

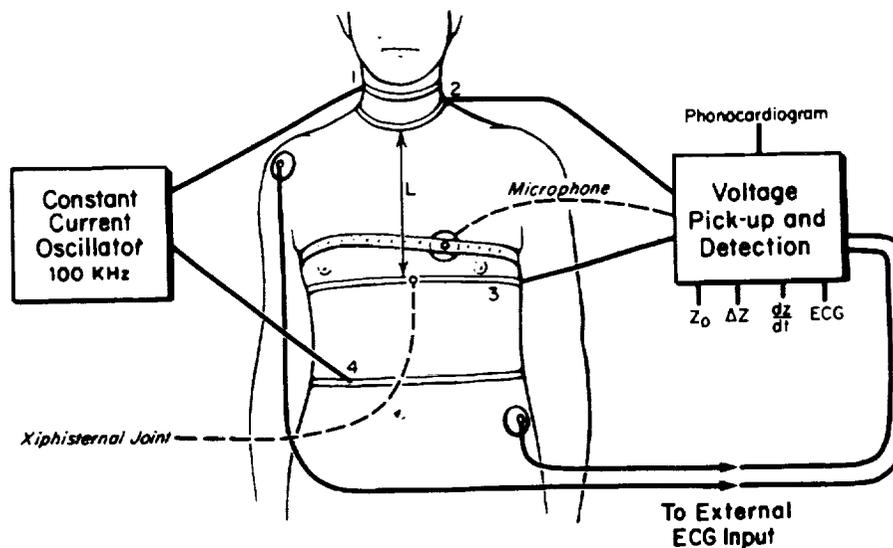
## Cardiac Output and Cardiac Contractility by Impedance Cardiography during Exercise of Runners

W. G. Kubicek, BSEE, Ph.D. and R. A. Tracy, Ph.D.  
 Department of Physical Medicine and Rehabilitation  
 University of Minnesota Medical School  
 Minneapolis, Minnesota

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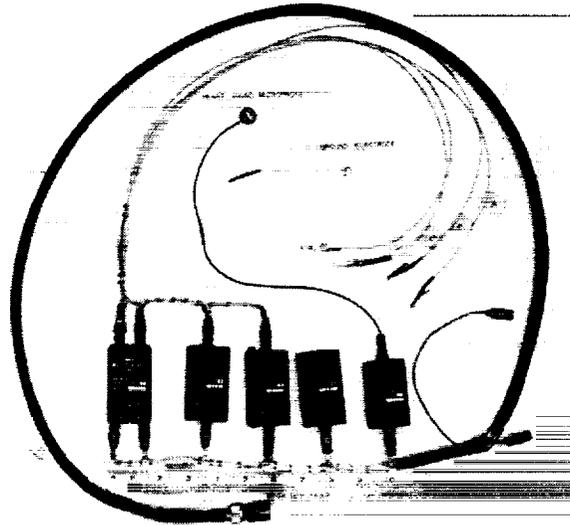
### Historical Perspective

Most of the solid state electronic engineering of the system now generally known as the Minnesota Impedance Cardiograph was performed with the support of a 5-year contract, NAS9-4500, with the NASA Lyndon B. Johnson Space Center, Houston, Texas. This contract ran from 1965 to 1970, W. G. Kubicek, Principal Investigator. In addition to the engineering design and development of the hardware (Figure 1), the contract called for testing on both animals and human subjects. This project also provided funds to construct twenty impedance cardiographs and place them in selected research and clinical facilities for further evaluation. This, then, led to the First Symposium on Impedance Cardiography, held at the NASA Lyndon B. Johnson Space Center, Houston, Texas, June 2 to June 4, 1969. Twenty-four excellent papers were presented.



**Figure 1.** A schematic diagram of the main elements of the Minnesota Impedance Cardiograph. From left to right, the constant current oscillator at 100 kHz, 4 ma (RMS).  $L$ =distance between electrodes 2 and 3 in cm,  $Z_0$ =longitudinal thoracic impedance between electrodes 2 and 3 in ohms,  $\Delta Z$ =magnitude of impedance change during cardiac cycle in ohms,  $dZ/dt$ =first time derivative of  $\Delta Z$  in ohms per second, ECG=electrocardiogram and finally, a phonocardiogram output.

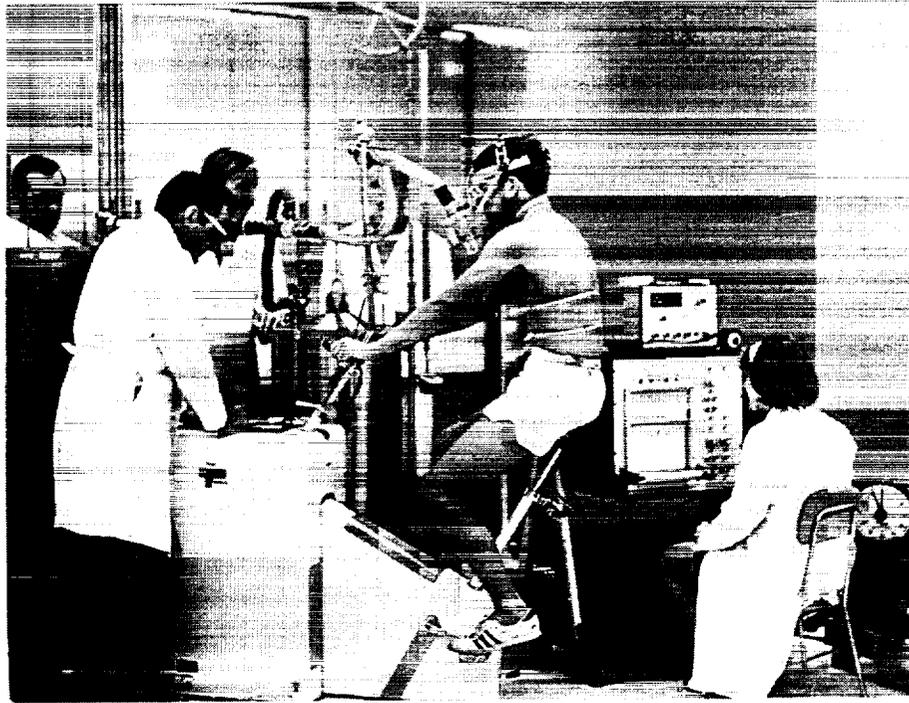
A separate contract was negotiated by the NASA Center with Space Labs, Inc., Van Nuys, California, to construct six miniaturized impedance units as shown in Figures 2 and 3. Testing of one of the systems showed fairly good function (Figure 4). However, a satisfactory calibration system was not incorporated into the design, making use of the device very difficult. One of these units was used during space flight by Dr. William Thornton (NASA).



**Figure 2.** *A photograph of one of the six miniaturized impedance cardiographs, patterned after the circuitry shown in Figure 1. A satisfactory calibration circuit was not incorporated into these units. These units were constructed by Space Labs, Inc., Van Nuys, California, about 1968.*



**Figure 3.** *A photograph of the unit in Figure 2 worn in a "cartridge belt" suspension.*



**Figure 4.** *A photograph of the laboratory arrangement for bicycle ergometer exercise of six middle distance runners (4,000 meters) . From left to right, Dr. R. A. Tracy, a runner in place on the bicycle ergometer with a face mask attachment for measuring oxygen consumption rate, and the strip chart recorder with the impedance cardiograph mounted on top with the technician ready to start the recorder, when needed.*

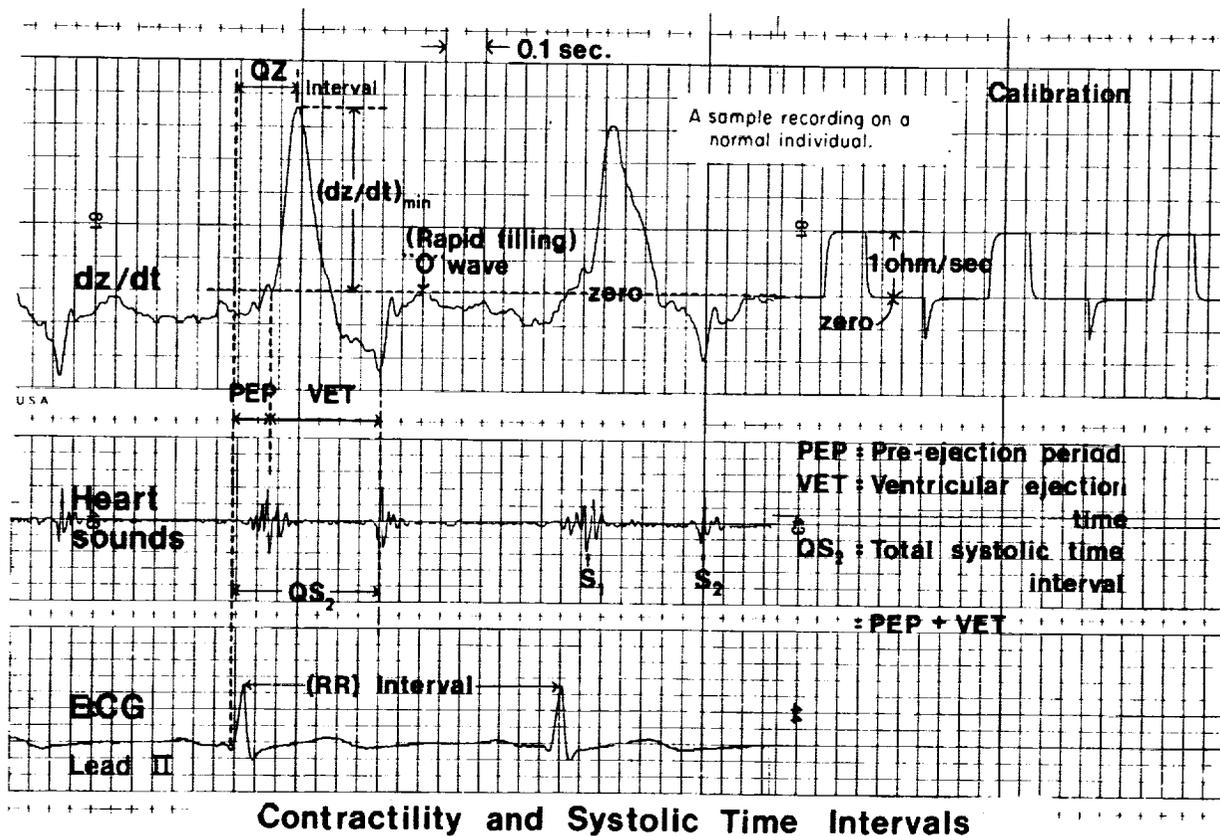
An excellent comprehensive review by Miles and Gotshall [1] on the subject, "Impedance Cardiography: Noninvasive Assessment of Human Central Hemodynamics at Rest and During Exercise," is most appropriate for this conference.

#### **Scientific Observations of Importance during Exposure to Microgravity**

Two major scientific achievements were made during our NASA contract. First, the derivation of a stroke volume formula and second, the use of the first time derivative ( $dZ/dt$ ) of thoracic impedance change ( $\Delta Z$ ) during cardiac cycle to refine the stroke volume formula as widely used today [2].

Later experiments on anesthetized dogs revealed that peak ( $dZ/dt$ ) occurs simultaneously with peak ascending aortic blood flow and that peak ( $dZ/dt$ ) is directly proportional to peak aortic flow [3].

An example of a strip chart recording of ( $dZ/dt$ ), phonocardiogram and ECG on a normal individual is shown in Figure 5. In addition to use in computing stroke volume and cardiac output, this recording to determine several systolic time intervals and contractility indices. It would appear that these parameters would be of great importance if there is deterioration in cardiac mechanical function during prolonged space flight.



**Figure 5.** *An example of a strip chart recording on a normal individual at rest. From left to right, (Q-Z) interval in seconds=time from Q wave to peak  $dZ/dt$ . PEP preejection period in seconds, VET=ventricular ejection time in seconds,  $QS_2$ =total systolic time interval in seconds,  $(dZ/dt)_{min}$  in ohms per second, "O" wave=rapid ventricular filling wave, (RR)=ime interval between two heart beats in seconds. This recording illustrates the type of recording used to compute or measure the various parameters shown in Figures 6 to 10.*

It is generally accepted that when a normal individual changes from a standing position to supine (at one g) cardiac output increases due to an augmented venous return from the lower parts of the body. Table 1 illustrates the change in several parameters obtained by impedance cardiography when normal individuals changed from standing to supine. Of special importance here is the decrease in  $Z_0$  in the supine position. This indicates an increase in fluid in the pulmonary vascular bed.

**Table 1.** *Standing and supine data from 19 (8 female, 11 male) normal individuals, aged 21 to 54 years (Mean  $\pm$ SD)*

	Standing	Supine (1 to 2 min)
SV	67 $\pm$ 17	123 $\pm$ 30
HR	79 $\pm$ 13	64 $\pm$ 12
CO	5.3 $\pm$ 1.4	7.9 $\pm$ 2.0
CI	2.9 $\pm$ 0.8	4.3 $\pm$ 1.2
dZ/dt	2.4 $\pm$ 0.7	2.6 $\pm$ 0.8
ET	230 $\pm$ 21	306 $\pm$ 25
PEP	117 $\pm$ 14	88 $\pm$ 10
Q-Z	157 $\pm$ 15	142 $\pm$ 12
HI	15 $\pm$ 5.5	19 $\pm$ 6.5
Z <sub>o</sub>	29 $\pm$ 3.7	26 $\pm$ 3.5
Z <sub>o</sub> /L	1.0 $\pm$ 0.17	0.9 $\pm$ 0.15

SV=ventricular stroke volume (CC), HR=heart rate in beats per minute, CO=cardiac output in liters per minute, CI=cardiac index, CO/body surface area (M<sup>2</sup>)=CO/M<sup>2</sup>, dZ/dt=first time derivative of thoracic impedance change ( $\Delta Z$ ) during cardiac cycle in ohms/second, (dZ/dt)<sub>min</sub> (Figure 5), ET=ventricular ejection time in milliseconds, (VET Figure 5), PEP=preejection period in milliseconds (Figure 5), Q-Z=time interval between ECG Q wave and peak dZ/dt in milliseconds (Figure 5), HI=Heather index (dZ/dt)/(Q-Z) in ohms/sec/sec, Z<sub>o</sub> thoracic impedance (ohms) between electrodes 2 and 3 (Figure 1), Z<sub>o</sub>/L=ohms/cm.

$$SV = \rho L^2 / Z_o^2 \cdot T (dZ/dt)_{min}$$

where  $\rho=150$  ohm cm, T=ejection time (see references 2 and 3), CO=SV•heart rate/1000=liters per minute

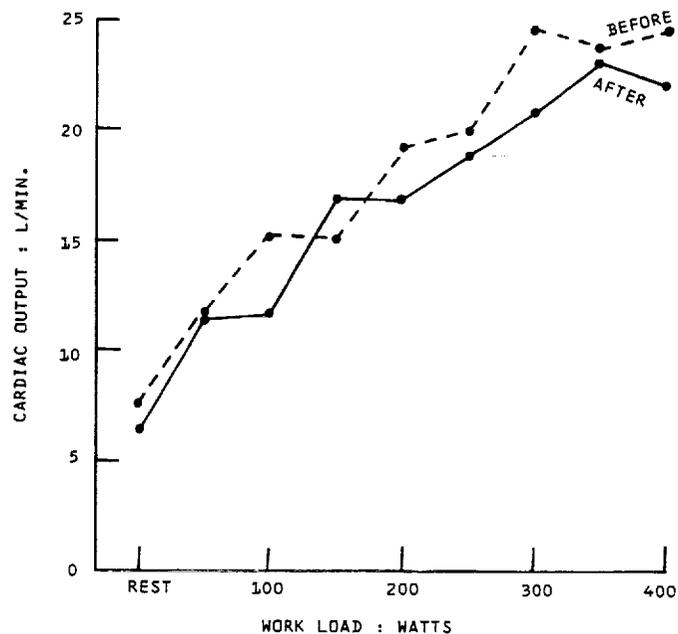
It would be reasonable to predict that immediately after reaching microgravity, the cardiovascular response would be similar to a ground-based individual changing from standing to supine. Z<sub>o</sub>

Table 1 over an extended time, any adaptation to microgravity should be apparent.

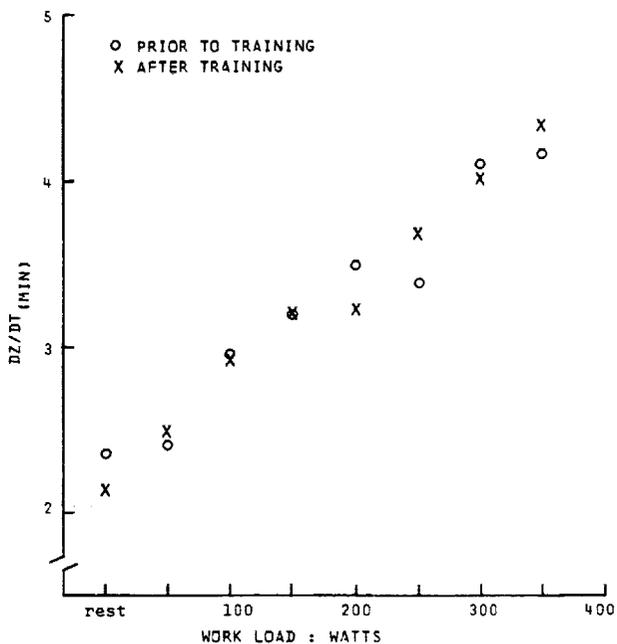
If there is any tendency toward congestive heart failure during prolonged space flight, these relatively simple measurements could be of great importance.

### **Response to Exercise of Well Conditioned Runners**

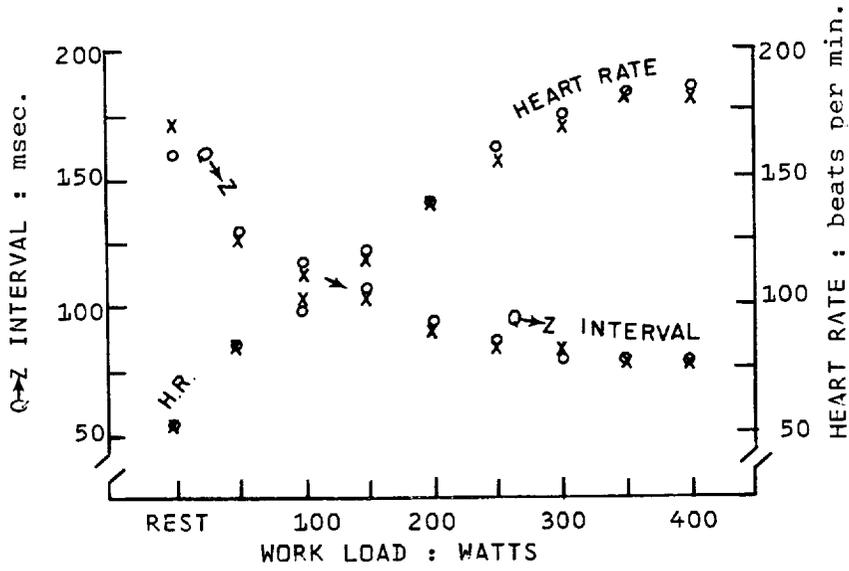
An exercise study was performed on six well-conditioned middle distance (4000 meters) runners. The primary objective was to determine if a special 6-weeks training program would improve their overall cardiac function. A perusal of the results presented graphically in Figures 6 to 10 indicates that the special training program had no effect on cardiac performance.



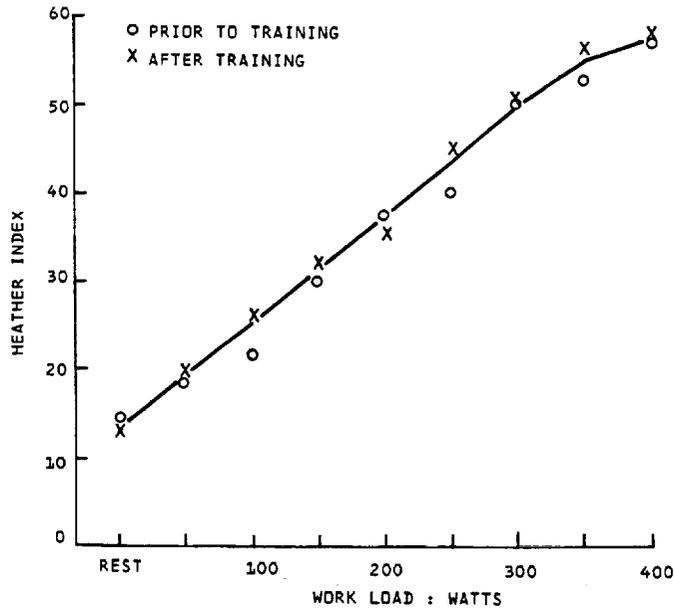
**Figure 6.** Relationship between mean cardiac output and bicycle ergometer work load for six middle distance runners before and after 6 weeks of special training.



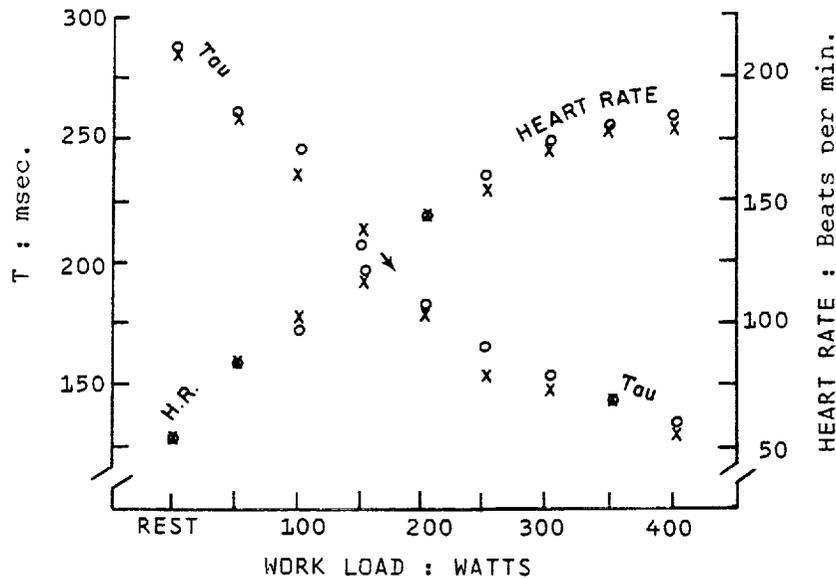
**Figure 7.** A graph showing the relationship between mean dz/dt values and increasing work loads on the bicycle ergometer for six middle distance runners before and after 6 weeks of special training.



**Figure 8.** *The relationship between the mean heart rate values and mean Q-Z interval values and increasing work loads on the bicycle ergometer for six middle distance runners before and after 6 weeks of special training.*



**Figure 9.** *A graph illustrating the relationship between the mean Heather Index values from rest to maximal bicycle ergometer exercise for six middle distance runners before and after 6 weeks of special training.*



**Figure 10.** *A graph showing the relationship between mean T (ejection time in milliseconds) values and mean heart rate values and increasing work loads on the bicycle ergometer for six middle distance runners before and after 6 weeks of special training.*

These data are presented here as an illustration of how impedance cardiography could be used in relation to space flight and microgravity. Careful and repeated ground-based testing of the response to appropriate exercise could be carried out to establish a pattern of response prior to space flight. These baseline data could then be used for comparison, either for pre- and postflight testing for short-duration flights or for onboard testing during prolonged space flight.

### Summary

Impedance cardiography is here to stay. About 500 published articles, utilizing impedance cardiography, are available. It is safe, convenient, noninvasive, and cost effective. It is the only proven method available to NASA to monitor the various parameters, described here, related to the intimate physiology of cardiac dynamics. In addition, changes in thoracic fluid volume can be followed. If desired, peripheral circulation can be studied by impedance.

Cardiac output is the historic standard for measuring cardiac mechanical function. However, changes in parameters such as the Heather contractility index (HI) may provide an early warning of impending serious myocardial dysfunction before any changes in cardiac output occur.

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## References

- [1] MILES, D. S. AND R. W. GOTSHALL. Impedance Cardiography: Noninvasive Assessment of Human Central Hemodynamics at Rest and During Exercise. In: *Exercise and Sport Sciences Reviews*, edited by K. B. Pandolf. Baltimore, MD: Williams & Wilkens, 1989, p. 231-263.
- [2] KUBICEK, W. G., J. M. KARNEGIS, R. P. PATTERSON, D. A. WITSOE, AND Evaluation of an Impedance Cardiac Output System. *Aerospace Medicine* 37:1208-1212, 1966.
- KUBICEK, W. G., F. J. KOTTKE, M. U. RAMOS, R. P. PATTERSON, D. A. WITSOE, J. W. LABREE, W. REMOLE, T. E. LAYMAN, H. SCHOENING, AND J. T. GARAMELLA. The Minnesota impedance cardiograph-theory and applications. *Biomedical Engineering* 9:410-416, 1974.

## Acknowledgment

The material shown in Figures 4, 6, 7, 8, 9, 10, is part of an unpublished Ph.D. thesis study carried out in our laboratory by Robert Tracy (1971).

