IMPEDANCE CARDIOGRAPHY AS A NONINVASIVE METHOD OF MONITORING CARDIAC FUNCTION AND OTHER PARAMETERS OF THE CARDIOVASCULAR SYSTEM*

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Classical physiology texts describe the basic function of the heart as a blood pump. Ironically, after centuries of research since William Harvey's disclosure of the nature of the circulatory system,[1] the pumping action of the heart remains an elusive parameter to measure without resorting to inconvenient, expensive, and somewhat traumatic procedures requiring sterile surgery to insert catheters into or near the heart. At the same time, relatively simple, noninvasive methods are available to record other parameters related to myocardial function such as electrical activity, pulse rate, and blood pressure. Obviously, a great need exists for a similarly simple noninvasive method of obtaining information concerning the mechanical activity of the heart.

About 300 years elapsed following Harvey's classic experiment before Atzler and Lehmann attempted to utilize small transthoracic electrical impedance changes observed during the cardiac cycle to study myocardial function by a capacitance system.[2] Nyoboer and co-workers[3,4] and others[5] later modified and improved on this work. Geddes and Baker have published an excellent review of the use of electrical impedance measurements in the detection of a variety of physiological events.[6]

A previous report[7] presents our first results with the present impedance system to measure cardiac output by a somewhat different approach. Smith and colleagues,[8] Harley and associates,[9] and Judy and co-workers[10] have reported varying degrees of success in measuring cardiac output with this approach. Siegel and Fabian[11] have reported on the application of this system to the quantification of myocardial contractility. We have also reported on the time relations between left ventricular ejection and the negative value of dZ/dt.[12]

The purpose of this communication is to present the system described as the impedance cardiograph that has evolved after several years of research in this laboratory and some of its applications to measurements of parameters related to the cardiovascular system.

The four-band electrode configuration is shown in FIGURE 1. Conductive strip electrodes, approximately 6 mm wide, are placed, two around the neck and two around the abdomen. The outer two electrodes are spaced at least 3 cm away from the inner electrodes in order to obtain accurate readings and to avoid nonlinearities in the electrical parameters involved. Of the inner two electrodes, one is placed around the base of the neck and the second at the level of the xiphisternal joint. The outer two electrodes are positioned as shown. The electrodes are numbered 1, 2, 3, and 4 from the neck down and are connected to the impedance cardiograph by the appropriate, numbered clips on the patient-connecting cable of the instrument.

A disposable tape-on electrode has been fabricated by the 3M Company, St. Paul, Minn. The electrode is constructed from one mil aluminum deposited on a polyester film and bonded to an adhesive backing, and usually does not require

* Supported by National Aeronautics and Space Administration contract NAS 9-4500 and Social and Rehabilitation Service grant RT-2.

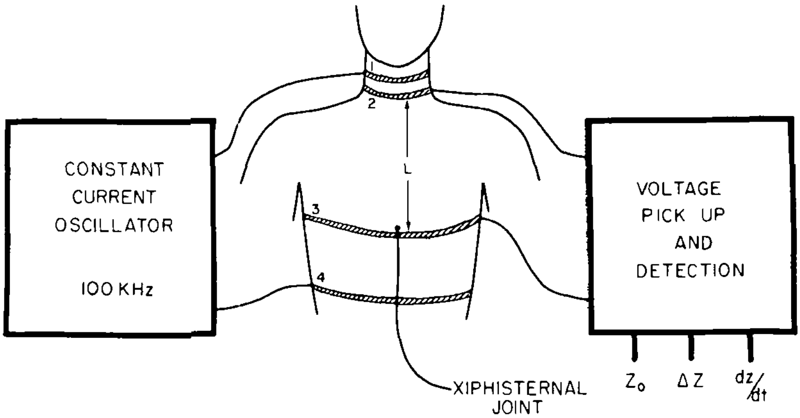

FIGURE 1. A diagram of the electrode configuration and the basic electrical cricuits.

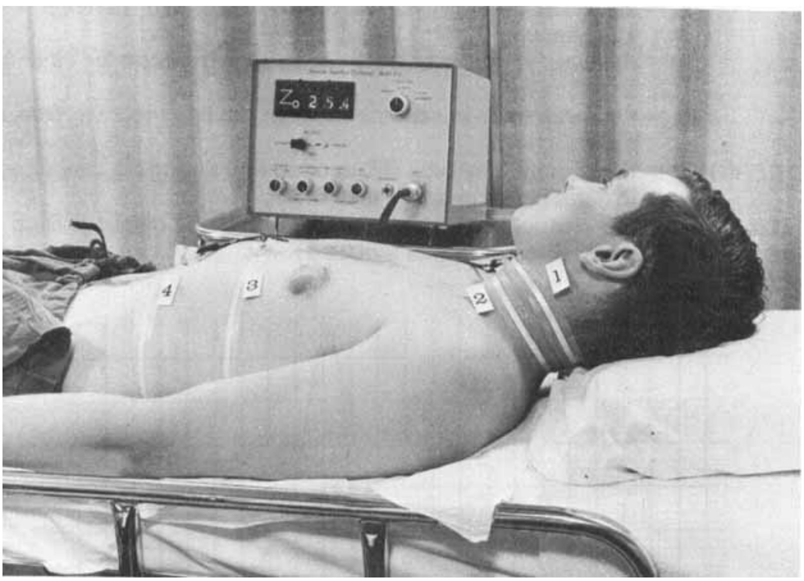

FIGURE 2. A photograph of the tape-on electrodes in place. It is important to maintain good separation between electrodes 1 and 2. This electrode configuration is used for obtaining 1) cardiac function data and 2) changes in total fluid in the chest by observing Z_0 (the total impedance between electrodes 2 and 3). The Z_0 measurement has been found to be a very sensitive indicator of the development or reversal of such conditions as pulmonary edema, pulmonary congestion, and pleural effusion.

electrode paste for thoracic impedance measurements. The electrode is lightweight and comfortable and possesses adequate electrical characteristics for transthoracic and limb impedance measurements. The tape-on electrodes are positioned on the subject as shown in FIGURE 2. The electrodes are easily attached to the impedance cardiograph by means of alligator clips on the patient-connecting cables.

A constant-current oscillator transmits a sinusoidal alternating current of 4 milliamperes at 100 kilohertz through the chest between electrodes 1 and 4. A voltage drop is then generated between electrodes 2 and 3 proportional to the product of the current times the magnitude of the impedance (Z_0) between electrodes 2 and 3. This voltage is then sensed by the high-input impedance (100 k ohms) amplifiers in the detection system. An average value of Z_0 in a healthy adult is about 25 ohms. At rest, this value will decrease by about 0.1–0.15 ohms during the cardiac cycle (ΔZ). In our experience, we have not been able to equate the magnitude of ΔZ to stroke volume. However, use of the peak negative value of the first time derivative of ΔZ (dZ/dt) has yielded variable but encouraging degrees of success in the calculation of ventricular stroke volume and cardiac output.[7-10] Stroke volume is calculated from the following equation:

$$\Delta V = \rho \frac{L^2}{Z^2} T(dZ/dt)_{min}$$

where

ΔV = ventricular stroke volume (cc);
ρ = the electrical resistivity of blood at 100 kHz (average value 150 ohm-cm);
L = the mean distance between the two inner electrodes (2 and 3) in cm;
Z_0 = the mean body impedance between the two inner electrodes in ohms;
$(dZ/dt)_{min}$ = the minimum value of dZ/dt occurring during the cardiac cycle in ohms per second (see FIGURE 3);
T = the ventricular ejection time in seconds as obtained from the dZ/dt wave form (see FIGURE 3).

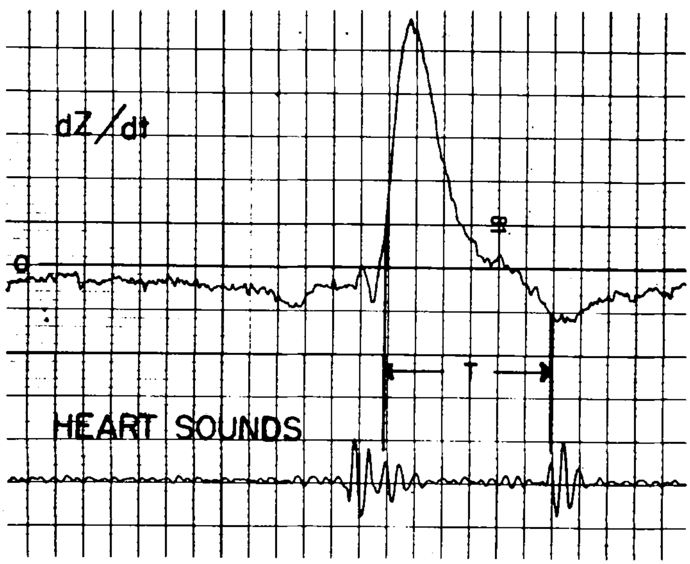

FIGURE 3. A dZ/dt wave form where there is not a positive point that clearly shows the end of the ventricular ejection.

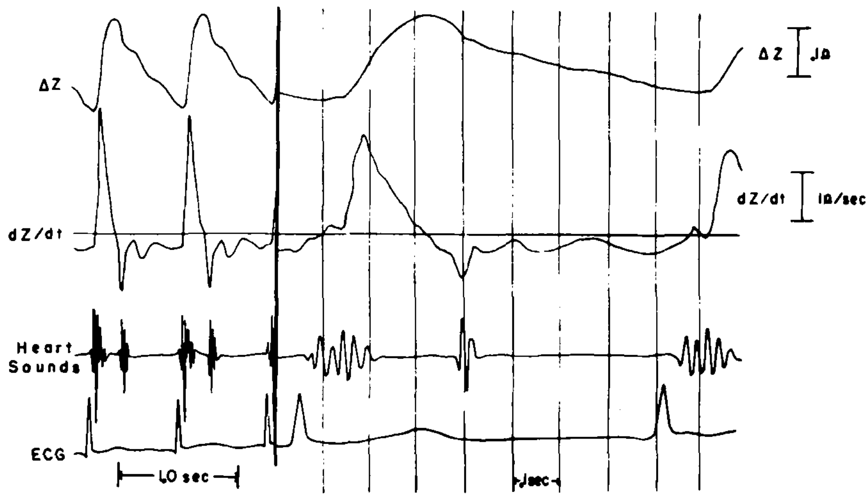

FIGURE 4. A record of ΔZ, dZ/dt, heart sounds and ECG waveforms. The time relation of the impedance information with respect to the heart sounds and ECG can be seen. Negative is upward in both the ΔZ and dZ/dt wave forms.

Cardiac output is calculated from the stroke volume and pulse rate as shown below:

$$\begin{aligned} \text{C.O.} &= \Delta V \cdot \text{PR}/1000; \\ \text{C.O.} &= \text{cardiac output in liters/min}; \\ \Delta V &= \text{stroke volume in cc}; \\ \text{PR} &= \text{pulse rate in beats/min}. \end{aligned}$$

A typical recording of ΔZ, dZ/dt heart sounds and the ECG is shown in FIGURE 4.

The value of $(dZ/dt)_{min}$ is measured from zero to the most negative point (negative is upward) on the waveform illustrated in FIGURE 5. The ventricular ejection time T is measured in time from $.15(dZ/dt)_{min}$ to the most positive peak of dZ/dt. The starting point for determining T is obtained by going back in time down the dZ/dt wave form from the negative peak to a point on the curve equal to $.15(dZ/dt)_{min}$. The zero crossing of dZ/dt before the negative peak could also be used, but because of occasionally small oscillations in the wave form before the large negative peak, $.15(dZ/dt)_{min}$ is a more reliable point. The difference between the two is usually small. The end of T is usually determined from the sharp positive point in the dZ/dt waveform after $(dZ/dt)_{min}$ as shown in FIGURE 5. With some subjects, no single sharp positive point is apparent. Therefore, the dZ/dt waveform cannot be used accurately to determine the end of ventricular ejection.

FIGURE 3 shows a (dZ/dt) wave form where there is not a positive point that clearly shows the end of ejection. In such cases the beginning of the second heart sound is used to indicate the end of ejection.

The impedance cardiograph can also be used as a visual monitor of the mechanical action of the heart. The ΔZ and dZ/dt recordings can indicate a variety of cardiac irregularities. An example of pulsus alternans in a dog is shown in FIGURES 6 and 7. Note that the pulsus alternans was not indicated by the ECG recording.

The impedance cardiograph has also been used to study circulation in the legs. An example of the unit in use as a venous occlusion plethysmograph is shown in FIGURE 8. The same electrode arrangement can be used to study leg volume changes (between electrodes 2 and 3) during the application of lower-body negative pressure or gravitational forces. The valsalva maneuver also results in leg volume changes. The instrument can also be used in peripheral circulatory disease by observing the difference between recordings of ΔZ and dZ/dt in normal and abnormal conditions. FIGURE 9 shows examples of the ΔZ output recordings during venous occlusion and the valsalva maneuver.

For best results it is recommended that ECG electrode paste be used for limb impedance recordings, especially in cases where hair is present. The circuits are designed primarily for transthoracic impedance recordings, and therefore some precautions should be observed in attempting to use the system on the extremities.

The following formula has been used to calculate the leg volume change between electrodes 2 and 3:

$$\Delta V = \rho \frac{L^2}{Z_0^2} \Delta Z_1 = cc$$

where

ρ = 220 ohm-cm (with more research this value may be changed);
L = the distance (cm) between electrodes 2 and 3;
Z_0 = the total impedance between electrodes 2 and 3;
ΔZ_1 = the impedance change during the applied stress.

The blood-flow rate into the limb segment between electrodes 2 and 3 can be calculated from $\Delta V/\Delta T$, where T = the time interval for the impedance change ΔZ_1 to occur.

A new application of impedance measurements to the cardiovascular system is developing in the area of detection of changes in fluid volume in the chest. With

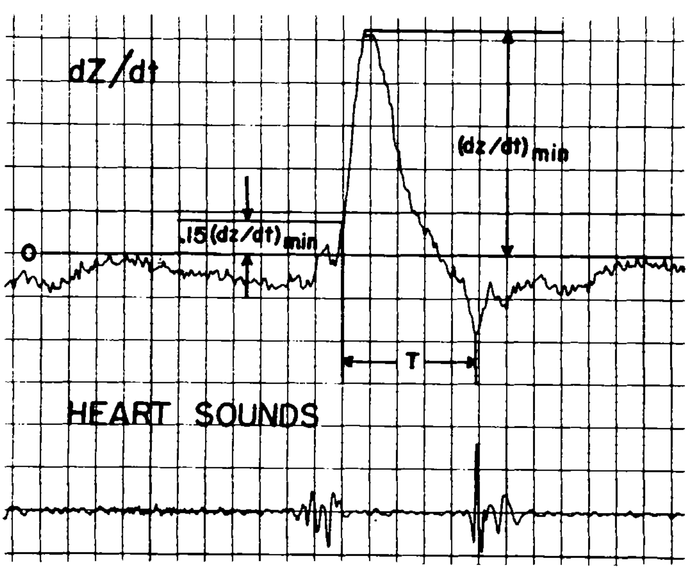

FIGURE 5. A typical dZ/dt wave form along with the heart sounds.

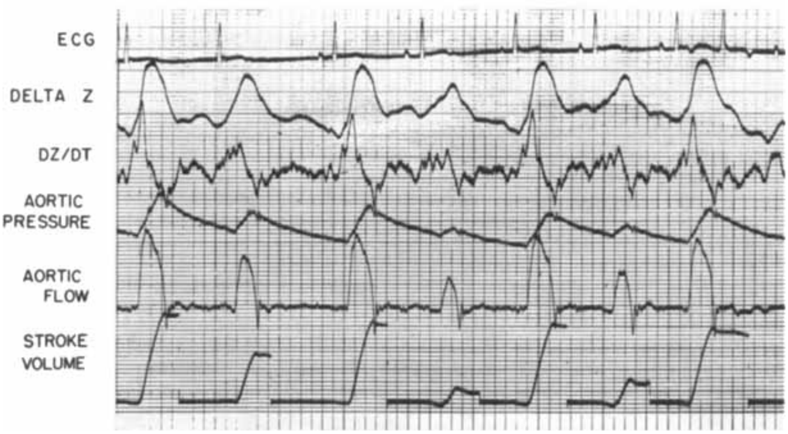

FIGURE 6. A record of the ECG, ΔZ (dZ/dt), aortic pressure, ascending aortic flow, and left ventricular stroke volume in an anesthetized dog. Note that the ECG record gives no hint of the pulsus alternans clearly indicated in the (dZ/dt), aortic pressure, aortic flow, and stroke volume tracings.

FIGURE 7. The same record as in FIGURE 6 except that only the ECG and (dZ/dt) tracings are included better to illustrate the use of the (dZ/dt) output as a visual monitor of cardiac mechanical irregularities not evidenced by the ECG.

the electrode configuration described in FIGURES 1 and 2, it has been found that the transthoracic impedance Z_0 is a very sensitive indicator of changes in the volume of fluid in the chest. Pilot experiments in our laboratory (FIGURE 10) resulted in a sharp decrease in the value of Z_0 when saline was injected into the chest of an anesthetized dog. It had also been observed that the value of Z_0 increased following the removal of pleural effusion as evidenced by x-ray.

Pomerantz and associates[13] have reported a more complete study in which they produced pulmonary edema in dogs and concluded that the impedance system as described here could be used for the early detection of pulmonary edema.

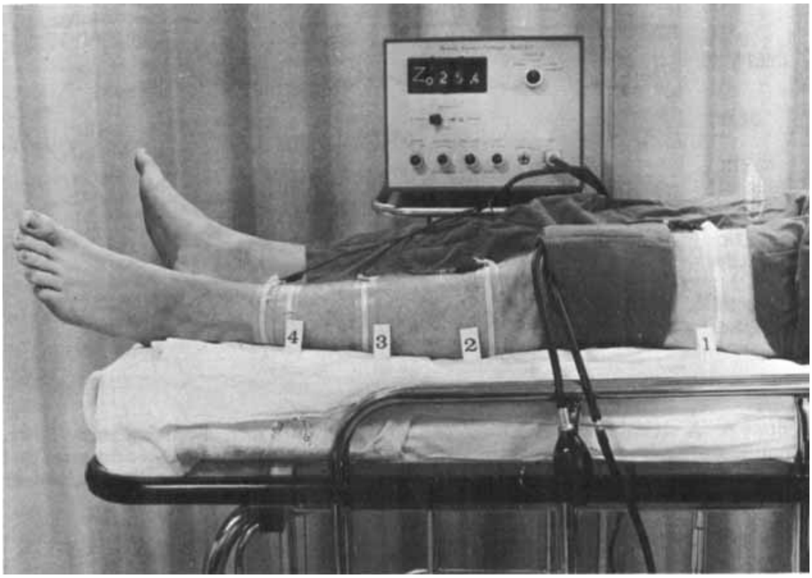

FIGURE 8. A view of the four electrodes in place to record leg volume changes between electrodes 2 and 3 as a result of inflating the blood pressure cuff between electrodes 1 and 2.

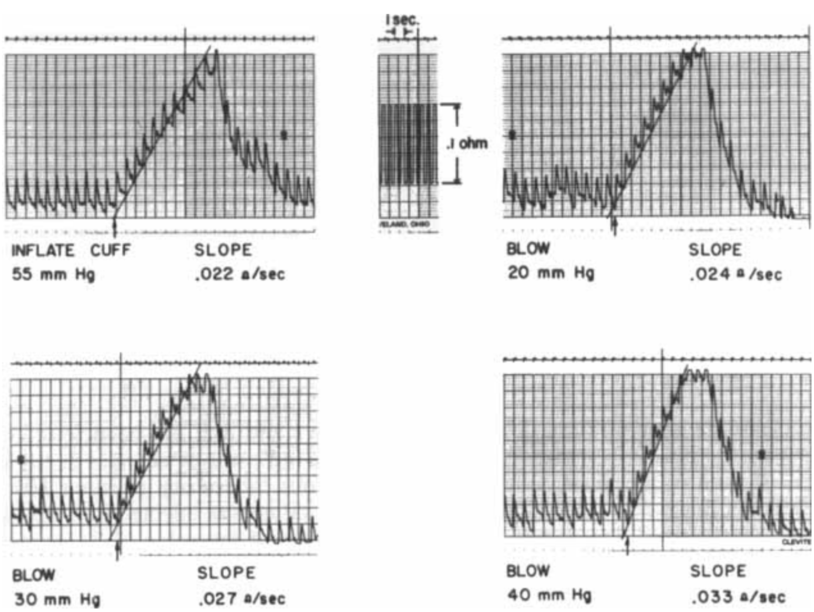

FIGURE 9. Minnesota impedance cardiograph: Records obtained from the electrode placement shown in FIGURE 8 by: 1) inflating the cuff to 55 mmHg; 2) after deflating the cuff, the subject blew (with the glottis open) 20, 30, and 40 mm Hg.

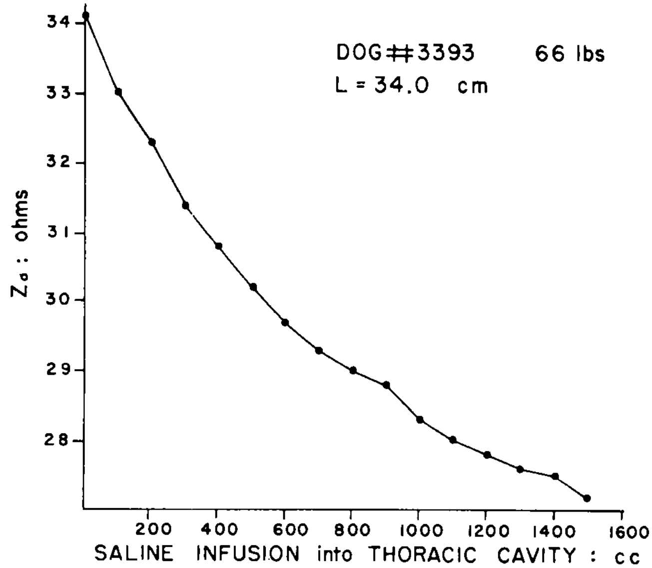

FIGURE 10. An example of the decrease in the value of Z_0 resulting from a saline infusion into a dog's chest. Similar changes in Z_0 have been observed by Pomerantz and associates[18] during the development of experimental pulmonary edema. The reversal of these conditions then results in an increase in the value of Z_0.

DISCUSSION

One limitation of the impedance technique for the measurement of fluid changes in the chest is that it probably cannot indicate the exact location of a collection of fluid such as blood, edema fluid, or pleural effusion. The main advantage of this approach is in the sensitivity of the transthoracic impedance to relatively small changes in total fluid content of the chest. This should provide for an early warning for such conditions as developing pulmonary edema or pulmonary congestion. Additionally, the reversal of these conditions can be followed by the increases in thoracic impedance.

There is a great potential role for this system in monitoring overall cardiac function and myocardial dynamics. Similarly, it appears that the system will find many applications in studies on the peripheral vascular system.

REFERENCES

1. HARVEY, W. 1628. Exercitatio Anatomica de motu cordis et sanguinis in animalibus. Frankfurt, Germany.
2. ATZLER, E. & G. LEHMANN. 1932. Über ein neues verfahren zur darstellung der herztätigkeit (dielektrographie). Arbeitsphysiologie **6:** 636–680.
3. NYBOER, J., S. BAGNO, A. BARNETT & R. H. HALSEY. 1940. Radiocardiograms—the electrical impedance changes of the heart in relation to electrocardiograms and heart sounds. Amer. Soc. Clin. Inv. **19:** 773.
4. NYBOER, J. 1959. Electrical Impedance Plethysmography. Charles C Thomas. Springfield, Ill. 243 pp.
5. WHITEHORN, W. V. & E. R. PERL. 1949. The use of change in capacity to record cardiac volume in human subjects. Science **109:** 262–263.

6. GEDDES, L. A. & L. E. BAKER. 1968. Principles of Applied Biomedical Instrumentation. : 150–205. John Wiley & Sons. New York, N. Y.
7. KUBICEK, W. G., J. M. KARNEGIS, R. P. PATTERSON, D. A. WITSOE & R. H. MATTSON. 1966. Development and evaluation of an impedance cardiac output system. Aerospace Med. **37**: 1208–1212.
8. SMITH, J. J., V. T. WIEDMEIER, F. E. TRISTANI & K. E. COOPER. 1968. Measurement of cardiac output during body tilt using the impedance cardiograph. Fed. Proc. **28**: 643.
9. HARLEY, A. & J. C. GREENFIELD, JR. 1968. Determination of cardiac output in man by means of impedance plethysmography. Aerospace Med. **39**: 248–252.
10. JUDY, W. V., F. M. LANGLEY, K. D. MCCOWEN, D. M. STINNETT, L. E. BAKER & P. C. JOHNSON. 1969. Comparative evaluation of the thoracic impedance and isotope dilution methods for measuring cardiac output. Aerospace Med. **40**: 532–536.
11. SIEGEL, J. H. & M. FABIAN. 1968. The quantification of myocardial contractility by impedance plethysmography. Fed. Proc. **27**: 445.
12. KUBICEK, W. G., A. H. L. FROM, R. P. PATTERSON, A. CASTANEDA, R. C. LILLEHEI & R. ERSEK. 1969. Impedance cardiography as a non-invasive means to monitor cardiac function. American Association for Advancement of Medical Instrumentation. In press.
13. POMERANTZ, M., R. BAUMGARTNER, J. LAURIDSON & B. EISEMAN. 1969. Transthoracic electrical impedance for early detection of pulmonary edema. Surgery **66**: 260–268.