PROGRESS REPORT

[redacted]

A Technique for Testing Heart Function by Analysis of its Vibration Spectrum

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1.0 INTRODUCTION

The initial research grant for the project entitled, "A Technique for Testing Heart Function by Analysis of its Vibration Spectrum", was awarded to this laboratory in June of 1962. The prime objective of the research was to establish a simple method for the accurate assessment of heart function. To this purpose it was necessary to develop an atraumatic technique which would be applicable to the environment of an office or a spacecraft, so designed as to permit complete freedom of movement.

In the first phase of research, described in the progress report of February, 1964, a capacitance microphone was developed, with the cooperation of Altec-Lansing, having a frequency range that encompassed with great fidelity the entire cardiac

vibrational spectrum*, **. In animals, by means of intracardiac pressure measurements, by the attachment of strain gauges directly to the heart muscle, and by the direct measurement of aortic flow, it was established that certain waves of the simultaneously recorded external chest wall vibrational tracing (vibrocardiogram), could be accurately correlated with the hemodynamic events of the cardiac cycle***. Essential phases of the heart beat, particularly the isovolumetric contraction and ejection periods, could be measured by an external transducer with millisecond accuracy. These observations have subsequently been

* The Normal Vibrocardiogram: Its Physiologic Variations and Relation to Cardiodynamic Events; C. M. Agress, L. G. Fields, S. Wegner, M. Wilburne, M. D. Shickman, and R. M. Muller; American Journal of Cardiology, Vol 8:22-31, July, 1961.

** The Common Origin of Precordial Vibrations; C. M. Agress, S. Wegner, D. J. Bleifer, H. M. Estrin, A. Lindsey, J. Van Houten, and K. Schroyer; American Journal of Cardiology, Vol 13, No 2:226-231, February, 1964.

*** Measurement of Cardiac Events by a Precise Technique, Comparison with Vibrocardiogram; C. M. Agress, S. Wegner, and S. Nakakura; Japanese Heart Journal, Vol 5, No 5:414-430, September, 1964.

confirmed by an independent study performed by North American Aviation, Incorporated, and reported to NASA in June, 1966, in NASA CONTRACTOR REPORT CR-504, and have also been verified by other workers in the field using various types of vibration transducers. The extension of these measurements to the human subject has been verified at cardiac catheterization. The variations in the resting human have also been carefully studied*. In exercise studies using treadmill, bicycle, or step-tests, it was found that the essential waves could still be identified, thus permitting measurements to be made in the active subject**.

The next period of research was spent examining vibrocardiographic data in normal and diseased

* Variations of the Vibrocardiogram over the Precordium; C. M. Agress and S. Nakakura; Aerospace Medicine, Vol 35, No 8:752-757, August, 1964.

** Influence of Heart Rate on the Phases of the Left Heart Cycle in Exercise; S. Nakakura, S. Wegner and C. M. Agress; Japanese Heart Journal, Vol 6, No 2:104-114, March, 1965.

subjects to determine if a means of detecting impaired cardiac function could be found *, **. While several measurements showed some promise, the results were, for the most part, discouraging. The application of various stress tests, such as tilt testing and respiratory maneuvers was equally unrewarding. By the time of our progress report of January, 1965, it had become apparent that it was more important in the definition of heart performance measurements to know <u>what</u> rather than <u>how</u> to measure. Our laboratory was then plunged into a comparison of ventricular function measurements***. From the evaluation of cardiovascular tests performed by the customary techniques it was concluded that two distinct properties of the cardiovascular system must

* Use of the Vibrocardiogram for the Detection of Heart Disease; C. M. Agress; The Teaching Rounds (Journal of the Wadsworth General Hospital) Part III, 5:285-296, August, 1962.

** The Vibrocardiographic Exercise Test for Coronary Insufficiency; C. M. Agress, S. Wegner; American Journal of Cardiology, Vol 9:541-546, April, 1962.

*** Interrelationships between Cardiac Performance Measurements; C. M. Agress and S. Wegner; Japanese Heart Journal, Vol 7, No 2:103-109, March, 1966.

be defined: performance and function. Performance can be evaluated by any test which measures the external work performed by the heart, without regard to the efficiency of performing that work; whereas, an examination of function implies a quantitation of the efficiency of the basic inotropic quality of heart muscle. Our research then was aimed at finding sensitive parameters for such measurements. After studies in animals in which direct examination was made of most of the important cardiodynamic measurements, it was concluded that the stroke volume and the maximum rate of ventricular pressure change were the most informative performance measurements; whereas measurements of contractility showed the most promise for the characterization of function*. Our efforts were then directed at developing methods for the external measurement of these parameters.

* Quantification and Prediction of Myocardial Failure; J. H. Siegel and E. H. Sonnenblick; Archives of Surgery, Vol 89:1026-1036, December, 1964.

The progress report of July, 1965 related our initial efforts in these directions. It began to appear that stroke volume could be measured by relating the duration of the isovolumetric contraction and ejection times. This ratio was implied in the frog experiments of Frank in 1895, and was actually attempted by Blumberger in 1941 in his "chronodynogram"*. A paper was presented before the American Physiological Society where the preliminary observations were reported**. The work during the last six months under NASA Grant #N_sG 289/05-12-001 has pursued these goals. These and other measurements have been applied to the clinical subject and to the experimental animal.

It is now evident from correlative measurements with

* Was sagt das Grossenverhaltnis Austreibungszeit/ Anspannungzeit uber die Arbeit des Herzens aus? Blumberger, K.; Klin. Wchnser. 20:681 and 708, 1941.

** Determination of Stroke Volume be Measurement of Isovolumetric Contraction and Ejection Times (Abstract); C. M. Agress, S. Wegner and S. Nakakura; The Physiologist (American Physiological Society) Vol 8, No 3, August, 1965.

flow-meter studies on animals, from simultaneous pressure and flow measurements on humans at cardiac catheterization and from dye dilution and vibrocardiographic studies on the acutely ill cardiac patient (Section 3.20), that the interval ratio technique obtained from a simple microphone recording over the precordium will reliably measure stroke volume and cardiac output*, **. Furthermore, a computer has been constructed which will automatically recognize the signals, compute the intervals and calculate the stroke volumes in a continuous monitoring system***. This system supplies on-line data which can be taped and/or telemetered for the continuous estimation of cardiac performance during stress.

* Correlation of Stroke Volume with Left Ventricular Isovolumetric Contraction and Ejection Time; C. M. Agress and S. Wegner (In Press).

** Determination of Stroke Volume from the Vibrocardiogram; C. M. Agress, S. Wegner, R. P. Fremont and D. J. Day (In Press).

*** A Computer for Continuous Monitoring of Stroke Volume from the Vibrocardiogram; C. M. Agress, L. Beman and S. Wegner (In Press).

Many other parameters are also adding greatly to our knowledge of heart function and these also can be measured by external techniques: the maximum rate of change of left ventricular pressure (dP/dt), left ventricular end diastolic pressure, the ejection time-heart rate index, mean ejection rate, etc.

In summary, the research program to date has developed techniques for recording heart vibrations, has established significant cardiovascular parameters which can be obtained from such recordings, and has devised methods by which these data may be obtained under most environmental conditions. It is now feasible to obtain meaningful data describing cardiovascular performance and function by application of the vibrocardiogram under conditions where direct physiologic measurements are impractical. The experimental background for these conclusions is described in the following sections.

2.0 ANIMAL RESEARCH

The animal experimentation has been divided into two phases: Correlation of stroke volume measurements with the durations of the ejection and isometric periods and study of cardiac contractility under various types of stress.

2.10 Stroke Volume Studies using the Electromagnetic Flowmeter

Because of the high correlation obtained between stroke volume measurements and the durations of isometric and ejection times in human subjects at heart catheterization (Section 3.10), this observation was further tested by the most accurate technique available for the measurement of stroke volume: the electromagnetic flowmeter in open-chest animals.

2.11 Methods

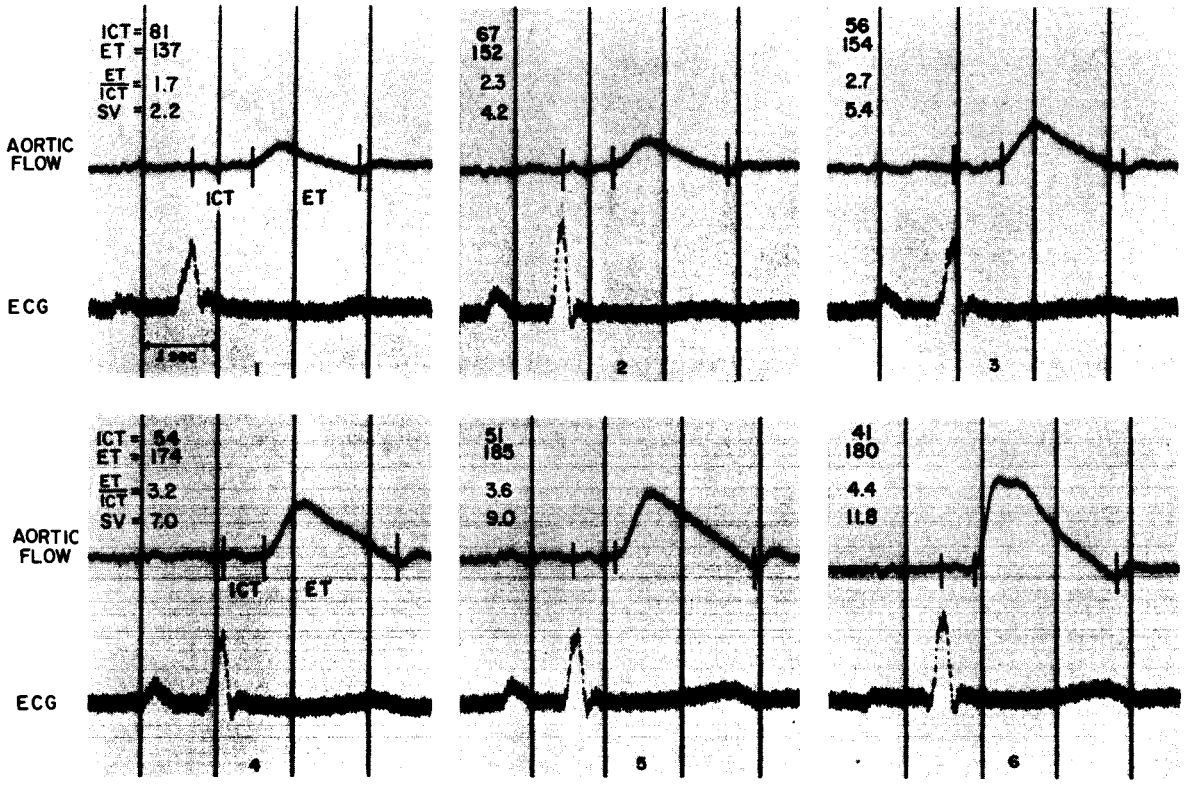
Eight dogs, whose weights ranged from 15 to 40 kgs, were pre-medicated with Tranvet (2 mg/kg) and anesthetized with pentobarbital (60 mg/kg). After a

transverse thoracotomy, the ascending aorta was dissected free, and a Statham pulsed-field electromagnetic flowmeter was placed distal to the aortic valve. To facilitate the infusion of drugs and the rapid depletion and expansion of blood volume, a catheter was passed into the right atrium through the right jugular vein. A left ventricular pressure curve was obtained with a Statham transducer tipped catheter and a simultaneous ECG Lead II was inscribed. The data were recorded on an Electronics for Medicine Recorder at a paper speed of 200 mm/sec. The stresses imposed on the animal were: withdrawal of 100 cc of blood obtained directly from, and rapidly reinfused into, the right atrium; exhibition of isoproterenol (4 micrograms/kg/min for 3 to 5 min); infusion of levarterenol (0.2 micrograms/kg/min for 3 to 5 min); and administration of angiotensin (7 micrograms/kg/min for 3 to 5 min). Under these experimental conditions a wide range of cardiovascular changes associated with varying function could be obtained: i.e., independent

variation of preload and afterload, as well as the combined effects of altered preload, afterload and the inotropic state of the myocardium.

2.12 Results

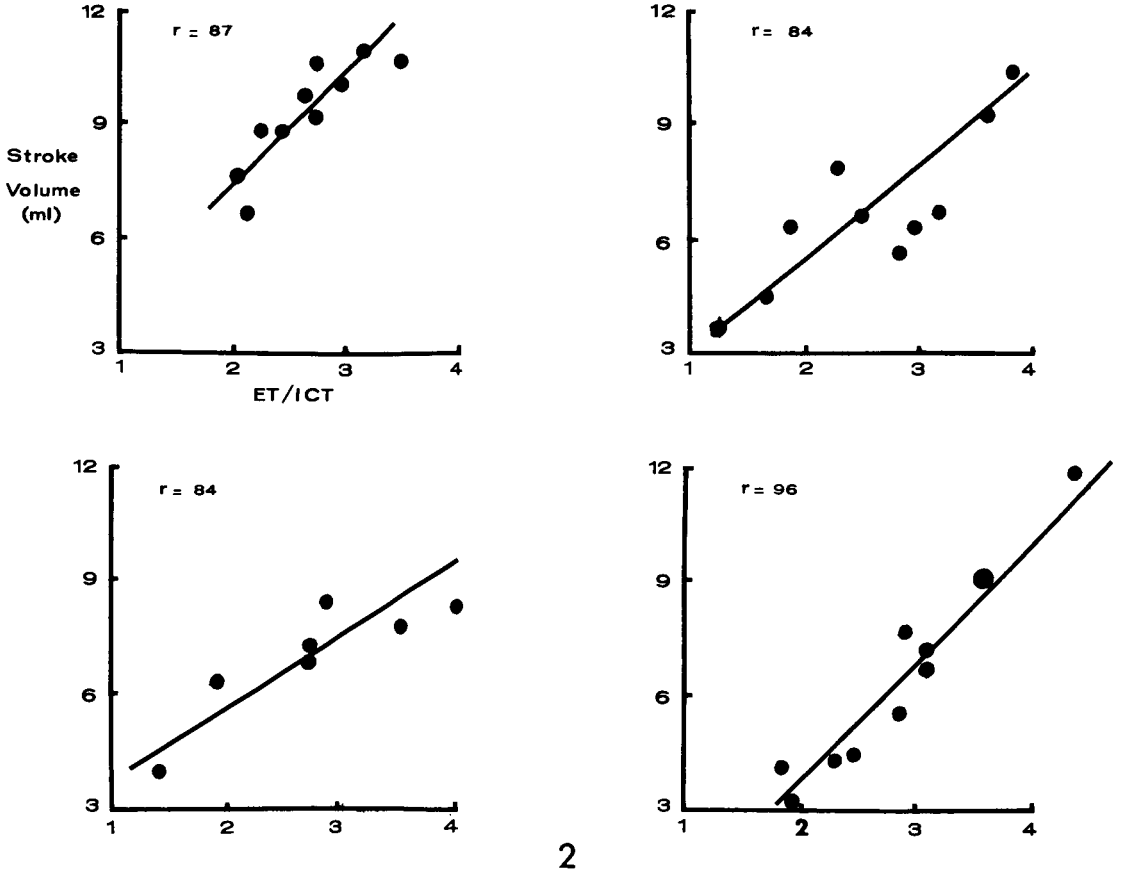
Figure 1 illustrates typical curves obtained in the flowmeter experiments and shows the methods by which the isometric and ejection intervals were measured. Also illustrated in this figure is the relationship between the isometric interval, the ejection interval and changing stroke volume in an animal in which 100 cc of blood was rapidly infused into the right atrium over a period of approximately 5 seconds. As can be seen, the isometric interval shows a progressive decrease as the stroke volume is enhanced, while the ejection interval shows an increase. The resultant ratio thus closely parallels the increasing stroke volume. Figure 2 shows in 6 such experiments the results of rapid infusion of blood into the right atrium,


ICT = 81
ET = 137
ET/ICT = 1.7
SV = 2.2
AORTIC FLOW
ICT
ET
ECG
1 sec
1
67
152
2.3
4.2
2
56
154
2.7
5.4
3
ICT = 54
ET = 174
ET/ICT = 3.2
SV = 7.0
AORTIC FLOW
ICT
ET
ECG
4
51
185
3.6
9.0
5
41
180
4.4
11.8
6

1

FIGURE 1

as well as the effects of different drugs. The correlation coefficients in these experiments ranged from .84 to .96. The data were analyzed independently because of the fact that minor differences in the calibration of the flowmeter for each experiment could not be standardized.



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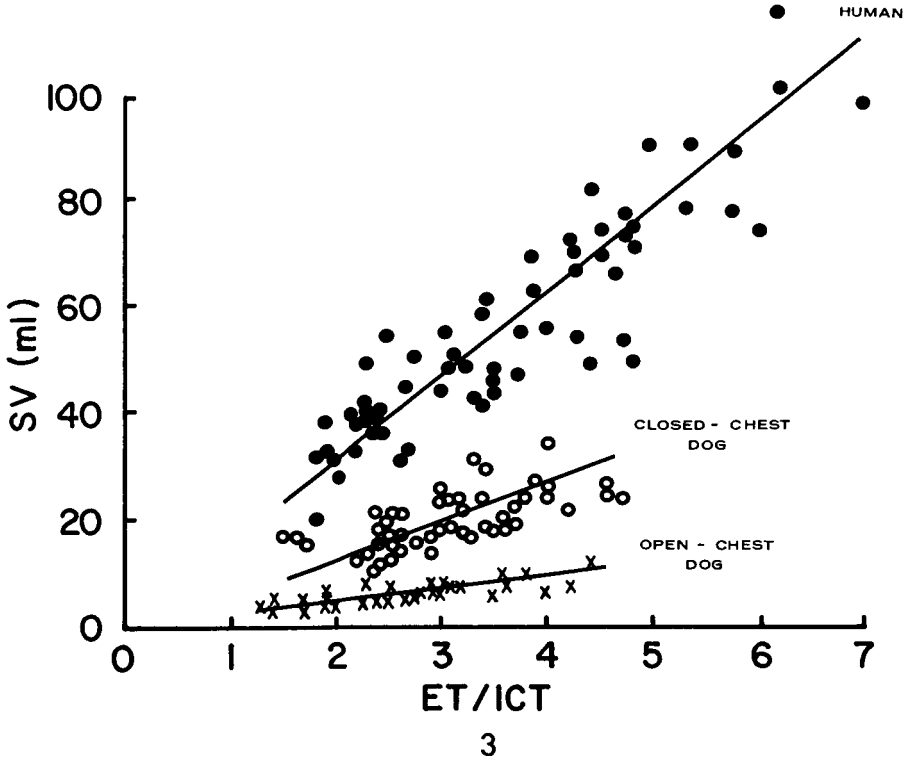
2.13 Discussion

In the open-chest dog experiments it is possible to use the electromagnetic flowmeter, which is a most accurate technique for obtaining continuous stroke volume. The dependability with which the ejection - isometric interval ratio can be used to predict stroke volume is evident. When comparing these results to those obtained in the closed-chest animal and in the human at heart catheterization (Figure 3) it can be seen that the relationship between this ratio and the stroke volume, while



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different for each of the experimental conditions, nonetheless shows the same trends. With the open-chest dogs there is less of an increase of stroke volume for a given change in the ratio as opposed to the closed-chest dogs, and much less than in the human experiments. These differences may be explained on the basis of varying heart size in each of these preparations; e.g., in the small heart of the open-chest dog, lesser fiber-shortening during ejection results in smaller stroke volumes.

2.14 Summary

The relationship of the isometric-ejection ratio to stroke volumes has been examined in dogs using electromagnetic flowmeters placed about the aorta. It was found that the ratio correlated highly with the stroke volume in all situations, the correlation coefficients ranging from .84 to .96.

2.20 Direct Measurement of Cardiac Contractility

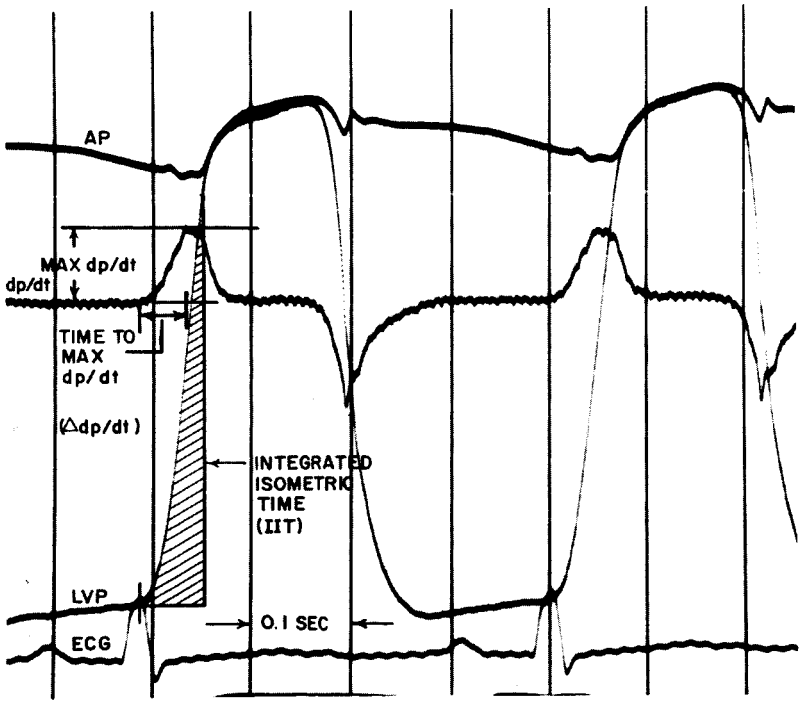
The work of the laboratory to the present has indicated

that the standard methods of estimating cardiac performance do not provide a measurement of the contractile state of the myocardium (Progress Report of July, 1965). Studies by Siegel and Sonnenblick have indicated that the force-velocity relationship of cardiac contraction offers a means of characterizing cardiac contractility. This parameter can be obtained indirectly from the ventricular pressure derivative and the area under the ventricular pressure curve. This laboratory, therefore, undertook a study of the closed-chest dog to determine whether such an index was useful under varying types of stress.

2.21 Methods

Ten experiments were performed on dogs under Nembutal anesthesia. Catheters were placed in the left ventricle and the aorta, and the resultant curves were recorded simultaneously with an ECG Lead II on an Electronics for Medicine Recorder using a 200 mm/sec paper speed. The first derivative of left ventricular pressure was obtained from a Dymec operational amplifier

using a 14 msec time constant. The resultant data consisted of aortic pressure, left ventricular pressure and the ECG. Figure 4 illustrates the methods for measuring the two contractility indices. The experimental conditions imposed on these animals were: infusion of isoproterenol, levarterenol and angiotensin; and aortic narrowing, produced either by direct constriction of the aorta in open-chest experiments, or



CONTACTILITY INDICES:

$$1 = \frac{\text{MAX } dp/dt}{IIT} \left(\frac{1}{SEC^2}\right)$$

$$2 = \frac{\text{MAX } dp/dt}{\Delta\, dp/dt} \left(\frac{mm\ Hg}{SEC^2}\right)$$

4

by the inflation of a balloon placed in the descending aorta in the closed-chest animals.

2.22 Results

The preliminary results of this study are summarized in Figure 5. The maximum dP/dt was regularly increased with the administration of levarterenol, angiotensin and isoproterenol with approximately equal changes. The integrated isometric time (IIT), however, was diminished with isoproterenol, prolonged with angiotensin and materially unchanged with levarterenol. The ratio of $\frac{\text{Max dP/dt}}{\text{IIT}}$ was increased with all three drugs; however isoproterenol showed the greatest increase because of the diminished IIT. The time to maximum dP/dt was also diminished with the three drugs, isoproterenol influencing the interval more than angiotensin or levarterenol. The ratio of dP/dt to the time to maximum dP/dt, therefore, also showed an increases; however the experiments with levarterenol showed a much more marked increase than either angiotensin or isoproterenol in

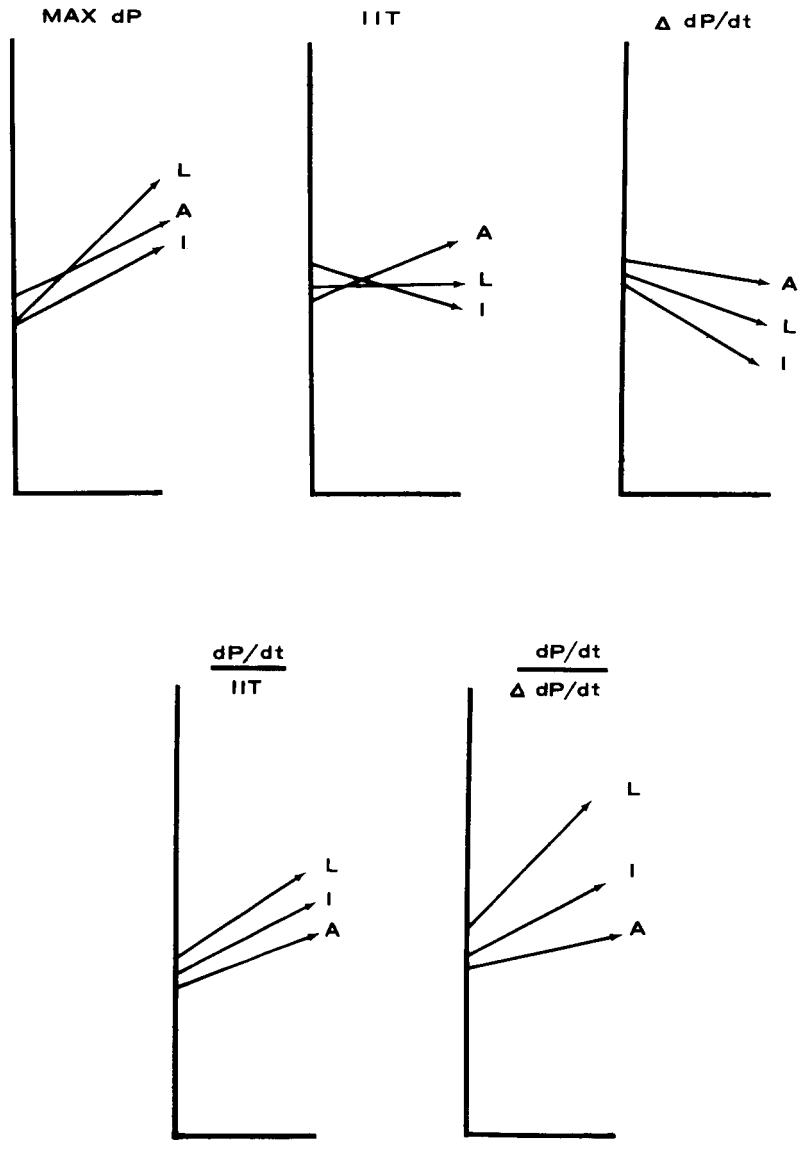


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FIGURE 5

contrast to the other contractility ratio. Although these studies represent pilot experiments, they do indicate that these two methods of determining cardiac contractility afford a means by which inotropic effects of drugs can be quantitated in terms of cardiovascular response. Further experiments, however, are being undertaken to determine whether any new information is gained as a result of studying these indices as compared to the standard function measurements of stroke work versus end diastolic pressure, or maximum dP/dt independently.

2.30 Indirect Measurement of Cardiac Contractility

Because of the apparent usefulness of the contractility index, it was attempted to devise a means of predicting this value using externally obtained measurements. One such approach has been based on the observation that the ventricular pressure curve can be represented in humans and animals by a common mathematical expression.

2.31 Methods

Two methods of analysis were used. The first was found

by dividing pressure derivatives obtained in animal experiments into three equal time segments and determining the percentage of amplitude achieved at each of these 30% values. A third degree curve was derived from the data using time to maximum dP/dt and maximum dP/dt as variables. By integrating this function twice, the following formula was obtained:

$$IIT = 0.135 \text{ (max } dP/dt)(\text{time-}dP/dt)^2$$

The second was based on using a triangle to estimate the area under the ventricular pressure curve, using a constant fraction of the isovolumetric contraction interval as the base and the diastolic pressure as the height.

2.32 Results

At the time of writing this report, the regression analyses of these parameters are incomplete. However, initial examination of the correlation between the first method and the actual isometric time indicates that the integrated isometric time can be estimated by this technique with some reilability. When the method showing

the highest correlation is determined, this measurement will be applied to the clinical research program.

3.0 HUMAN RESEARCH

Work with humans was designed 1) to test whether stroke volume and cardiac output could be reliably measured with the vibrocardiogram and 2) to assess the use of vibrocardiographic as well as other indirect methods for the evaluation of cardiovascular function in the acutely ill patient. Additionally, exercise studies have been performed with the specific purpose of comparing stroke volume and cardiac output responses in the normal subject and the cardiac injured patient.

3.10 Correlation of Dye Dilution Stroke Volume with Directly Measured ET-ICT Ratio at Human Heart Catheterization

The relationship between the ejection - isovolumetric contraction ratio and stroke volume was first described in the NASA Progress Report of July, 1965, and was

presented at the Los Angeles meeting of the American Physiological Society in August, 1965*. The study has now been expanded by the addition of normal data obtained from the Mayo Clinic**. These data were combined with previously reported normal data for the purpose of establishing a more accurate relationship between the interval ratio and stroke volume.

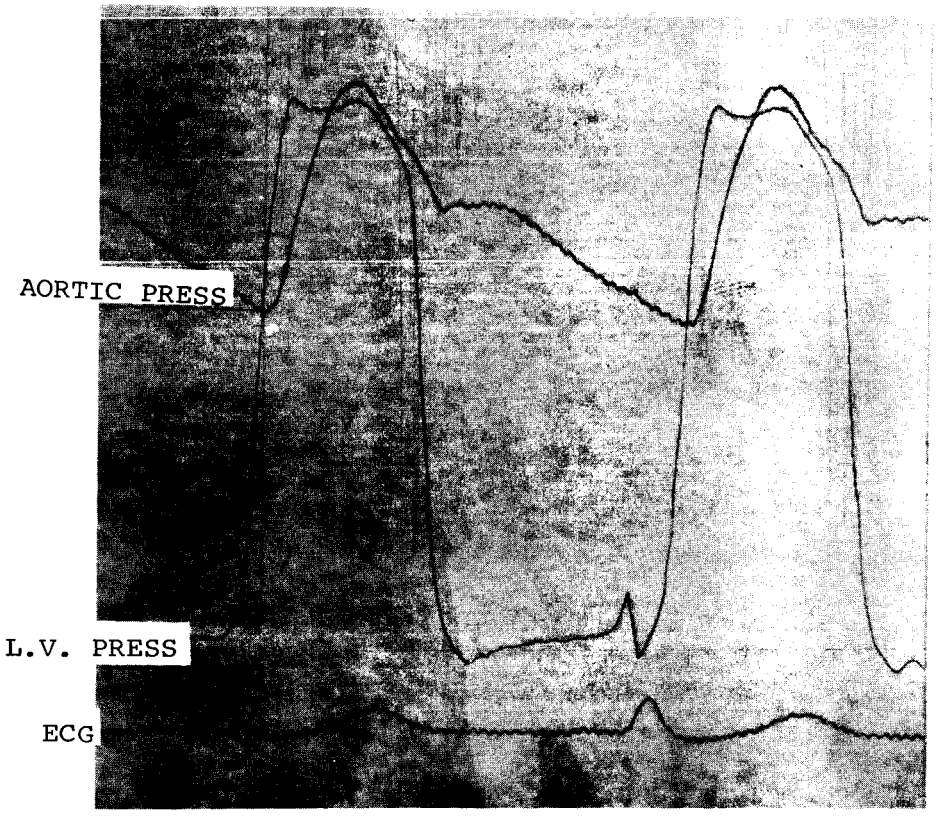
3.11 Methods

Data were obtained from 33 subjects undergoing left heart catheterization. They were found to have normal left heart hemodynamics; i.e., normal sinus rhythm, normal end diastolic pressure, absence of valvular insufficiency and shunts. Patients with minimal aortic stenosis were included if the gradient did not exceed 10 mm Hg. The data consisted of simultaneous

* Determination of Stroke Volume by Measurement of Isovolumetric Contraction and Ejection Times; (Abstract) C. M. Agress, S. Wegner and S. Nakakura; The Physiologist, Vol 8, No 3, August, 1965.

** These data were obtained through the courtesy of Donald Ritter, M. D.

left ventricular and aortic pressures, and ECGs recorded on an oscillographic recorder at a speed of 100 mm/sec (Figure 6). The measurements of the isovolumetric contraction and ejection intervals were made in the standard manner directly from the paper charts. Cardiac outputs were obtained from simultaneous dye dilution tests calculated by the Stuart-Hamilton formula.



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3.12 Results

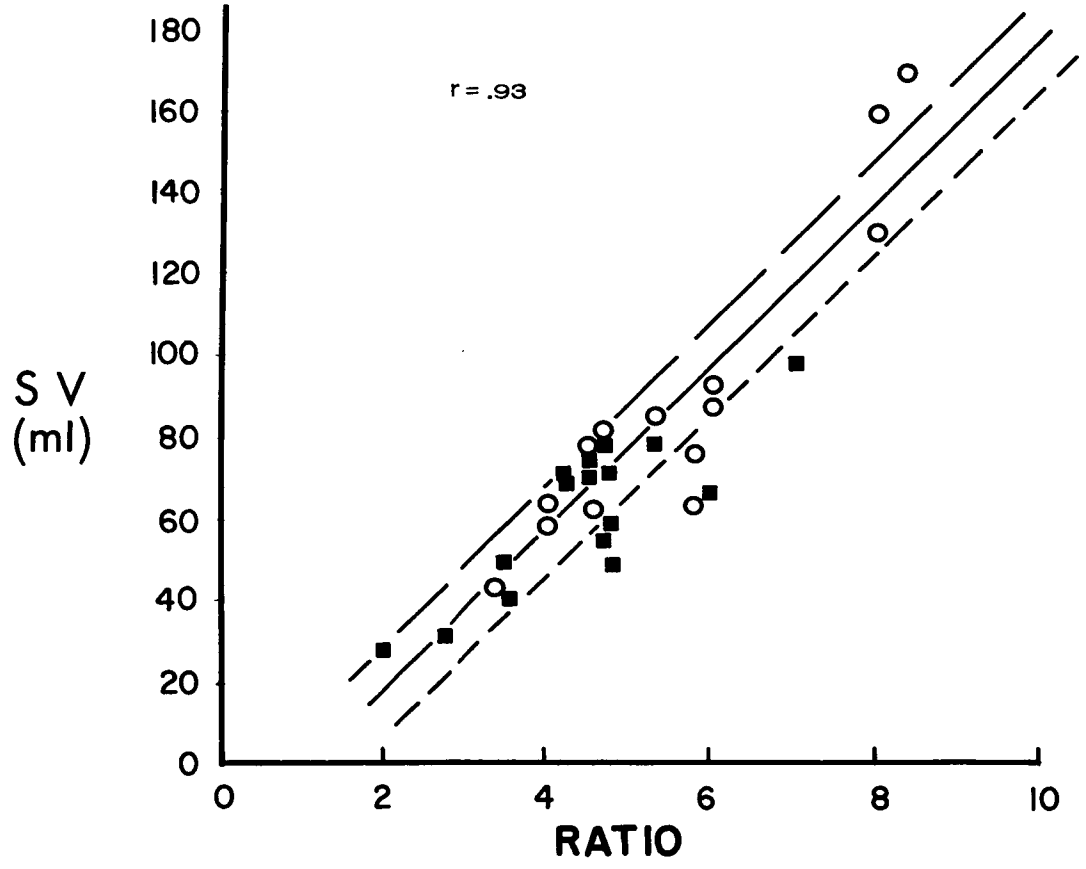
The data from these studies are presented in Table I. Included also are the normal data from the previous study. These were used in the analysis to provide a more significant number of cases. Figure 7 illustrates the relationship of the ejection - isovolumetric ratio to stroke volume. A direct relationship between these two parameters was found with a correlation coefficient of $r = 0.93$. This result is consistent with that previously reported and substantiates the use of the ratio in the determination of stroke volume.

3.13 Discussion and Summary

Since these studies represent normal data, low stroke volumes were not often encountered. For this reason it is not possible to describe accurately the ratio - stroke volume curve in this region. While the present data indicate a linear relationship between these two variables, inclusion of stroke volume data in the

PATIENT	ICT	ET	RAT	SV
1	90	300	3.3	43
2	60	320	5.3	86
3	45	270	6.0	92
4	65	320	8.0	59
	40	250	8.3	63
	25	200	8.0	61
5	40	320	8.0	160
	30	250	8.3	170
	25	200	8.0	129
6	50	300	6.0	108
7	45	210	4.7	81
	45	180	4.0	64
8	60	350	5.8	76
9	55	250	4.5	78

TABLE I



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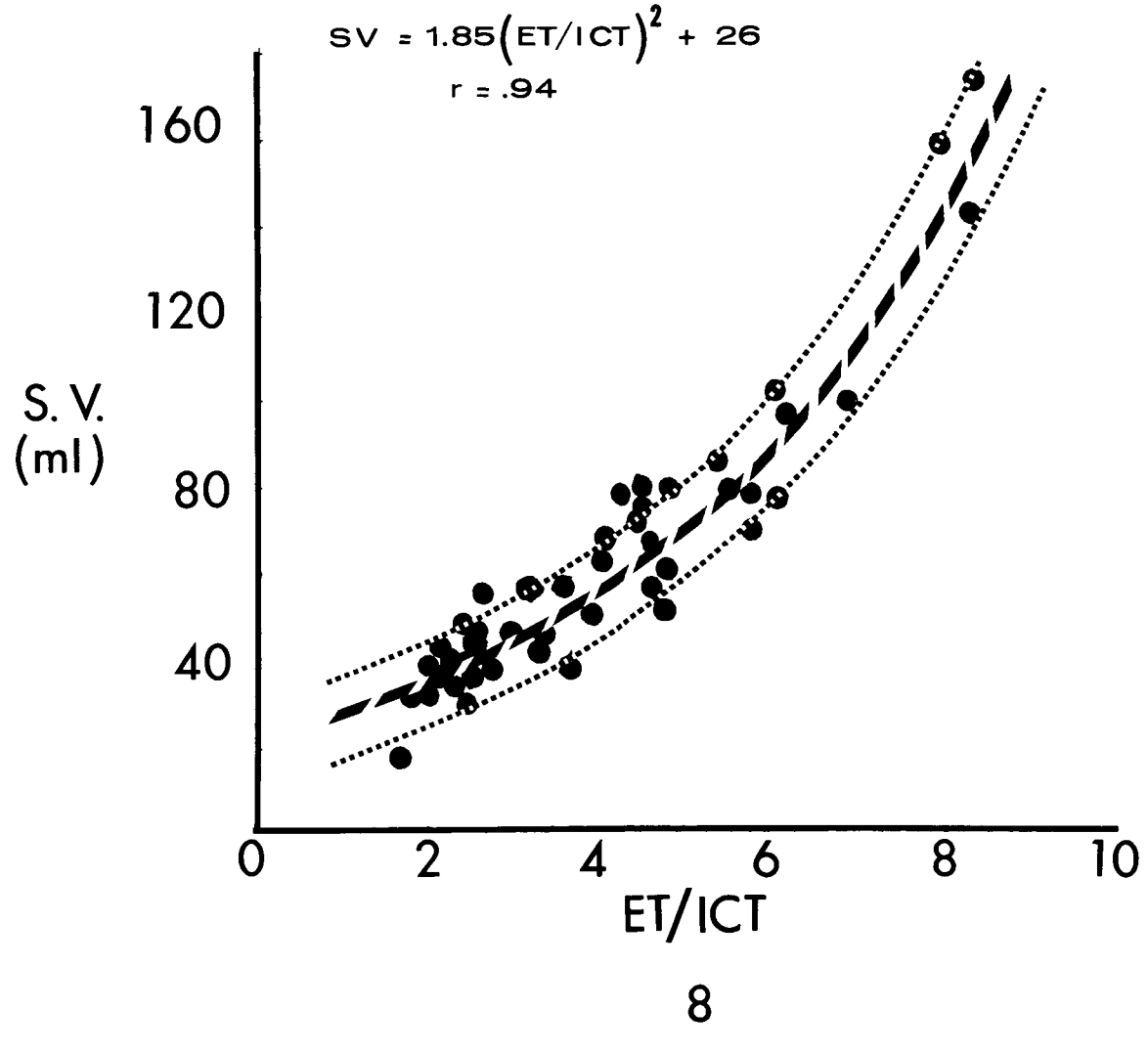
lower ranges may alter this relationship. Such data were available through the vibrocardiographic correlations with stroke volume, which are described in the next section. Comparison of these indirect measurements with those in this study (Figure 8) indicates that the function relating stroke volume and the ratio is not linear but parabolic. Since the correlation coefficient using the combined vibrocardiographic and direct data is the same as the direct data itself, justification for the use of the quadratic relationship is provided. While more data would refine further this formula, it is felt that the correlations are significantly high to justify using the ejection - isometric ratio in the described formula to predict stroke volume and cardiac output.

3.20 Correlation of Dye Dilution Stroke Volume with the Vibrocardiographic ET-ICT Ratio

This phase of research dealt with the correlation of stroke volume obtained in the acutely ill subject with



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the vibrocardiographic ET-ICT ratio and stroke volume obtained by means of the dye dilution technique. Particular emphasis was placed on the study of patients with low cardiac outputs in order to assess the usefulness of the vibrocardiographic method of continuous monitoring in circulatory failure.

3.21 Methods

Eleven subjects suffering from severe acute myocardial infarction (and without valvular insufficiency) were used in this study. Cardiac outputs were obtained using 2.5 mg indocyanine dye injections through a catheter placed in the vena cava in proximity to the right atrium. A Harvard withdrawal pump was used in conjunction with a Gilford Densitometer and Honeywell oscillographic recorder for inscription of the dye curves. Before each injection the system was calibrated with 5, 10 and 15 mg/L dye concentration samples of the patient's blood. The vibrocardiographic technique consisted of placing the condensor microphone at the left

parasternal area and recording the trace simultaneously with Lead II of an electrocardiogram. These curves were displayed on a Honeywell oscillographic recorder at a speed of 100 mm/sec. The isovolumetric and ejection intervals were measured in the standard manner from the vibrocardiographic trace. These measurements were averaged from 5 - 10 heart cycles obtained from a continuous strip recorded during the withdrawal of the dye.

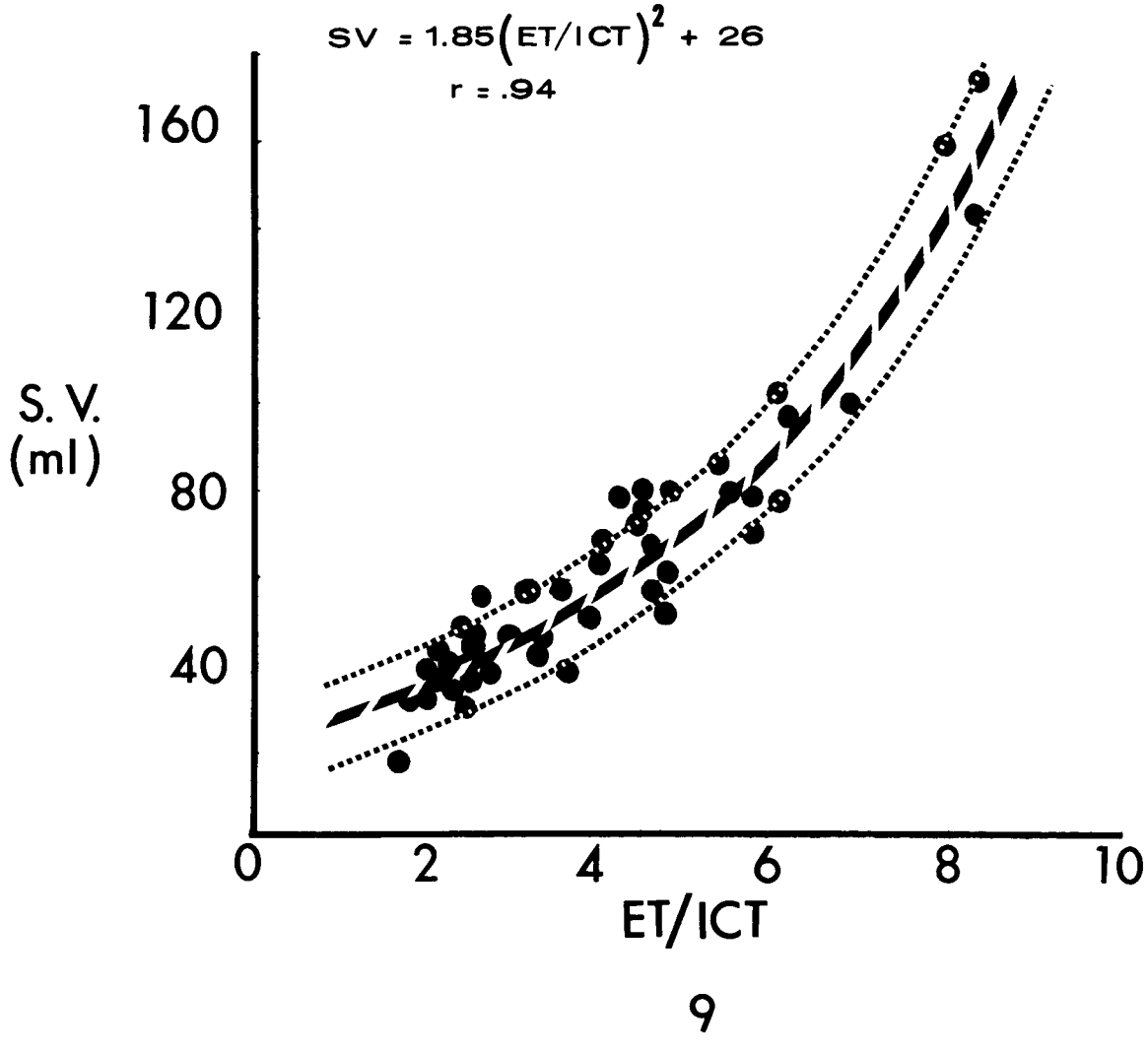
3.22 Results

Table II summarizes the measurements obtained in these subjects. The cardiac outputs ranged from 2 liters to 5.6 liters per minute, stroke volumes varied from 19 to 56 ml, and the ECT/ICT ratio ranged from 1.7 to 3.5.

Figure 9 illustrates the relationship of ET/ICT ratio to stroke volume; it also includes the direct stroke volume ratio data. There was a direct correlation between these variables which was sufficiently comparable

PATIENT	RATIO	SV
1	1.7	19
2	2.3	48
	2.5	51
3	2.0	36
4	3.1	41
5	2.3	37
6	3.5	54
	3.0	52
	3.4	51
	2.4	39
7	3.9	47
	2.4	36
	3.5	36
	2.3	36
8	2.4	32
	2.2	28
9	2.5	31
	2.0	30
10	1.8	30
	2.7	41
	2.4	36
	2.7	28
11	2.0	30
	2.5	40
	2.3	39
	2.8	45

TABLE II



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to the direct measurements described in the previous section that the data were treated as one group. The correlation coefficient obtained was r = 0.94.

3.23 Discussion and Summary

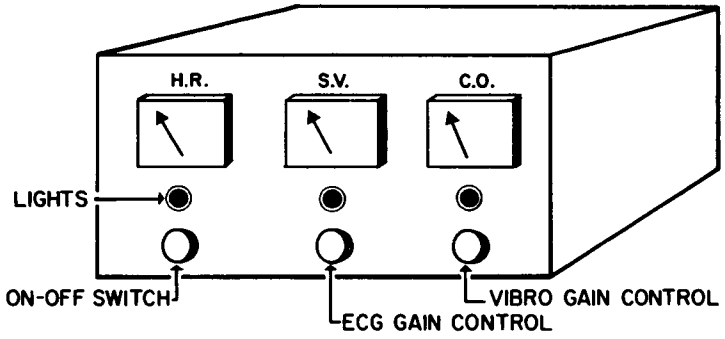
The relationship between the isovolumetric contraction and ejection intervals to stroke volume has been reported from previous investigations and its usefulness in measuring stroke volume has been studied both in the human and the experimental animal. The application of the vibrocardiogram provides an external means for the measurement of these intervals and lends itself to the continuous calculation of stroke volume and cardiac output.

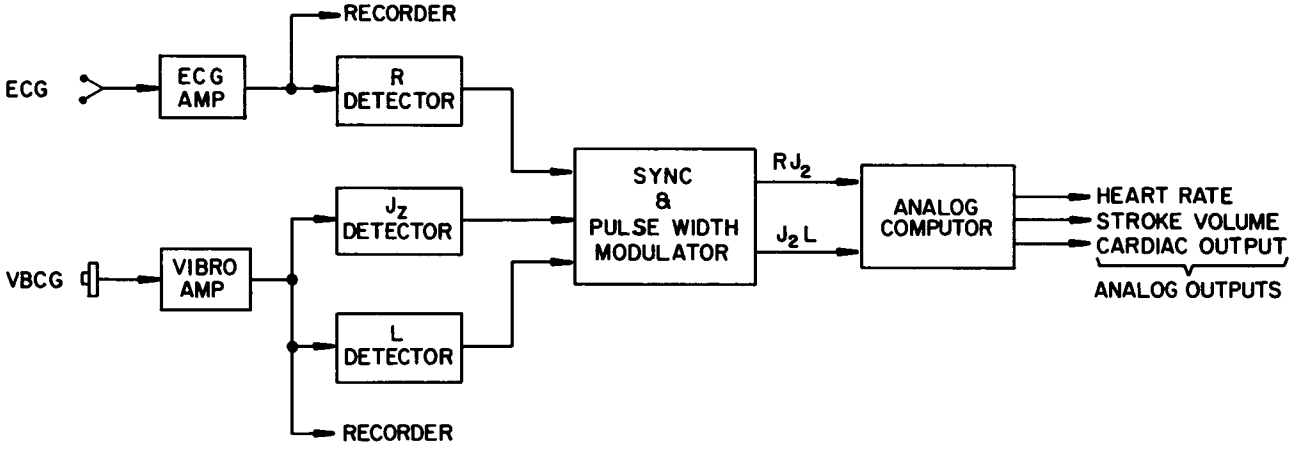
Such a technique is particularly useful in circulatory failure, or in any condition of rapidly changing cardiovascular function where continuous monitoring may provide significant evaluation of therapy used.

3.30 Automatic Computation of Stroke Volume and Cardiac Output from the Vibrocardiogram

The establishment of the vibrocardiographic technique for measuring stroke volume and cardiac output has provided a means by which these parameters can be continuously monitored in either human or animal subjects. In order to facilitate rapid measurements an electronic computer has been designed which will provide on-line, continuous computation of stroke volume, cardiac output and heart rate. This computing device was designed (Figure 10) to measure from an electrocardiographic and vibrocardiographic input the time intervals between the peak of the R wave of the ECG and the J_2 wave of the vibrocardiogram (representing the period of isometric contraction) and the time interval between the J_2 wave of the vibrocardiogram and the L wave of the vibrocardiogram (representing the ejection interval) and apply these in the stroke volume formula (Section 3.10). Heart rate is determined from the time between successive ECG R wave peaks and cardiac output determined by

STROKE VOLUME COMPUTER





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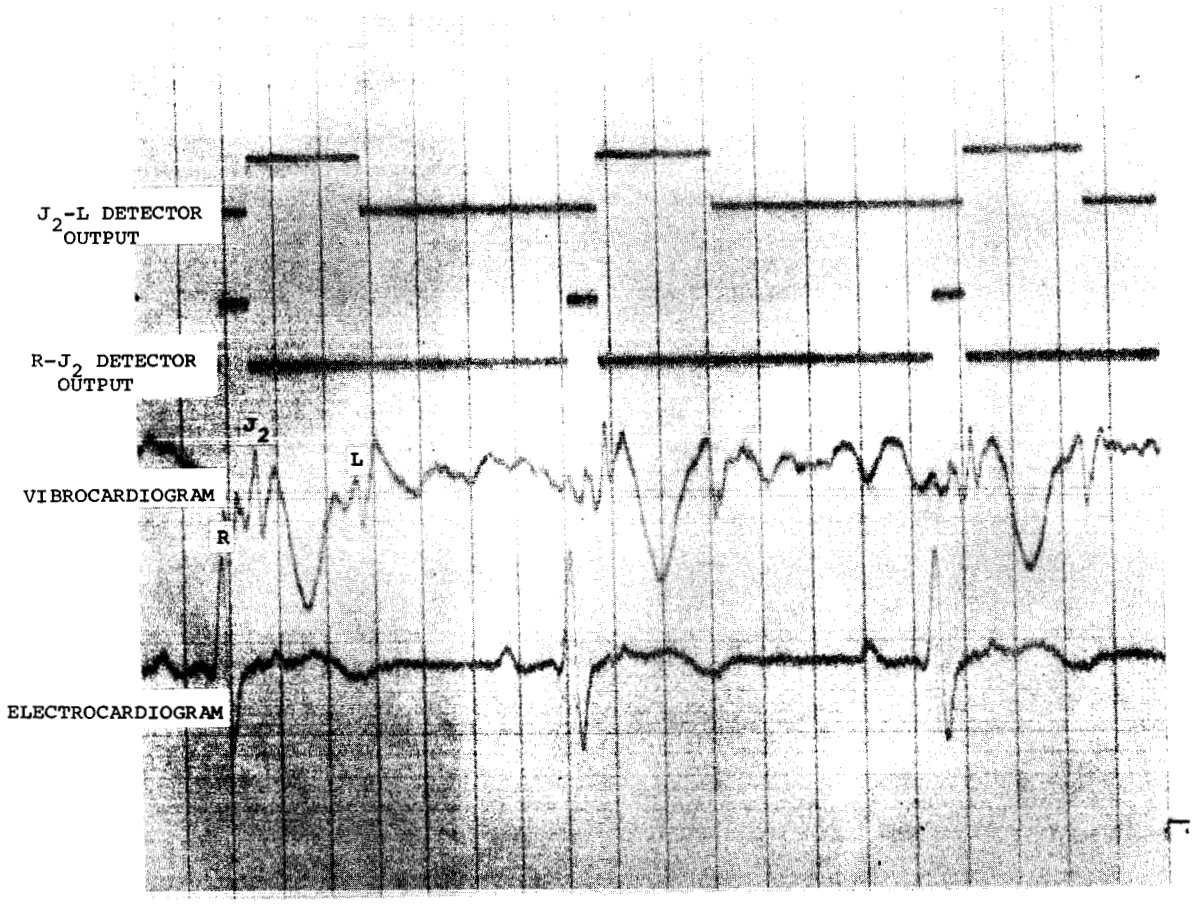
the product of stroke volume and heart rate. These outputs are in analog as well as digital form (Figure 11). This device, when completed, will be used for long term monitoring of animal as well as human experiments.



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3.40 Application of Various External Techniques to the Measurement of Cardiovascular Function during Acute Myocardial Infarction

This phase of research represented a clinical application of vibrocardiographic as well as other indirect monitoring techniques to the acutely ill subject. The purposes of this study were to establish methods for the application of monitoring techniques, to determine which of the techniques thus applied gave the most reliable information reflecting the clinical state of the subject, and to determine if this information could be used to detect alterations in the functional state of the cardiovascular system. The techniques applied consisted of the vibrocardiogram, the apexcardiogram, the phonocardiogram, the electrocardiogram and the carotid pulse.

3.41 Methods

Following is a description of the recorded parameters:

1. Vibrocardiogram: The vibrocardiogram was obtained

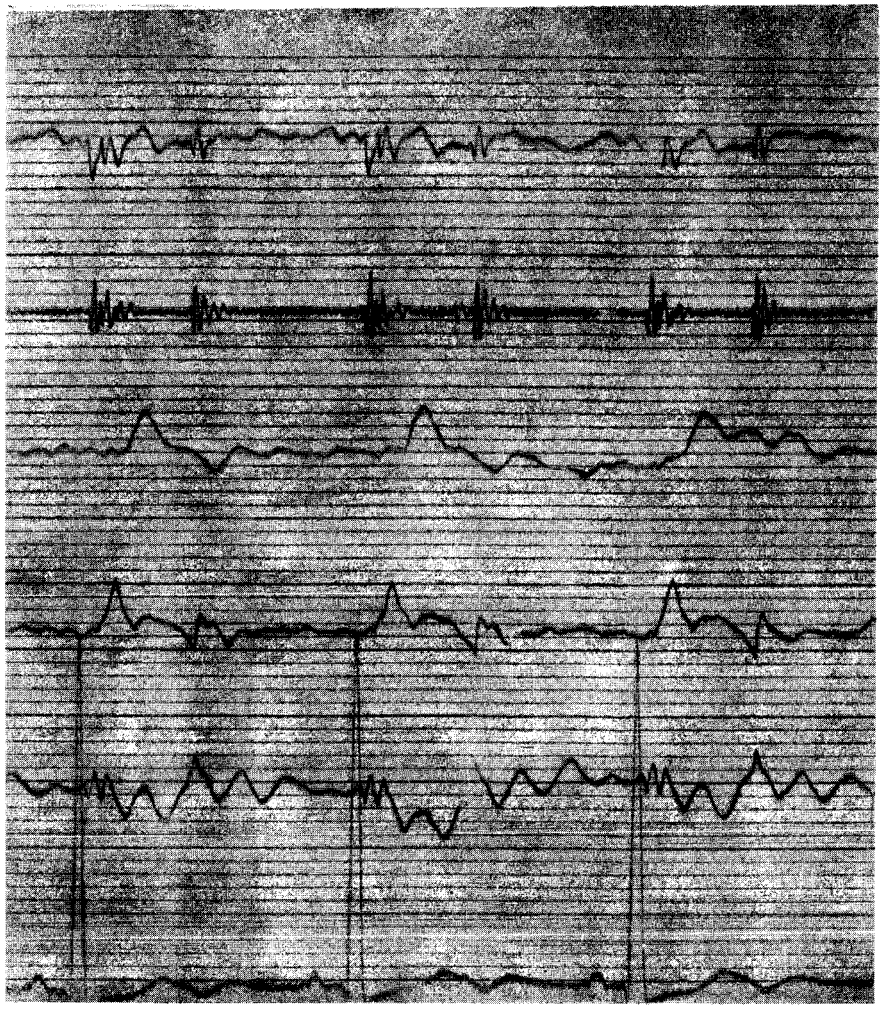
with the standard LTV transducer placed at the left parasternal area.

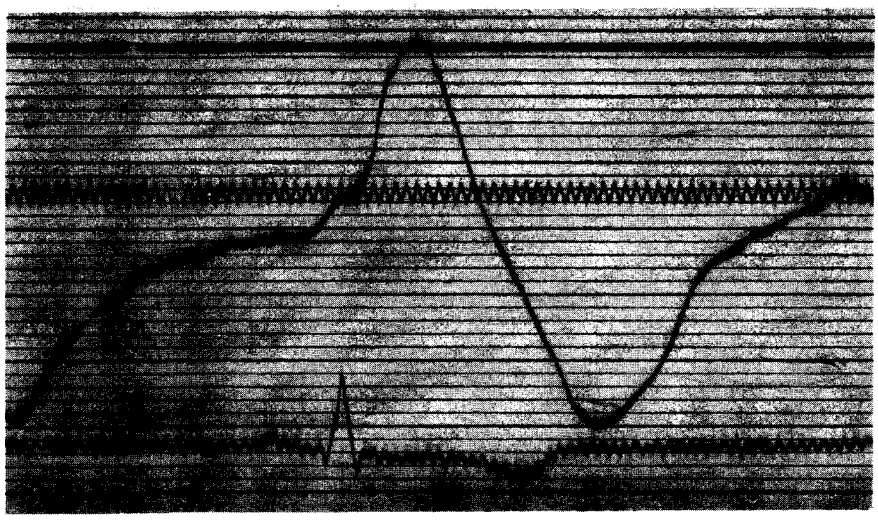
2. Apexcardiogram: The apexcardiogram was obtained with the Sanborn Crystal Transducer placed over the apical beat or at the point of maximal intensity with the subject in the left lateral position.

3. Phonocardiogram: The phonocardiogram was obtained at the left parasternal region (third to fourth interspace) with a crystal microphone using a 50 cps high pass filter.

4. Electrocardiogram: The electrocardiogram was a modified (precordial) Lead I.

These parameters were obtained on a Honeywell photographic recorder with a paper speed of 100 mm/sec. A sample of the records obtained is shown in Figure 12. From each record, three heart cycles were measured to





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obtain averages of the determinations listed below. A sample data sheet is shown in Figure 13.

R - R interval	Time between two consecutive R peaks of the ECG (used for calculation of heart rate).
P - R	Time interval from the onset of the P wave to the onset of the R wave of the ECG.
Q - T	Duration of electrical systole. Measured from the onset of the Q wave to the termination of the T wave of the ECG.
S_1, S_2	Peak to peak amplitudes in centimeters of the first and second heart sounds of the phonocardiogram.
Q - S_1	Electromechanical lag period measured from the onset of the Q wave of the ECG to the onset of the first heart sound in the phonocardiogram.

DATA MEASUREMENTS

Date	R-R	P-R	Q-I	Q-T	a/e	S_1/S_2	$A\text{-}J_2/J_2\text{-}L$	BP	MAP
4/8	1048	182	47	343	35/192	80/62	63/262	102/72	82
	1174	187	52	337	55/232	92/65	63/262		
	1082	180	51	337	47/165	75/72	58/264		
4/10	942	228	42	333	43/230	57/62	46/272	98/78	85
	889	216	47	333	43/205	45/95	44/272		
	856	222	57	331	40/257	55/85	46/272		
4/13	1023	228	52	364	93/547	54/135	46/303	138/80	99
	1002	228	54	355	158/663	44/68	45/298		
	1064	232	56	366	66/437	54/67	46/297		

DATA CALCULATIONS

	SV	CO	dP/dt	HR	ET%	MS%	CQT	$R\text{-}J_2/J_2\text{-}L$	a/e
4/8	58	3306	1658	57	-10.0	-1.9	.335	.237	18.2
	58	2958	1658	51	-14.4	-6.9	.312	.240	23.7
	61	3355	1908	55	-11.5	-4.2	.324	.220	28.5
4/10	77	4928	2622	64	- 3.3	1.2	.344	.169	18.7
	79	5293	2722	67	- 1.5	3.6	.354	.162	20.9
	77	5390	2622	70	- 0.3	6.3	.358	.169	15.6
4/13	84	4956	2660	59	4.1	5.7	.357	.152	17.0
	84	5040	2710	60	3.1	5.8	.355	.151	24.2
	83	4648	2660	56	.0	2.6	.355	.155	15.1

	S W	Min. Work	Cont. Index	M.E.R.	S_1/S_2	TPR
4/8	4756	2710	26.3	.221	1.29	.248
	4756	2425	26.3	.221	1.42	.277
	5002	2751	32.9	.231	1.04	.244
4/10	6545	4188	57.0	.283	0.92	.172
	6715	4499	61.9	.290	0.47	.161
	6545	4581	57.0	.283	0.65	.158
4/13	8316	4906	57.8	.277	0.40	.199
	8316	4989	60.2	.282	0.65	.196
	8217	4601	57.8	.279	0.81	.213

$R - J_2$	Isovolumetric contraction period measured from the peak of the R wave of the ECG to the peak of the J_2 wave of the vibrocardiogram.
$J_2 - L$	Ejection period measured from the peak of the J_2 wave in the vibrocardiogram to the onset of the L wave in the vibrocardiogram.
PD	Pulse delay period (the interval between the J_2 wave of the vibrocardiogram and the upstroke of the carotid pulse tracing).
BP	The arterial pressure measured by sphygmomanometer.

From these measurements calculations were made of the following parameters:

PARAMETER	METHOD	DIMENSIONS
Stroke Volume (SV)	$1.85\left(\frac{ET}{ICT}\right)^2 + 26$	cc/beat

PARAMETER	METHOD	DIMENSIONS
Heart Rate (HR)	$\frac{60}{R\text{-}R}$	beats/min
Cardiac Output (CO)	SV · HR	L/min
Maximum Left Ventricular Pressure Derivatives (dP/dt)	* $-50\ (R\text{-}J_2)$ $+19\ (dP)$ $+3440$	mm Hg/sec
Predicted Ejection Time (PET)	* $402 - 1.9\ (HR)$	msec
Predicted Mechanical Systole (PMS)	* $.324\ \sqrt{R\text{-}R}$	Index
Corrected Q-T (CQT)	$\frac{Q\text{-}T}{\sqrt{R\text{-}R}}$	Index
Mean Arterial Pressure (MAP)	$\frac{PP}{3}$ + diastolic P	mm Hg
Stroke Work (SW)	SV · MAP	$\frac{ml\text{-}mm\ Hg}{beat}$

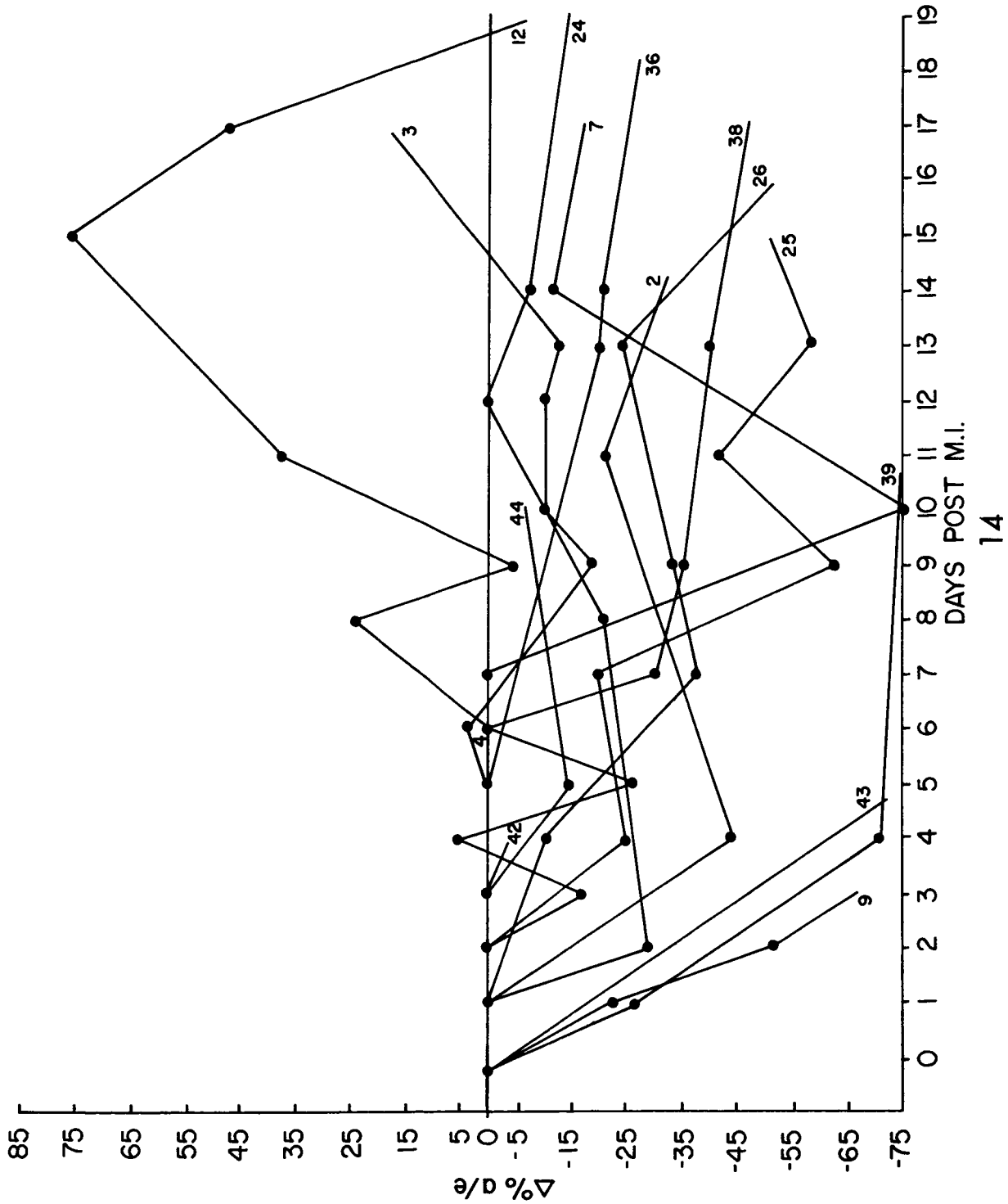
* See Progress Report, July, 1965

PARAMETER	METHOD	DIMENSIONS
Minute Work (MW)	SW • HR	$\frac{\text{ml-mm Hg}}{\text{min}}$
Peripheral Resistance (PR)	$\frac{\text{MAP}}{\text{CO}}$	$\frac{\text{mm Hg}}{\text{L}}$
Contractility Index (CI)	$\frac{dP/dt}{\text{ICT}}$	Index

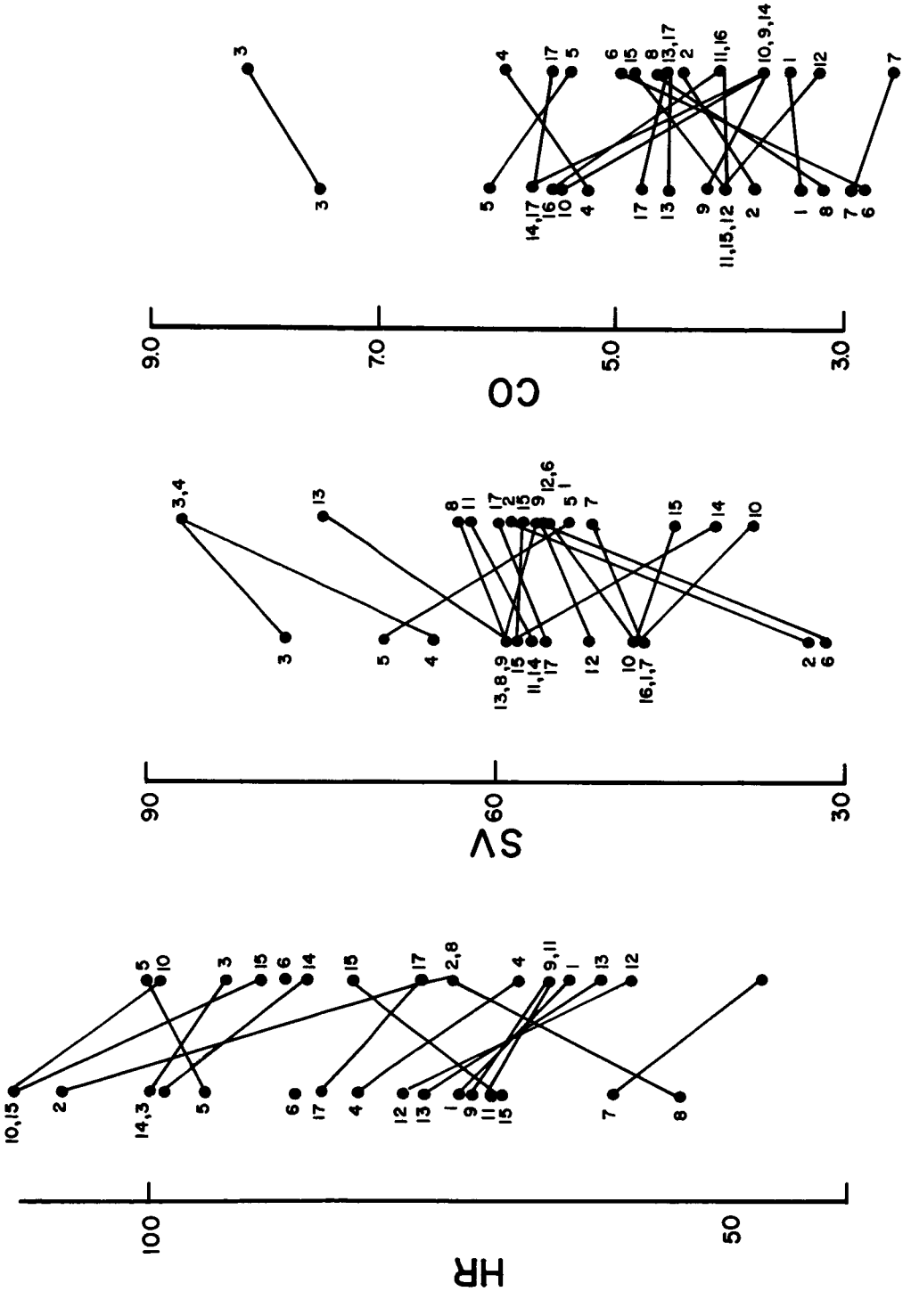
3.42 Results

Seventeen subjects recovering from acute myocardial infarction have been studied thus far. There were an average of six tests performed serially on each patient over a period of two weeks. Because of the quantity of data generated, the graphic presentations were designed to summarize the results, by showing only the initial and terminal values of the measurements. Figure 14 illustrates one example of the day to day plot of a single variable.

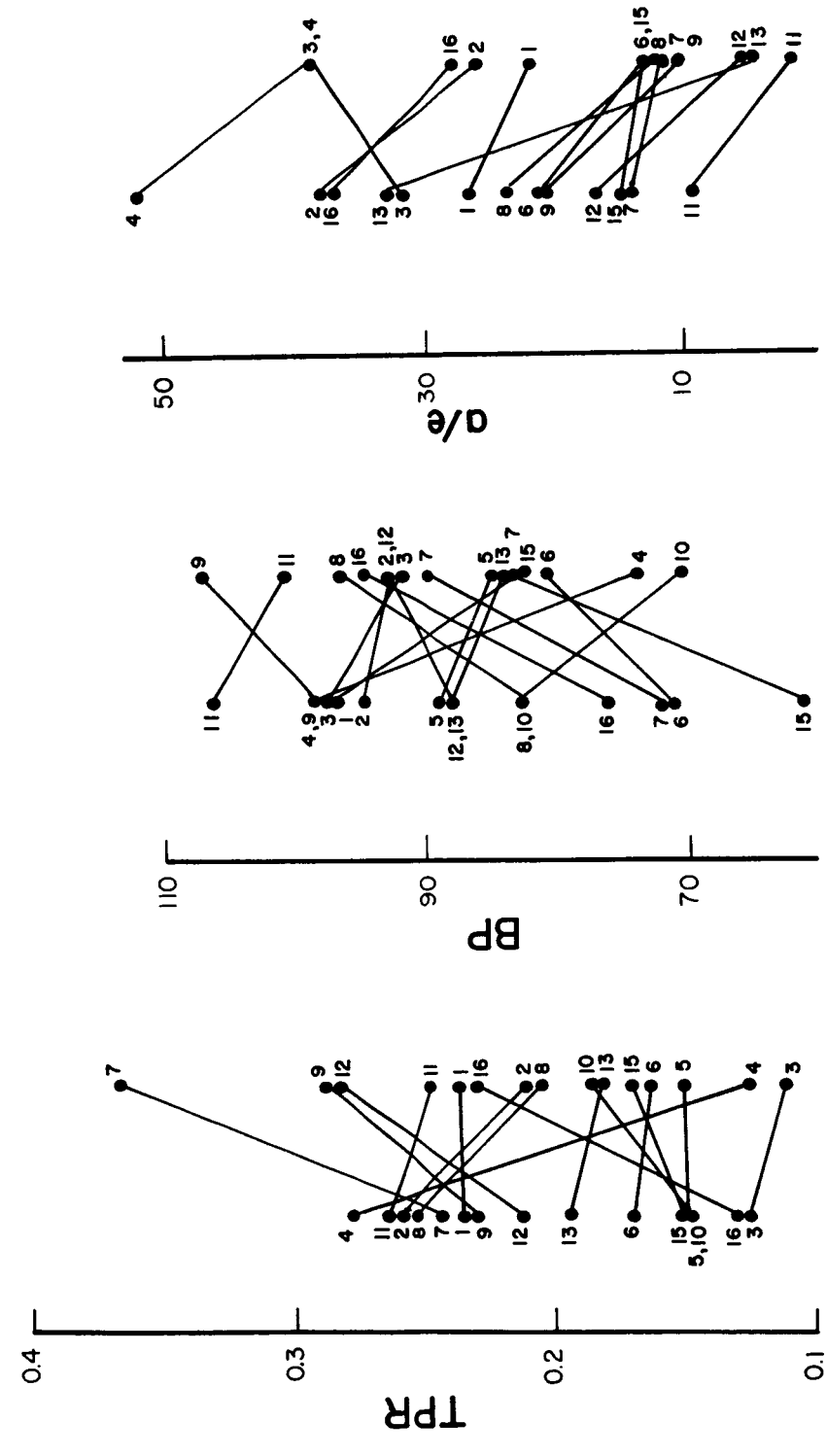
In Figure 15, the heart rate, stroke volume and cardiac output data are plotted.


Δ% a/e
85
75
65
55
45
35
25
15
5
0
-5
-15
-25
-35
-45
-55
-65
-75
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
DAYS POST M.I.
12
24
36
7
3
38
26
25
2
39
44
4
43
42
9

14



15



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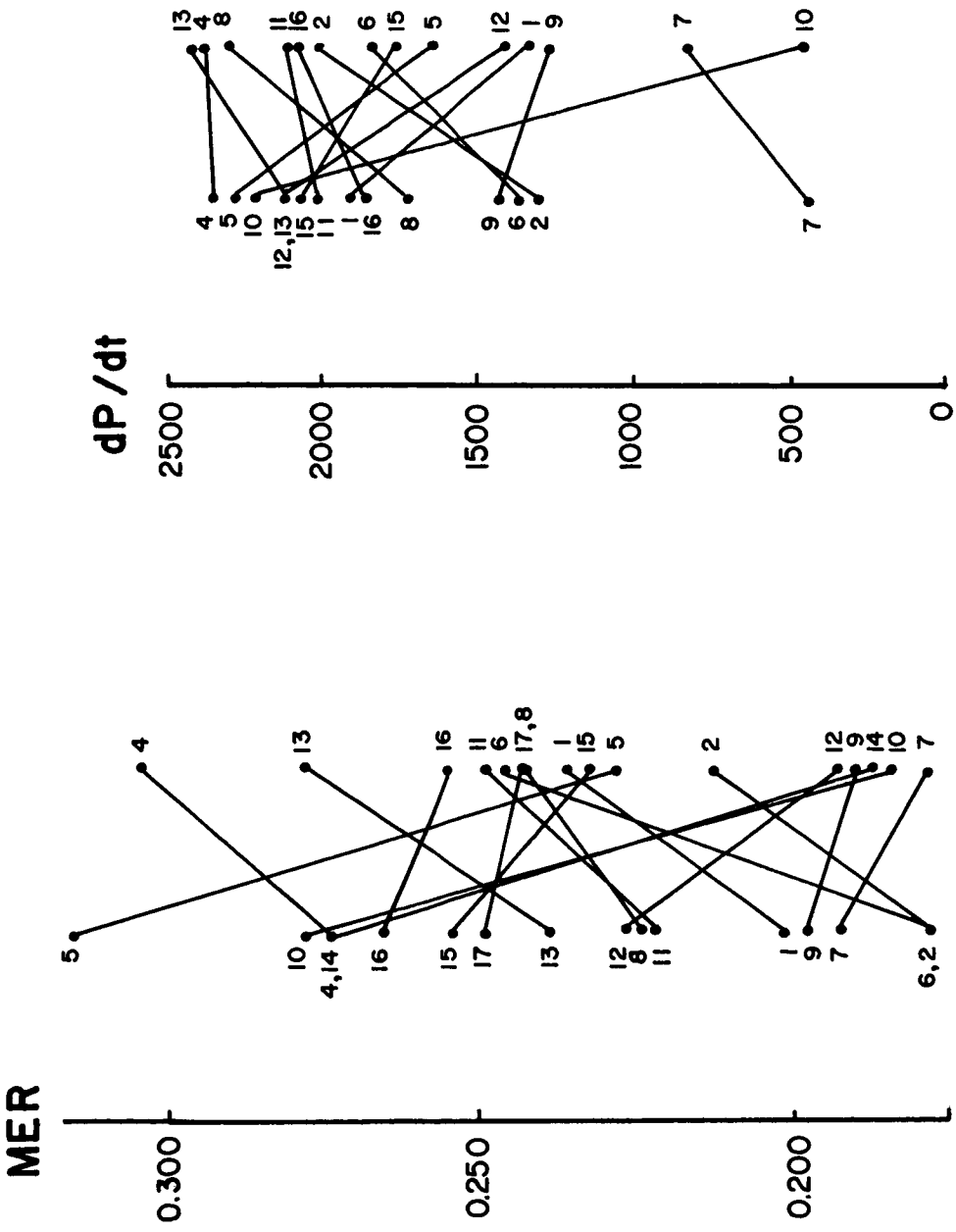
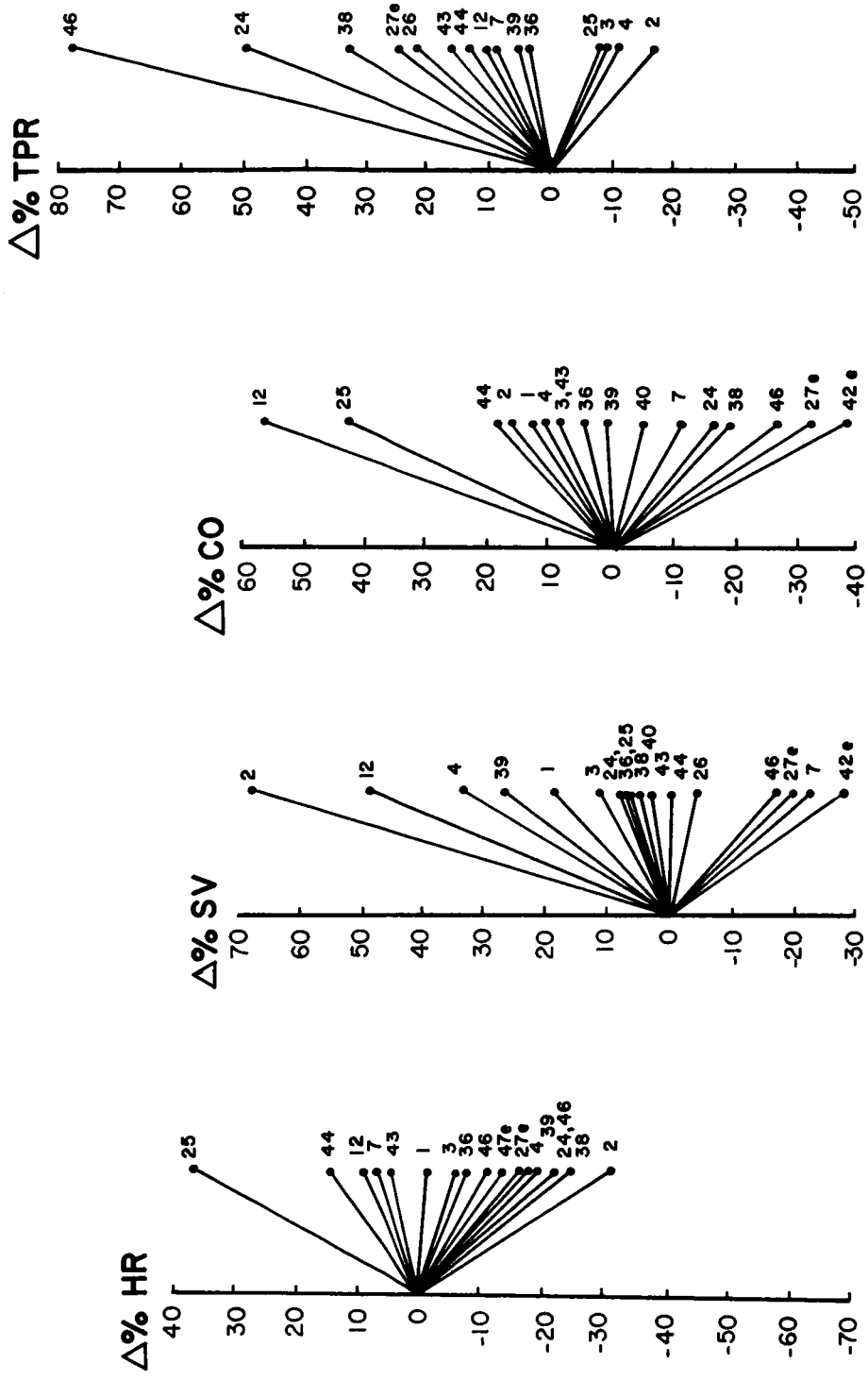
The heart rates were uniformly diminished with nearly equal incremental changes over the study period. The stroke volumes showed large rises in the first two days with only slight increases thereafter. The cardiac outputs did not show such consistent changes, but in most instances, were either increased or unchanged over the monitoring period.

Figure 16 presents the peripheral resistance, blood pressure and apex cardiographic a/e ratio. The peripheral resistances, while exhibiting some scatter, were in general elevated, as were the blood pressures. The apexcardiographic a/e ratios showed the most consistent changes of any of the parameters under study. Large decreases, consistent with improving myocardial function, were observed in the early recovery phases with gradual declining values by the termination of the study. The mean ejection rate and dP/dt are presented in Figure 17. Both showed inconsistent variations over the monitoring period. The percent change

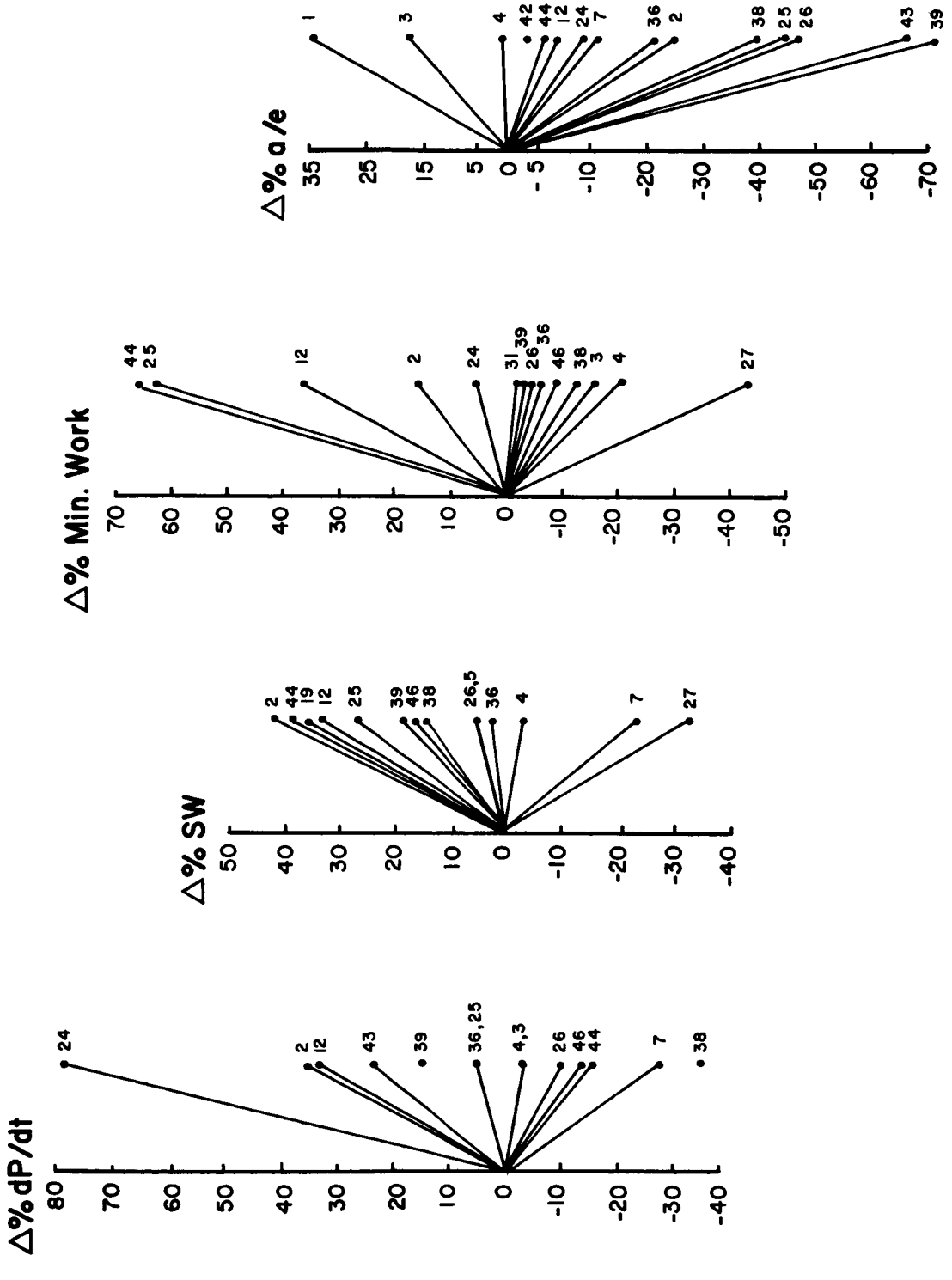


17

of the above data are summarized in Figures 18 and 19. These results ignore entirely the variation in severity of infarction, the occurrence of complications, drug therapy affecting the inotropic state of the myocardium, the effects of posture, activity, etc. This was a pilot study to discover which of the available non-traumatic measurements might prove useful in the assessment of myocardial function during the changing conditions of acute heart injury. The crude results need great refinement but serve the purpose of indicating that such measurements can be made and can reflect the progress or lack of progress of the patient. The results show that many measurements are uninformative while others are very revealing. They point the way to a much more definitive study which should provide parameters for predicting recovery, judging therapy, guiding increases in activity, etc. These are guides which are sadly lacking in the present care of patients with myocardial infarction. More to the aims of NASA, the measurements show that sensitive parameters for detecting changes in ventricular performance can be obtained


Δ% TPR
80 70 60 50 40 30 20 10 0 -10 -20 -30 -40 -50
46 24 38 27● 26 43 44 12 7 39 36 25 3 4 2
Δ% CO
60 50 40 30 20 10 0 -10 -20 -30 -40
12 25 44 2 1 4 3,43 36 39 40 7 24 38 46 27● 42●
Δ% SV
70 60 50 40 30 20 10 0 -10 -20 -30
2 12 4 39 1 3 24 36,25 38 40 43 44 26 46 27● 7 42●
Δ% HR
40 30 20 10 0 -10 -20 -30 -40 -50 -60 -70
25 44 12 7 43 1 3 36 46 47● 27● 4 39 24,46 38 2

18


Δ% dP/dt
80 70 60 50 40 30 20 10 0 -10 -20 -30 -40
24 2 12 43 39 36,25 4,3 26 46 44 7 38
Δ% SW
50 40 30 20 10 0 -10 -20 -30 -40
2 44 19 12 25 39 46 38 26,5 36 4 7 27
Δ% Min. Work
70 60 50 40 30 20 10 0 -10 -20 -30 -40 -50
44 25 12 2 24 31 39 26 36 46 38 3 4 27
Δ% a/e
35 25 15 5 0 -5 -10 -20 -30 -40 -50 -60 -70
1 3 4 42 44 12 24 7 36 2 38 25 26 43 39

19

by atraumatic methods.

3.50 Exercise Testing with the Vibrocardiogram

From the data obtained in exercise studies performed earlier in the research program*, it was determined that none of the measurements in current use showed clear-cut differences between normal and cardiac-impaired subjects. Further exercise testing also revealed that the test could not be interrupted in order to obtain measurements, since stopping the exercise, even for only a few seconds, resulted in marked cardiodynamic changes. It was concluded that if definitive exercise measurements were to be performed, data would have to be obtained throughout the course of exercise. For the elimination of artifacts on-line recording of precordial vibrations in an active subject requires the application of signal averaging techniques.

* See Progress Report, January, 1965

The exercise program was therefore designed so that data could be continuously recorded without cessation of the test. New measurements such as SV and CO, ejection time, mean ejection rate, Max dP/dt, etc., could thus be added for evaluation of stress.

3.51 Methods

The methods of exercise testing employed in this study consisted of walking on a treadmill at a speed of 1.7 miles per hour at a 10% grade for ten minutes (single Bruce test). A modified ECG Lead I (precordial) and vibrocardiogram were continuously recorded on a Consolidated Electrodynamics Corporation F.M. tape recording system at a speed of 3 3/4 inches per second. The data were analyzed by means of a signal averaging device, Enhancetron*. Averaged recordings were made at control levels and at two minute increments throughout the exercise test and recovery. From these averaged records, calculations were made of the

* Described in detail in Progress Report, January, 1965

patient's heart rate, isometric contraction time, ejection time, dP/dt, stroke volume and CO.

3.52 Results

An example of data obtained during exercise are presented in Figure 20. The results indicate that during exercise the heart rate, in the normal subject, shows an initial increase, then reaches a steady state which is maintained throughout the test and is accompanied by an increase in stroke volume and cardiac output. In contrast, the subject with heart disease exhibits a diminishing stroke volume but tends to maintain his cardiac output by a greater increase in heart rate. These studies are being continued to see if such changes in SV during exercise can provide a reliable means of detecting diminishing cardiovascular function.