pacing was instituted after a pause of 10 minutes at similar heart rate as achieved during handgrip. A third experimental run was obtained after 2 minutes after the onset of right atrial pacing.

The average handgrip performance in the three groups was as follows: 0.28 ± 0.01 (SE) kg/cm² in group 1, 0.29 ± 0.02 kg/cm² in group 2, and 0.29 ± 0.01 kg/cm² in group 3.

Results

The means and the standard errors of the haemodynamic data of each group at rest,

TABLE 1 Haemodynamic data in group 1 (5 women, 1 man)

	Age (yr)	Cardiac index (l./min/m ²)	Heart rate (min ⁻¹)	Stroke volume index (ml/m ²)	LV peak systolic pressure (mmHg)	LV end- diastolic pressure (mmHg)	Systolic aortic pressure (mmHg)	Diastolic aortic pressure (mmHg)	Mean aortic pressure (mmHg)	LV stroke work index (g m/m ²)
A. Control	29.3	3.5	63	56	111	12.2	111	68	89	58.4
SE	±3.7	±0.1	±3	±4	±5	±0.9	±5	±3	±3	±6.1
No.		6	6	6	6	6	6	6	6	6
B. Handgrip (0.28 ± 0.01 kg/cm ²)		4.8	85	57	134	12.6	134	87	109	75.1
		±0.2	±3	±4	±8	±1.3	±8	±4	±5	±8.8
P _{BvsA}		<0.001	<0.001	NS	<0.01	NS	<0.01	<0.01	<0.01	<0.01
No.		6	6	6	6	6	6	6	6	6
C. RA Pacing		4.4	87	50	116	9.7	116	78	97	59.2
		±0.2	±2	±3	±3	±0.7	±3	±3	±3	±3.9
P _{CvsA}		<0.01	<0.001	NS	NS	<0.05	NS	<0.001	<0.01	NS
P _{CvsB}		NS	NS	NS	<0.05	NS	<0.05	NS	<0.05	<0.05
No.		6	6	6	6	6	6	6	6	6

No. = number of observations; P values are determined by the paired t-test; NS = not significant ($P > 0.05$).

during handgrip, and during right atrial pacing are given in Tables 1–5. Statistical analysis was achieved by the Student paired t-test.

Group 1 The results are shown in Table 1. During handgrip there was a significant increase of heart rate, LV peak systolic pressure, systolic aortic pressure, diastolic aortic pressure, mean aortic pressure, and cardiac index. Stroke volume index remained unchanged. The LV end-diastolic pressure did not change, whereas LV stroke work index increased significantly from 58 g m/m² to 75 g m/m².

When the values during right atrial pacing were compared with the data obtained during handgrip the following observations were made: LV peak systolic pressure, systolic aortic pressure, and mean aortic pressure were significantly higher during handgrip than

during right atrial pacing. Cardiac index, diastolic aortic pressure, and stroke volume index were not different. LV end-diastolic pressure showed no difference, whereas LV stroke work index was augmented significantly (59 g m/m² during right atrial pacing and 75 g m/m² during handgrip).

No statistically significant difference was observed when LV stroke work index in the control state was compared with that determined during right atrial pacing. LV end-diastolic pressure was significantly lower during right atrial pacing compared to the control state.

Group 2 Table 2 shows the data of group 2. Heart rate, LV peak systolic pressure, systolic aortic pressure, diastolic aortic pressure, and mean aortic pressure increased significantly during handgrip. Forward cardiac

TABLE 2 Haemodynamic data in group 2 (1 woman, 8 men)

	Age (yr)	Forward cardiac index (l./min/ m ²)	Total cardiac index (l./min/ m ²)	Heart rate (min ⁻¹)	Forward stroke volume index (ml/m ²)	Total stroke volume index (ml/m ²)	LV peak systolic pressure (mmHg)	LV end- diastolic pressure (mmHg)	Systolic aortic pressure (mmHg)	Diastolic aortic pressure (mmHg)	Mean aortic pressure (mmHg)	LV stroke work index (g m/m ²)
D. Control	37.4	3.3	4.3	70	49	61	134	13.9	131	77	101	55.6
SE	±6.7	±0.5	±0.7	±3	±7	±11	±5	±0.8	±5	±2	±1	±7.6
No.		7	8	9	7	8	9	9	9	9	9	9
E. Handgrip (0.29 ± 0.02 kg/cm ²)		4.0	5.4	88	51	64	151	14.9	149	91	116	66.0
		±0.5	±0.9	±7	±8	±10	±6	±1.4	±6	±3	±4	±9.8
P _{EvsD}		<0.001	<0.05	<0.01	NS	NS	<0.001	NS	<0.001	<0.001	<0.001	<0.05
No.		7	8	9	7	8	9	9	9	9	9	9

Abbreviations as in Table 1.

TABLE 3 Haemodynamic data in 5 patients (1 woman, 4 men) of group 2 in whom in addition to handgrip right atrial pacing was carried out

	Age (yr)	Forward cardiac index (l./min/ m ²)	Total cardiac index (l./min/ m ²)	Heart rate (min ⁻¹)	Forward stroke volume index (ml/m ²)	Total stroke volume index (ml/m ²)	LV peak systolic pressure (mmHg)	LV end- diastolic pressure (mmHg)	Systolic aortic pressure (mmHg)	Diastolic aortic pressure (mmHg)	Mean aortic pressure (mmHg)	LV stroke work index (g m/m ²)
F. Control	33.8	3.5	4.4	68	55	63	128	15.0	128	79	100	63.4
SE	±9.7	±0.8	±1.1	±4	±12	±17	±4	±0.6	±5	±2	±2	±11.2
No.		4	4	5	4	4	5	5	5	5	5	5
G. Handgrip (0.32 ± 0.01 kg/cm ²)		4.3	5.2	93	59	68	143	17.0	143	91	115	76.4
		±0.9	±1.4	±5	±13	±20	±7	±1.3	±7	±6	±6	±14.4
P _{GvsF}		<0.05	NS	<0.001	NS	NS	NS	NS	NS	<0.05	<0.05	<0.05
No.		4	4	5	4	4	5	5	5	5	5	5
H. RA Pacing		4.4	5.1	89	54	60	126	10.0	126	82	102	63.7
SE		±0.9	±1.1	±7	±14	±18	±5	±1.9	±5	±3	±3	±12.4
P _{HvsF}		<0.01	<0.05	<0.01	NS	NS	NS	<0.05	NS	NS	NS	NS
P _{HvsG}		NS	NS	<0.05	<0.05	NS	<0.05	<0.05	<0.05	NS	NS	<0.05
No.		4	4	5	4	4	5	5	5	5	5	5

Abbreviations as in Table 1.

TABLE 4 Haemodynamic data in group 3 (4 women, 6 men)

	Age (yr)	Forward cardiac index (l./min/ m ²)	Total cardiac index (l./min/ m ²)	Heart rate (min ⁻¹)	Forward stroke volume index (ml/m ²)	Total stroke volume index (ml/m ²)	LV peak systolic pressure (mmHg)	LV end- diastolic pressure (mmHg)	Systolic aortic pressure (mmHg)	Diastolic aortic pressure (mmHg)	Mean aortic pressure (mmHg)	LV stroke work index (g m/m ²)
I. Control	40.3	3.3	4.0	72	47	57	157	23.6	127	73	94	49.3
SE	±4.9	±0.3	±0.7	±4	±4	±9	±21	±1.4	±9	±2	±5	±6.8
No.		10	10	10	10	10	10	10	10	10	10	10
K. Handgrip (0.29 ± 0.01 kg/cm ²)		3.9	4.3	89	44	49	176	27.7	148	87	111	54.9
		±0.4	±0.5	±5	±4	±6	±20	±2.8	±9	±3	±5	±8.2
P _{KvsI}		<0.01	NS	<0.001	NS	NS	<0.001	<0.05	<0.001	<0.001	<0.001	NS
No.		10	10	10	10	10	10	10	10	10	10	10

Abbreviations as in Table 1.

TABLE 5 Haemodynamic data in 4 patients (2 women, 2 men) of group 3 in whom in addition to handgrip right atrial pacing was carried out

	Age (yr)	Forward cardiac index (l./min/ m ²)	Total cardiac index (l./min/ m ²)	Heart rate (min ⁻¹)	Forward stroke volume index (ml/m ²)	Total stroke volume index (ml/m ²)	LV peak systolic pressure (mmHg)	LV end- diastolic pressure (mmHg)	Systolic aortic pressure (mmHg)	Diastolic aortic pressure (mmHg)	Mean aortic pressure (mmHg)	LV stroke work index (g m/m ²)
L. Control	37.8	3.9	5.1	73	55	71	178	21.3	126	73	94	54.2
SE	±10.9	±0.2	±1.3	±5	±4	±19	±38	±1.3	±8	±2	±5	±5.0
No.		4	4	4	4	4	4	4	4	4	4	4
M. Handgrip (0.3 kg/cm ²)		4.7	5.3	93	51	57	197	25.3	149	89	112	60.6
		±0.3	±0.8	±4	±4	±10	±37	±3.4	±8	±2	±4	±7.1
P _{MvsL}		<0.05	NS	<0.001	NS	NS	<0.05	NS	<0.001	<0.001	<0.01	NS
No.		4	4	4	4	4	4	4	4	4	4	4
N. RA Pacing		4.3	5.1	88	50	58	181	16.0	127	77	95	54.0
SE		±0.2	±0.9	±4	±2	±9	±38	±3.1	±7	±4	±5	±5.3
P _{NvsL}		<0.01	NS	<0.05	NS	NS	NS	NS	NS	NS	NS	NS
P _{NvsM}		NS	NS	NS	NS	NS	<0.05	<0.02	<0.01	<0.05	<0.02	NS
No.		4	4	4	4	4	4	4	4	4	4	4

Abbreviations as in Table 1.

index and total cardiac index rose significantly, whereas forward stroke volume index and total stroke volume index remained unchanged. LV end-diastolic pressure showed no significant change whereas LV stroke work index increased significantly from 56 g m/m² to 66 g m/m².

In Table 3 the findings during handgrip and at similar heart rate (right atrial pacing) are summarized. LV peak systolic pressure and systolic aortic pressure were significantly raised during handgrip, whereas diastolic aortic pressure and mean aortic pressure were insignificantly higher compared to right atrial pacing. Forward cardiac index, total cardiac index, and total stroke volume index were essentially the same, whereas forward stroke volume index was significantly increased during handgrip. At similar heart rates end-diastolic pressure and LV stroke work index were significantly higher during handgrip than during right atrial pacing. When the haemodynamic parameters during right atrial pacing and at rest were compared, a significant decrease in LV end-diastolic pressure was observed while LV stroke work index did not change significantly.

Group 3 The results are given in Table 4. A significant increase of heart rate, LV peak systolic pressure, systolic aortic pressure, diastolic aortic pressure, mean aortic pressure, and forward cardiac index occurred during handgrip. Total cardiac index increased only slightly and insignificantly. Forward stroke volume index and total stroke volume index remained unchanged. LV end-diastolic pressure increased significantly from 24 mmHg to 28 mmHg. LV stroke work index averaged 49 g m/m² at rest and rose only insignificantly to 55 g m/m².

The results during handgrip and right atrial pacing are shown in Table 5. LV peak systolic pressure, systolic aortic pressure, diastolic aortic pressure, and mean aortic pressure were significantly higher during handgrip compared to right atrial pacing. Forward cardiac index, total cardiac index, forward stroke volume index, and total stroke volume index showed no differences. LV end-diastolic pressure was significantly higher during handgrip than during right atrial pacing (25 mmHg and 16 mmHg) whereas no significant difference in LV stroke work index (61 g m/m² and 54 g m/m²) was noted.

Between the control state and right atrial pacing no significant differences in LV end-diastolic pressure and LV stroke work index were observed.

FIG. 1 Relation between left ventricular end-diastolic pressure (LVEDP) and left ventricular stroke work index (LVSWI) at rest, in sinus rhythm, and during handgrip. The closed circles represent the mean values of group 1, the open circles those of group 2, and the squares those of group 3. The vertical and horizontal bars indicate ± 1 SE. HG = handgrip; HR = heart rate; NS = not significant ($P > 0.05$).

In groups 1 and 2 there is a similar haemodynamic response to handgrip though the increase in LVSWI is somewhat less in group 2 than in group 1. In group 3 there is a clearly pathological response, since LVSWI increases only slightly and insignificantly whereas LVEDP increases significantly. This response is indicative of depressed left ventricular function.

Discussion

It has become evident in recent years that only incomplete insight into the functional state of the left ventricle is obtained from conventional haemodynamic parameters determined at rest. For example, left ventricular end-diastolic pressure may be moderately raised at rest without compromised left ventricular performance being present. Such rises in left ventricular end-diastolic pressure have been reported in patients with hypertrophied hearts from chronic pressure over-

load (Braunwald and Ross, 1963; Mirsky, Ellison, and Hugenholz, 1971). A better definition of left ventricular performance can be achieved by additional loading of the heart. Dynamic exercise is the most physiological stress test but is unpractical for routine use during diagnostic cardiac catheterization. Handgrip offers, however, a new and simple means of stressing the heart (Lind and McNicol, 1967; Lind, 1970; Houston *et al.*, 1970; Jacobs *et al.*, 1970; Kivowitz *et al.*, 1970; Mullins *et al.*, 1970).

In the present study three groups of patients were exposed to an approximately equal pressure load as judged from the similar increase of mean aortic pressure during handgrip (Tables 1, 2, and 4). Whereas in the patients considered to have normal left ventricular function (group 1), handgrip was associated with a significant increase of stroke work index at essentially unchanged left ventricular end-diastolic pressure, the patients with definitely increased end-diastolic pressure at rest (group 3) showed only a small and insignificant increase of left ventricular stroke work index but a significant increase of left ventricular end-diastolic pressure. Thus, the slope of the 'ventricular function curve' in group 3 was very flat (Fig. 1). This indicates a clearly depressed left ventricular function in group 3. Similar observations have been made by Kivowitz *et al.* (1970) and Mullins *et al.* (1970). The haemodynamic response to handgrip in group 2, which comprised patients with loaded or coronary diseased left hearts but with normal or only slightly raised left ventricular end-diastolic pressures at rest, was characterized by a slope of the 'ventricular function curve' similar to that of the controls. One may however note that the magnitude of increase of left ventricular stroke work index was somewhat smaller in group 2 than in group 1. It appears then that left ventricular function is slightly altered in group 2.

Of particular interest for the evaluation of the functional state of the left ventricle was the comparison of the left ventricular dynamics during handgrip with those obtained during right atrial pacing. Since left ventricular end-diastolic pressure has been shown in animals (Noble *et al.*, 1969) and man (Rutishauser *et al.*, 1968) to decrease when heart rate is increased by electrical pacing, it was anticipated that the increase in heart rate occurring during handgrip would tend to diminish the increase in end-diastolic pressure produced by the acute pressure load. That such a mechanism was in fact at work became clearly evident in groups 2 and 3 (Tables 3 and 5): comparisons carried out at similar

FIG. 2 Relation between left ventricular end-diastolic pressure (LVEDP) and left ventricular stroke work index (LVSWI) during right atrial (RA) pacing and during handgrip. The symbols and abbreviations are the same as in Fig. 1.

In contrast to Fig. 1, there is now a clearly different response to handgrip in group 2 compared to that in group 1 when comparisons are made at similar heart rates. This response is intermediate between that of group 1 and that of group 3: LVSWI still increases as in group 1 but is associated with a significant increase of LVEDP (abnormal left ventricular dynamics).

heart rates showed a significant increase of left ventricular end-diastolic pressure in group 2, not existing when the comparison was made between the control state and handgrip (Table 2), and in group 3 the increase of left ventricular end-diastolic pressure under handgrip was clearly accentuated with respect to the augmentation of end-diastolic pressure observed when the control state was compared with handgrip (Table 4). Thus, the comparison at similar heart rates proved to be very helpful for the haemodynamic evaluation of the left ventricular function, especially in group 2. Though some alteration of left ventricular performance in this group could already be suspected from Fig. 1, a clearly

different response to handgrip compared with that in group 1 became evident at similar heart rates (Fig. 2). One may note that the slope of group 2 was intermediate with respect to the slopes of group 1 and group 3. We are therefore in the presence of three different responses to handgrip that may reflect three different functional states. Whereas one would certainly not hesitate to classify the response to handgrip in group 3 as a clearly pathological one, indicative of depressed left ventricular function, the question now arises of how to define the response in group 2. Ross and coworkers (1966) have classified patients with aortic stenosis in which both the stroke volume index and the left ventricular end-diastolic pressure increased under dynamic exercise as having abnormal left ventricular dynamics. In analogy to these observations the same terminology is proposed to characterize the patients of group 2 of the present investigation. If the utilization of the Frank-Starling mechanism as a means to increase left ventricular stroke work index in group 2 has to be considered as an early sign of myocardial depression, there remains, however, an open question. In this context it is noteworthy that in occasional patients with normal or nearly normal left ventricles, increases of stroke volume and left ventricular end-diastolic volume have been reported under dynamic exercise (Gorlin *et al.*, 1965), and that the transplanted (denervated) human heart mobilizes the Frank-Starling mechanism to meet an exercise load (Carleton *et al.*, 1969). From experimental studies in cat papillary muscles obtained from denervated hearts, there is, however, no indication that the intrinsic functional state of the myocardium is depressed (Coleman, Dempsey, and Cooper, 1969). It then seems possible that 'abnormal' left ventricular dynamics can be present even in the functionally unaltered myocardium.

That the Frank-Starling mechanism is mobilized in groups 2 and 3 is shown by the significant increase of left ventricular end-diastolic pressure (Tables 3 and 5, Fig. 2). In the patients whose left ventricular function was considered to be normal (group 1) there was however also a slight, though not significant, increase of end-diastolic pressure when comparison was made at similar heart rates (Fig. 2). Moreover, end-diastolic pressure did not decrease when heart rate increased during handgrip (Table 1, Fig. 1). It appears, therefore, that the Frank-Starling mechanism was mobilized to some extent in group 1. This means that even the normal left heart needs both an increase in contractility (Krayenbuehl

et al., 1972) and the Frank-Starling mechanism to overcome the pressure burden of handgrip.

Handgrip is a simple and useful stress test for the haemodynamic evaluation of normal and depressed left ventricular function. Furthermore, the comparison of haemodynamic data at similar heart rate during handgrip and at rest (right atrial pacing) allows the characterization of an intermediate type of haemodynamic response that reflects 'abnormal' left ventricular dynamics. There is evidence that not only the diseased left ventricle but also the normal or nearly normal left heart mobilizes the Frank-Starling mechanism to overcome the acute pressure burden produced by handgrip.

We thank Mrs. S. Jaschke for her skilful technical assistance and preparation of the Figures.

References

- Braunwald, E., and Ross, J. (1963). Editorial. The ventricular end-diastolic pressure: appraisal of its value in the recognition of ventricular failure in man. *American Journal of Medicine*, **34**, 147.
- Carleton, R. A., Heller, S. J., Najafi, H., and Clark, J. G. (1969). Hemodynamic performance of a transplanted human heart. *Circulation*, **40**, 447.
- Carter, S. A., Bajec, D. F., Yannicelli, E., and Wood, E. H. (1960). Estimation of left-to-right shunt from arterial dilution curves. *Journal of Laboratory and Clinical Medicine*, **55**, 77.
- Coleman, H. N., Dempsey, P. J., and Cooper, T. (1969). The regulation of myocardial energy utilization after chronic cardiac denervation. (Abstract.) *Journal of Clinical Investigation*, **48**, 17a.
- Gorlin, R., Cohen, L. S., Elliott, W. C., Klein, M. D., and Lane, F. J. (1965). Effect of supine exercise on left ventricular volume and oxygen consumption in man. *Circulation*, **32**, 361.
- Houston, J. D., Atkins, J. M., and Blomqvist, G. (1970). Cardiovascular response to isometric forearm contraction. (Abstract.) *Clinical Research*, **18**, 70.
- Jacobs, W. F., Nutter, D. O., Siegel, W., Schlant, R. C., and Hurst, J. W. (1970). Hemodynamic responses to isometric handgrip in patients with heart disease. (Abstract.) *Circulation*, **42**, Suppl. 3, 169.
- Kivowitz, C., Marcus, H., Donoso, R., Ganz, W., Swan, H. J. C., and Parmley, W. W. (1970). Evaluation of cardiac performance with a handgrip dynamometer in patients with heart disease - 'the grip test'. (Abstract.) *Circulation*, **42**, Suppl. 3, 122.
- Krayenbuehl, H. P. (1969). Die Dynamik und Kontraktilität des linken Ventrikels. *Bibliotheca Cardiologica*, **23**, 1.
- Krayenbuehl, H. P., Schoenbeck, M., Amende, I., and Rutishauser, W. (1972). Evaluation of left ventricular function from isovolumic pressure measurements under isometric exercise. *American Journal of Cardiology*, **29**, 323.
- Lacy, W. W., Goodson, W. H., Wheeler, W. G., and Newman, E. V. (1959). Theoretical and practical requirements for the valid measurement by indicator-dilution of regurgitant flow across incompetent valves. *Circulation Research*, **7**, 454.

- Lind, A. R. (1970). Editorial. Cardiovascular responses to static exercise (isometrics, anyone?). *Circulation*, **41**, 173.
- Lind, A. R., and McNicol, G. W. (1967). Muscular factors which determine the cardiovascular responses to sustained and rhythmic exercise. *Canadian Medical Association Journal*, **96**, 706.
- MacDonald, H. R., Sapru, R. P., Taylor, S. H., and Donald, K. W. (1966). Effect of intravenous propranolol on the systemic circulatory response to sustained handgrip. *American Journal of Cardiology*, **18**, 333.
- Mirsky, I., Ellison, R. C., and Hugenholtz, P. G. (1971). Assessment of myocardial contractility in children and young adults from ventricular pressure recordings. *American Journal of Cardiology*, **27**, 359.
- Mullins, C. B., Leshin, S. J., Mierzwiak, D. S., Matthews, O. A., and Blomqvist, C. G. (1970). Isometric exercise (handgrip) as a stress test for evaluation of left ventricular function. (Abstract.) *Circulation*, **42**, Suppl. 3, 122.
- Noble, M. I. M., Wyler, J., Milne, E. N. C., Trenchard, D., and Guz, A. (1969). Effect of changes in heart rate on left ventricular performance in conscious dogs. *Circulation Research*, **24**, 285.
- Ross, J., Gault, J. H., Mason, D. T., Linhart, J. W., and Braunwald, E. (1966). Left ventricular performance during muscular exercise in patients with and without cardiac dysfunction. *Circulation*, **34**, 597.
- Rutishauser, W., Wirz, P., Gander, M., and Noseda, G. (1968). Vergleich der Hämodynamik bei Frequenzsteigerung unter Arbeitsbelastung und elektrischer Stimulation. In *Heart Failure. Pathophysiological and Clinical Aspects*, p. 429. Ed. by H. Reindell, J. Keul, and E. Doll. Georg Thieme, Stuttgart.

Requests for reprints to Dr. H. P. Krayenbuehl, Medical Policlinic, Raemistrasse 100, 8006 Zürich, Switzerland.