Ventricular response to isometric and isotonic exercise¹

Echocardiographic assessment

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SUMMARY The effects of supine isometric handgrip and graded isotonic bicycle ergometer exercise on left ventricular performance were studied echocardiographically in 20 normal subjects, aged 18 to 36. Measurements of the left ventricular minor axis diameter were taken from recordings performed at rest, during each form of exercise, and during recovery. At the completion of isometric exercise, the pressure-rate product increased significantly. There was no significant change in percentage of fractional shortening ($\% \Delta D$), while there was a small but significant fall in peak velocity of circumferential fibre shortening (peak Vcf).

Isotonic exercise resulted in a significant increase in $\% \Delta D$ and peak Vcf. The pressure-rate product also increased and showed a positive correlation with peak Vcf.

Isotonic exercise produced a much greater stimulus to left ventricular contractility than isometric exercise and may be a useful means of detecting latent left ventricular dysfunction echocardiographically.

The echocardiogram can provide a useful assessment of left ventricular performance in patients with disease processes that affect the ventricle in a uniform fashion. This technique measures stroke volume, ejection fraction (Pombo *et al.*, 1971; Fortuin *et al.*, 1972), percentage of fractional shortening (McDonald *et al.*, 1972; Stack *et al.*, 1976), mean velocity of circumferential fibre shortening (Paraskos *et al.*, 1971; Cooper *et al.*, 1972; Fortuin *et al.*, 1972), and peak velocity of circumferential fibre shortening (Paraskos *et al.*, 1971; Gibson and Brown, 1973; Quinones *et al.*, 1975; Boughner *et al.*, 1976). These measurements readily detect severe left ventricular dysfunction but mild dysfunction may produce few measurable changes at rest. We undertook this study to determine the potential value of incorporating exercise as a part of the echocardiographic evaluation. Two forms of exercise stress testing lend themselves to echocardiographic assessment: (a) supine isometric handgrip exercise (Stefadourous *et al.*, 1974a) and (b) supine isotonic bicycle ergometer exercise (Stein *et al.*, 1978).

Subjects and method

The study population consisted of 20 healthy volunteers (age 18 to 36; eight women, 12 men). All were considered to be normal on the basis of history, physical examination, and 12 lead electrocardiogram. None of the subjects was taking any medications.

ECHOCARDIOGRAPHY

The echocardiograms were obtained using a Unirad, Series C echocardiograph unit equipped with a Honeywell 1858 strip chart recorder. Patients were studied in the slight left lateral position with the transducer positioned in the fourth or fifth left intercostal space. The left ventricular minor axis diameter was recorded by directing the ultrasound beam just inferior to the mitral valve and recordings were made at a paper speed of 100 mm/s. Care was taken to avoid alterations in transducer position during the study, thus avoiding spurious changes of left ventricular dimensions. Subjects were also instructed to avoid performing the Valsalva manoeuvre and were carefully observed for this.

ISOMETRIC EXERCISE PROCEDURE

Isometric handgrip exercise was performed using

¹Supported by a grant from the Ontario Heart Foundation, Drs Boughner and Paulsen are Ontario Heart Foundation Research Fellows.

a Stoelting dynamometer. Brachial blood pressure was measured using a Cardy-8 sphygmomanometer.

Supine resting measurements of blood pressure and heart rate were obtained and the resting left ventricular echocardiogram was recorded. Each subject was then asked to perform three minutes of supine isometric exercise at 30 per cent of the individual's predetermined peak grip strength. Simultaneous recordings of the left ventricular dimensions (approximately 10 seconds in duration), blood pressure, and heart rate were made at one-minute intervals during exercise. After handgrip exercise, similar recordings were made at one-minute intervals for two minutes during which time full recovery occurred.

ISOTONIC EXERCISE PROCEDURE

After an additional five minutes of rest, a further set of resting recordings were made. Isotonic exercise was then performed using a Siemens-Elema bicycle ergometer system mounted vertically at the foot of the bed. Each subject was asked to perform six minutes of supine bicycle ergometer exercise at loads of 25, 50, 75, 100, 125, and 150 watts, the load being increased at one-minute intervals. Recordings of the left ventricular dimensions, blood pressure, and heart rate were made at one-minute intervals during exercise and at two, four, and eight minutes after exercise, during which time complete recovery occurred.

Although total cardiocirculatory adaptation to any magnitude of exertion does not occur for two to three minutes (Astrand and Rodahl, 1977), it was technically difficult to obtain adequate quality left ventricular echocardiograms throughout a graded exercise procedure using three-minute stages. Since the cardiovascular adjustments to a submaximal workload reach a nearly steady state within the first minute of isotonic exercise (Donald *et al.*, 1955; Jones and Reeves, 1968; Van Citters and Franklin, 1969; Xenakis *et al.*, 1975), we elected to increase the workload at one-minute intervals during the bicycle exercise.

MEASUREMENTS AND CALCULATIONS

Analysis of the instantaneous left ventricular dimension and calculation of its peak rate of change was performed using a Hewlett-Packard Model 1838 desk top computer, a model 986A digitiser, and x-y plotter combination by a method modified from that of Gibson and Brown (1973). The recordings of the left ventricular echograms were placed on a digitising table and the endocardial echoes of the septum and posterior wall were digitised beginning at the onset of the R wave and ending with the T wave. The computer noted the position of these

two echoes and automatically derived the instantaneous left ventricular diameter. It normalised this diameter measurement by dividing by the initial diameter, and this ratio was then displayed by the x-y plotter as a 'displacement ratio' versus time (Fig. 1). Peak Vcf was obtained manually by calculating the slope of the tangent to the mid portion of this curve, thus providing the normalised peak Vcf in circumferences per second. We decided to calculate peak Vcf in this fashion rather than having the computer calculate the instantaneous first derivative of the left ventricular diameter curve as described by other investigators (Gibson and Brown, 1973; Decoodt *et al.*, 1976) because we found that the normalised instantaneous diameter curve or 'displacement ratio' contained sufficient noise (produced by 'hand-shake' when tracing the echo) to make such a computer estimate of peak Vcf poorly reproducible. Such irregularities could be easily compensated for by the manual method resulting in a high degree of reproducibility for the peak Vcf estimate. The computer also calculated automatically the percentage of fractional shortening:

$$\frac{\text{EDD} - \text{ESD}}{\text{EDD}} \times 100 \text{ (McDonald } et al., 1972).$$

The pressure-rate product was obtained by multiplying the systolic blood pressure (mmHg) by the heart rate (beats/min).

Fig. 1 Computer plot of the displacement ratio versus time curves corresponding to the ventricular echograms of a normal subject (see Fig. 2) at rest, during three minutes of isometric exercise, and during six minutes of isotonic exercise. The slope of the mid portion of each curve provided the respective normalised peak Vcf in circ/s (displacement ratio = instantaneous left ventricular diameter divided by end-diastolic diameter).

All measurements were taken from recordings taken at rest (Fig. 2a), at one-minute intervals during isometric exercise (Fig. 2b), and during a two-minute recovery period. They were also made from recordings taken just before the initiation of isotonic exercise, at one-minute intervals during isotonic exercise (Fig. 2c), and at two, four, and eight minutes after exercise.

Measurements of four beats at each of these time intervals were carried out to establish the degree of beat-to-beat and interobserver variation in the ventricular function indices. These were performed for 48 sets of beats in four randomly selected patients. We found the coefficients of variation for percentage of fractional shortening to be 8 per cent and for peak Vcf to be 3 per cent. This indicated good reproducibility since the coefficient of variation was well below the 12 per cent level (England, 1975). It was not possible to obtain and measure this ideal number of cardiac cycles from the eight to 10 second long tracings at each time interval in all 20 subjects. Therefore we selected a single cardiac cycle at each time interval in which the endocardial surfaces of the septum and the posterior left ventricular wall just inferior to the valve were clearly seen as continuous echoes throughout systole and diastole. In order to avoid the small changes of left ventricular dimensions with respiration during isotonic exercise, measurements

were made only during expiration when the endocardial surfaces were clearly seen. During inspiration, those endocardial surfaces were often indistinct.

Statistical analysis was carried out using paired data comparison and Student's *t* test. Regression analysis was carried out by two variable analyses.

Results

RESTING

No significant difference was shown between resting left ventricular function indices before and after exercise. These are listed in Tables 1 and 2 and all values were within normal published ranges (Paraskos *et al.*, 1971; McDonald *et al.*, 1972; Quinones *et al.*, 1975; Boughner *et al.*, 1976).

ISOMETRIC EXERCISE

Three minutes of isometric handgrip exercise resulted in a significant ($P < 0.001$) increase in blood pressure, heart rate, and the pressure-rate product. The systolic blood pressure rose 32 (± 15) mmHg (mean ± 1 SD) and heart rate 23 (± 14) beats/min (mean ± 1 SD). No significant change in percentage of fractional shortening occurred. However, the peak Vcf showed a small but significant decrease from 1.80 ± 0.27 (mean ± 1 SD) circumferences/s to 1.61 ± 0.22 (mean

Fig. 2 Left ventricular echogram of a normal subject, paper speed 100 mm/s (a) at rest, (b) during three minutes of isometric handgrip exercise, and (c) during six minutes of supine bicycle ergometer exercise. Note the minor fall in peak Vcf with isometric exercise and the distinct increase with isotonic exercise. IVS, interventricular septum; LVPW, left ventricular posterior wall; ECG, electrocardiogram; Vcf, peak velocity of circumferential fibre shortening.

Table 1 *Echocardiographic variables during isometric exercise (mean $\pm$ SD)*

	Rest	Isometric exercise			Recovery	
		1 min	2 min	3 min	4 min	5 min
p Vcf (circ/s)	1.80 $\pm$ 0.27	1.78 $\pm$ 0.33	1.56 $\pm$ 0.21	1.61* $\pm$ 0.22	1.63 $\pm$ 0.19	1.81 $\pm$ 0.35
Percentage of fraction shortening	37 $\pm$ 4	36 $\pm$ 6	34 $\pm$ 5	35 $\pm$ 6	36 $\pm$ 4	38 $\pm$ 6
End-diastolic diameter (mm)	50 $\pm$ 5	50 $\pm$ 5	51 $\pm$ 5	51 $\pm$ 5	51 $\pm$ 5	51 $\pm$ 5
Heart rate (beat/min)	58 $\pm$ 8	68 $\pm$ 15	78 $\pm$ 15	79** $\pm$ 15	57 $\pm$ 9	59 $\pm$ 9
Systolic blood pressure (mmHg)	122 $\pm$ 13	137 $\pm$ 16	148 $\pm$ 19	154** $\pm$ 15	124 $\pm$ 14	122 $\pm$ 12
BP $\times$ HR ($\times 10^3$)	7.0 $\pm$ 1.1	10.5 $\pm$ 2.5	12.1 $\pm$ 3.0	12.4** $\pm$ 3.0	7.1 $\pm$ 1.3	7.1 $\pm$ 1.4

Note: Significant differences from resting values at completion of exercise are indicated by * $P < 0.01$ and ** $P < 0.001$. Vcf, velocity of circumferential fibre shortening; HR $\times$ BP, systolic pressure-rate product.

Table 2 *Echocardiographic variables during supine bicycle ergometer exercise and recovery*

	Rest	Isotonic exercise						Recovery		
		1 min	2 min	3 min	4 min	5 min	6 min	8 min	10 min	14 min
p Vcf (circ/s)	1.78 $\pm$ 0.21	1.83 $\pm$ 0.27	2.04 $\pm$ 0.30	2.13 $\pm$ 0.28	2.29 $\pm$ 0.34	2.49 $\pm$ 0.32	2.89** $\pm$ 0.22	1.96 $\pm$ 0.22	1.73 $\pm$ 0.28	1.87 $\pm$ 0.35
Percentage of fraction shortening	36 $\pm$ 5	38 $\pm$ 5	41 $\pm$ 6	43 $\pm$ 6	44 $\pm$ 6	44 $\pm$ 5	46** $\pm$ 6	42 $\pm$ 4	38 $\pm$ 4	37 $\pm$ 5
End-diastolic diameter (mm)	50 $\pm$ 5	51 $\pm$ 5	51 $\pm$ 5	51 $\pm$ 5	51 $\pm$ 6	51 $\pm$ 6	50 $\pm$ 6	52 $\pm$ 6	52 $\pm$ 6	50 $\pm$ 6
Heart rate (beats/min)	66 $\pm$ 13	90 $\pm$ 12	99 $\pm$ 11	108 $\pm$ 12	115 $\pm$ 14	123 $\pm$ 18	130** $\pm$ 14	78 $\pm$ 22	68 $\pm$ 14	69 $\pm$ 17
Systolic blood pressure (mmHg)	124 $\pm$ 12	138 $\pm$ 15	144 $\pm$ 15	152 $\pm$ 17	161 $\pm$ 18	173 $\pm$ 18	183** $\pm$ 17	138 $\pm$ 13	121 $\pm$ 11	122 $\pm$ 15
HR $\times$ BP ($\times 10^3$)	8.1 $\pm$ 1.5	12.3 $\pm$ 2.1	14.3 $\pm$ 1.9	16.4 $\pm$ 2.4	18.4 $\pm$ 2.6	21.2 $\pm$ 3.0	22.9** $\pm$ 3.0	10.5 $\pm$ 3.9	7.6 $\pm$ 2.3	8.2 $\pm$ 1.3

Note: Significant differences from resting values at completion of exercise are indicated by ** $P < 0.001$. Vcf, velocity of circumferential fibre shortening; HR $\times$ BP, systolic pressure-rate product.

± 1 SD) circumferences/s ($P < 0.01$, Table 1 and Fig. 3a).

ISOTONIC EXERCISE

Six minutes of isotonic exercise resulted in a pronounced rise in heart rate and blood pressure with a significant ($P < 0.001$) increase in the pressure-rate product to a value nearly twice that produced by isometric exercise. The percentage of fractional shortening and peak Vcf (Table 2 and Fig. 3b) rose significantly ($P < 0.001$).

Linear regression analysis showed a positive correlation between the peak Vcf and the pressure-rate product during isotonic exercise ($r = 0.71$, $N = 128$, $P < 0.001$) with a standard error of the estimate of ± 0.34 (Fig. 4). However, no such correlation was demonstrated for these variables during isometric exercise ($r = 0.14$).

Discussion

The cardiovascular responses to isometric and isotonic exercise differ in several important ways. Within seconds of initiating isometric handgrip

exercise, the heart rate begins to increase (Freyschuss, 1970; Petro *et al.*, 1970; Nutter *et al.*, 1972) apparently resulting from the withdrawal of vagal influences on the heart (MacDonald *et al.*, 1966; Nutter *et al.*, 1972). The degree of response is not related to the bulk of muscle involved in the isometric contraction and the exact mechanism by which these changes occur is not fully understood (Lind *et al.*, 1964; Nutter *et al.*, 1972). End-diastolic volume (preload) (Grossman *et al.*, 1973; Stefadourous *et al.*, 1974b) and end-diastolic pressure (Kivowitz *et al.*, 1971; Grossman *et al.*, 1973) do not change. Stroke volume also does not change significantly (Grossman, 1974). Cardiac output increases as a result of the tachycardia and, since the systemic vascular resistance remains unchanged (Stefadourous *et al.*, 1974b), the arterial pressure increases. An increase in myocardial contractility has been postulated to maintain stroke volume in the presence of an unchanged preload and increased afterload (Helfant *et al.*, 1971; Nutter *et al.*, 1972; Grossman *et al.*, 1973; Stefadourous *et al.*, 1974a).

Isotonic exercise also results in an immediate

Fig. 3 (a) Percentage change in peak Vcf during isometric exercise and recovery. Note the minor fall in peak Vcf with exercise (vertical bars denote mean ± 1 standard deviation). (b) Percentage change in peak Vcf during isotonic exercise and recovery. Note the distinct increase in peak Vcf with exercise (vertical bars denote mean ± 1 standard deviation).

increase in heart rate (Donald *et al.*, 1955; Xenakis *et al.*, 1975). In the supine position, preload does not change (Rushmer, 1959), myocardial contractility increases, and cardiac output rises (Marshall and Shepherd, 1968). Stroke volume in the resting supine position seems to be at or near the maximal level reached during heavy work, and exercise in this position produces little or no increase in stroke volume (Rushmer, 1959). This differs from the erect posture in which the end-diastolic volume and stroke volume are lower at rest (Rushmer, 1976). These lower values are restored to approximately those of the recumbent position with even the mildest exercise and heavy exertion produces only modest additional increases (Rushmer, 1976).

Our results show the distinct differences between the cardiac response to isometric and isotonic exercise and illustrate the ease with which they may be detected echocardiographically. With iso-

Fig. 4 The linear correlation between peak Vcf and pressure-rate product during isotonic exercise. The regression line for the 20 subjects is indicated by the solid line while the dotted lines indicate one standard error of the estimate.

metric exercise, we observed no alteration in end-diastolic diameter on the echocardiogram, a finding that is consistent with previous reports (Stefadourous *et al.*, 1974a). In contrast to those reports, we recorded a slight fall in the percentage fractional shortening and a small statistically significant fall in the velocity of circumferential fibre shortening. This would be consistent with previous observations where Vcf was found to be inversely related to ventricular afterload (Quinones *et al.*, 1975). However, the failure of peak Vcf to fall much during isometric exercise suggests that myocardial contractility increased sufficiently to almost maintain the resting contraction velocities.

In contrast, supine isotonic exercise produced a pronounced increase in the velocity of circumferential fibre shortening, indicating a major augmentation in myocardial contractility. We observed no change in the end-diastolic diameter, implying that an alteration in preload did not play a significant part in this increased contraction velocity (Rushmer, 1959; Stein *et al.*, 1978). Percentage fractional shortening rose significantly as would be expected.

It has been suggested that isometric exercise at 25 to 50 per cent of maximum voluntary contraction when performed during cardiac catheterisation can be useful in detecting latent left ventricular dysfunction (Helfant *et al.*, 1971; Kivowitz *et al.*,

1971; Grossman *et al.*, 1973; Grossman, 1974). An abnormal end-diastolic pressure may be produced during such exercise or, in patients in whom the ventricular end-diastolic pressure is already raised, a further increase may be produced. However, our results indicate that isometric exercise at 30 per cent of maximum voluntary contraction is unlikely to produce a sufficiently dramatic change in contractility to be a useful part of the echocardiographic assessment of left ventricular function. Though a severely diseased ventricle might be expected to show a definite fall in myocardial contraction velocity under these circumstances, a ventricle with borderline dysfunction might not.

In contrast, isotonic exercise produces a dramatic stimulus to myocardial contractility and would be a more suitable provocative test for uncovering latent left ventricular dysfunction as determined by echocardiography.

Although we were able to obtain satisfactory recordings during isotonic exercise in all of the relatively young individuals studied, it may not be possible to achieve the same degree of success in older patients or in those with some degree of emphysema.

CLINICAL IMPLICATIONS

This study has shown that echocardiographic assessment of left ventricular function in normal subjects during both supine isometric and isotonic exercise is practical. Whereas isometric exercise has little measurable effect on left ventricular performance, isotonic exercise produces a dramatic and easily measurable stimulus to myocardial contractility and may be a useful means of detecting left ventricular dysfunction in disease processes that affect the left ventricle in a uniform fashion.

The authors wish to thank Dr. Brian Findlay for writing the computer programmes and Dr. William Kostuk for his continued interest and assistance. The ultrasound equipment was provided by a grant from the Ivey Foundation.

References

- Astrand, P. O., and Rodahl, K. (1977). *Textbook of Work Physiology*. McGraw-Hill, New York.
- Boughner, D. R., Nolan, J., and Rechnitzer, P. (1976). Usefulness of echocardiographic peak velocity of circumferential fibre shortening. In *Ultrasound in Medicine*, vol. 2, ed D. White and R. Barnes, pp. 21–30. Plenum Press, New York.
- Cooper, R. H., O'Rourke, R. A., Karliner, J. S., Peterson, K. L., and Leopold, G. R. (1972). Comparison of ultrasound and cineangiographic measurements of the mean rate of circumferential fibre shortening in man. *Circulation*, **46**, 914–923.
- Decoodt, P. R., Mathey, D. G., and Swan, H. J. C. (1976). Automated analysis of left ventricular diameter time curve from echocardiographic recordings. *Computers and Biomedical Research*, **9**, 549–558.
- Donald, K. W., Bishop, T. M., Cumming, G., and Wade, O. L. (1955). The effect of exercise on the cardiac output and circulatory dynamics of normal subjects. *Clinical Science*, **14**, 37–73.
- England, J. M. (1975). *Medical Research, a Statistical and Epidemiological Approach*. Churchill Livingstone, Edinburgh.
- Fortuin, N. J., Hood, W. P., and Craige, F. (1972). Evaluation of left ventricular function by echocardiography. *Circulation*, **46**, 26–35.
- Freyschuss, U. (1970). Elicitation of heart rate and blood pressure increase on muscle contraction. *Journal of Applied Physiology*, **28**, 758–766.
- Gibson, D. G., and Brown, D. (1973). Measurement of instantaneous left ventricular dimension and filling rate in man, using echocardiography. *British Heart Journal*, **35**, 1141–1149.
- Grossman, W. (1974). *Cardiac Catheterization and Angiography*. Lea and Febiger, Philadelphia.
- Grossman, W., McAlurin, L. P., Saltz, S., Paraskos, J. A., Dalen, J. E., and Dexter, L. (1973). Changes in the inotropic state of the left ventricle during isometric exercise. *British Heart Journal*, **35**, 697–704.
- Helfant, R. H., deVila, M. A., and Meister, S. G. (1971). Effect of sustained isometric handgrip exercise on left ventricular performance. *Circulation*, **44**, 982–993.
- Jones, W. B., and Reeves, T. J. (1968). Total cardiac output response during four minutes of exercise. *American Heart Journal*, **76**, 209–216.
- Kivowitz, C., Parmley, W., Denoso, R., Marcus, H., Garz, W., and Swan, H. J. C. (1971). Effects of isometric exercise on cardiac performance—the grip test. *Circulation*, **44**, 994–1002.
- Lind, A. R., Taylor, S. H., Humphreys, P. W., and Donald, K. W. (1964). Circulatory effects of sustained voluntary muscle contraction. *Clinical Science*, **27**, 229–244.
- MacDonald, H. R., Sapru, R. P., Taylor, S. H., and Donald, K. W. (1966). Effects of intravenous propranolol on systemic circulatory response to sustained handgrip. *American Journal of Cardiology*, **18**, 333–343.
- McDonald, I. G., Feigenbaum, H., and Chang, S. (1972). Analysis of left ventricular wall motion by reflected ultrasound: application to assessment of myocardial function. *Circulation*, **46**, 14–25.
- Marshall, R. J., and Shepherd, J. T. (1968). *Cardiac Function in Health and Disease*. W. B. Saunders, Philadelphia.
- Nutter, D. O., Schlant, R. C., and Hurst, W. J. (1972). Isometric exercise and the cardiovascular system. *Modern Concepts of Cardiovascular Disease*, **51**, 3–15.
- Paraskos, J. A., Grossman, W., Saltz, S., Dalen, J. F., and Dexter, L. (1971). A noninvasive technique for determination of velocity of circumferential fiber shortening in man. *Circulation Research*, **29**, 610–615.
- Petro, J. K., Hollander, A. P., and Bowman, L. M. (1970). Instantaneous cardiac acceleration in man induced by a voluntary muscle contraction. *Journal of Applied Physiology*, **29**, 794–798.
- Pombo, J. F., Troy, B. L., and Russell, R. O. (1971). Left ventricular volumes and ejection fraction by echocardiography. *Circulation*, **43**, 480–489.
- Quinones, M. A., Gaasch, W. H., Cole, J. S., and Alexander, J. K. (1975). Echocardiographic determination of left ventricular stress-velocity relations in man, with reference to the effects of loading and contractility. *Circulation*, **51**, 689–700.
- Rushmer, R. F. (1959). Postural effects on the baselines of ventricular performance. *Circulation Research*, **20**, 897–905.

- Rushmer, R. F. (1976). *Cardiovascular Dynamics*. W. B. Saunders, Philadelphia.
- Stack, R. S., Lee, C. C., Reddy, B. P., Taylor, M. O., and Weissler, A. M. (1976). Left ventricular performance in coronary artery disease evaluated with systolic time intervals and echocardiography. *American Journal of Cardiology*, **37**, 331–339.
- Stefadourous, M. A., Grossman, W., El Shahawy, M., Stefadourous, F., and Witham, A. C. (1974a). Noninvasive study of effect of isometric exercise on left ventricular performance in normal man. *British Heart Journal*, **36**, 988–995.
- Stefadourous, M. A., Grossman, W., El Shahawy, M., and Witham, A. C. (1974b). The effect of isometric exercise on the left ventricular volume in man. *Circulation*, **49**, 1185–1189.
- Stein, R. A., Michielli, D., Fox, E. L., and Krasnow, N. (1978). Continuous ventricular dimensions in man during supine exercise and recovery—an echocardiographic study. *American Journal of Cardiology*, **41**, 655–660.
- Van Citters, R. L., and Franklin, D. L. (1969). Cardiovascular performance of Alaska sled dogs during exercise. *Circulation Research*, **24**, 33–42.
- Xenakis, A. P., Quarry, V. M., and Spodick, D. H. (1975). Immediate cardiac response to exercise: physiological investigation by systolic time intervals at graded workloads. *American Heart Journal*, **80**, 178–185.
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