Simultaneous Evaluation of Cardiac Wall Motion and Myocardial Ischemic Injury by Measurement of Electrical Impedance

EISAKU SASAKI, JEFF L. CONGER, KAMURAN A. KADIPASAOGLU, SECKIN PEHLIVANOGLU, AND O. H. FRAZIER

The authors devised a new method to simultaneously evaluate cardiac wall motion and myocardial ischemic injury by measurement of myocardial electrical impedance. This method is based on the principle that electrical properties of the myocardium are affected by intra- or extracellular structure. Impedance was assessed by measuring voltage while a constant alternating current (0.4 mA, 50 kHz) was being applied to the myocardium by way of an electrode that had two parallel 6 mm long needles. In five dogs, an electrode was placed in the left ventricular wall, adjacent to a pair of ultrasonic crystals that were used to estimate regional wall thickness. To change regional contractility and to induce ischemic injury, the left anterior descending coronary artery was ligated. The impedance waveforms were observed to be synchronized with cardiac contraction, and changes in impedance correlated well with changes in wall thickness. Dyskinetic movements in the ischemic myocardium could also be detected through assessment of the impedance waveform. During the first 2 hr, the average value of impedance increased significantly, from 254 ± 38 Ω-cm to 329 ± 13 Ω-cm ($P < 0.005$), and then decreased, indicating a correlation with the progression and irreversibility of ischemic injury. This simple technique may eventually allow us to simultaneously assess cardiac wall motion and myocardial ischemia in humans. *ASAIO Journal* 1994;40: M826–M829.

The electrical properties of tissue are influenced by multiple factors, such as changes in cellular and tissue structure or changes in the content or volume of extracellular and intracellular fluid. In the heart, cardiac contraction causes structural shifts, such as changes in myocardial wall thickness, and, thus, may affect the electrical properties of the myocardium. Ischemia can cause other changes in the electrical properties of the myocardium. For example, edema resulting from ischemia can cause cells to swell and, ultimately, to burst.[1-4] Many reports of *in vitro* and *ex vivo* studies[5-8] have described electrical changes under such conditions. Thus, monitoring the electrical properties of the ischemic myocardium may allow us to obtain useful information about kinetic function and to assess the extent of tissue damage. We conducted a study to evaluate a new method for the simultaneous assessment of regional myocardial wall motion and the detection of the progression of myocardial tissue damage by monitoring myocardial electrical impedance.

From the Cullen Cardiovascular Research Laboratories, Texas Heart Institute, Houston, Texas.

Reprint requests: Eisaku Sasaki, The Cullen Cardiovascular Research Laboratories, Texas Heart Institute, P.O. Box 20345, Mail Code 1-268, Houston, TX 77225-0345.

Methods and Materials

Five mongrel dogs weighing 27–34 kg (29.8 ± 2.4 kg) were anesthetized and intubated. They were placed on a volume cycled respirator and isoflurane was used to maintain adequate anesthesia. Electrocardiographic activity was monitored. Left ventricular pressure was measured with a micromanometer tipped catheter (Millar Instruments, Houston, TX) inserted in the left ventricle through the carotid artery. dp/dt was monitored by the left ventricular pressure differential.

The heart was exposed through a left thoracotomy. Next, a tourniquet was placed loosely around the left anterior descending (LAD) artery, just above the second diagonal branch. To measure changes in regional wall thickness, a pair of ultrasonic crystals (Triton Technology Inc., San Diego, CA) were placed in the projected distribution of the LAD distal to the ligature. A second pair, which served as a control, was placed in normal left lateral ventricular myocardium. Electrical impedance was measured by placing two electrodes in the left ventricular wall, adjacent to each pair of crystals **(Figure 1).** Each electrode had two needles placed in parallel (radius of each needle, 0.225 mm; length of needles, 6 mm; distance between needles, 5 mm). Electrical impedance was measured by voltage while constant alternating current (0.4 mA, 50 kHz) was being applied to the myocardium by way of the electrodes. The electrodes were calibrated before placement with standard solutions to calculate the specific resistivity from the measured impedance value. Electrical impedance was measured intermittently to avoid polarization between the electrode and myocardium. All hemodynamic data and waveforms obtained through the ultrasonic crystals and electrodes were recorded with a polyrecorder (Gould Inc., Cleveland, OH). After baseline mea-

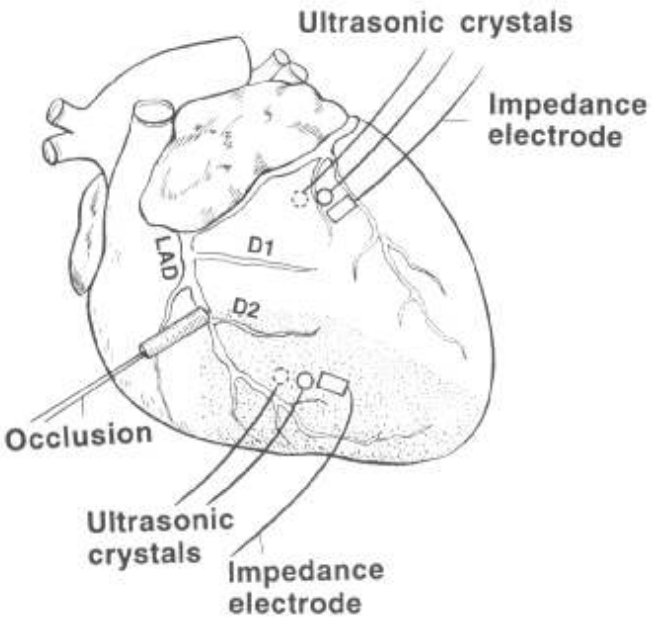


Figure 1. Schematic of installation of electrodes and ultrasonic crystals (LAD = left anterior descending coronary artery, D1 = first diagonal branch, D2 = second diagonal branch).

surements, the LAD was occluded with the tourniquet and regional ischemia was induced. All parameters were measured for up to 6 hr after coronary occlusion.

We evaluated the impedance waveform in regard to 1) specific resistivity (Ω-cm) calculated from the average value of impedance and 2) the amplitude of the phasic impedance waveform that synchronized with cardiac contraction. The amplitude of the impedance waveform and the change in wall thickness, measured with the ultrasonic crystals, were digitized every 1/250 sec. Then, these measurements were standardized to determine whether there were similarities between them. During two or three phasic cycles (two or three heart beats), minimum and maximum values of these measurements were defined as 0 and 100%, respectively, and the correlation coefficients between plots of these standardized waveforms were calculated.

The paired t-test was used to examine differences in the specific resistivity between the ischemic myocardium and the normal myocardium.

Results

The change in amplitude of the impedance waveform ranged from 5 to 20 Ω in normal myocardium. **Figure 2** shows hemodynamic parameters and impedance waveforms in normal and ischemic myocardium, as well as ultrasonic crystal measurements of the wall thickness. Inverted impedance waveforms are shown in **Figure 3** to make it easier to compare the similarities with changes in wall thickness. The impedance waveform in normal myocardium was highly synchronized with changes in wall thickness: there was a strong negative correlation between the amplitude of the impedance waveform and wall thickness ($r^2 = 0.840$) **(Figure 4).** In ischemic myocardium, dyskinetic motion was indicated by decreases in wall thickness during systole **(Figure 2).** The impedance waveform clearly reflects the phenome-

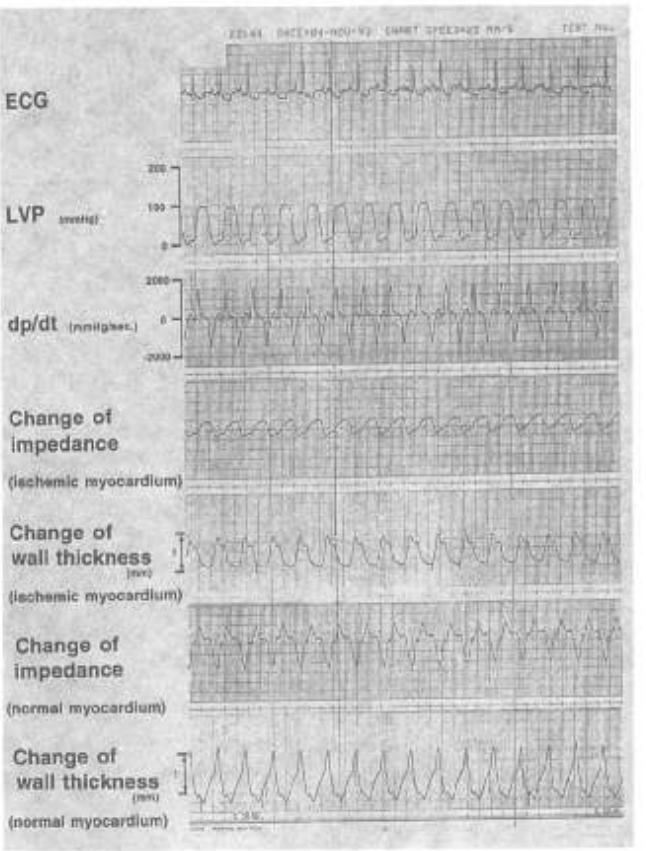


Figure 2. Records of hemodynamic data, changes in impedance, and wall thickness (dog, 29 kg) (ECG = electrocardiogram, LVP = left ventricular pressure, dp/dt = differential of LVP).

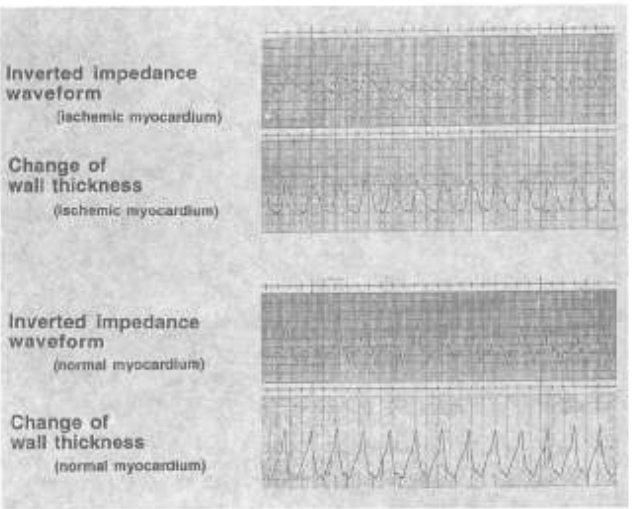


Figure 3. Inverted impedance waveforms and changes in wall thickness (dog, 29 kg).

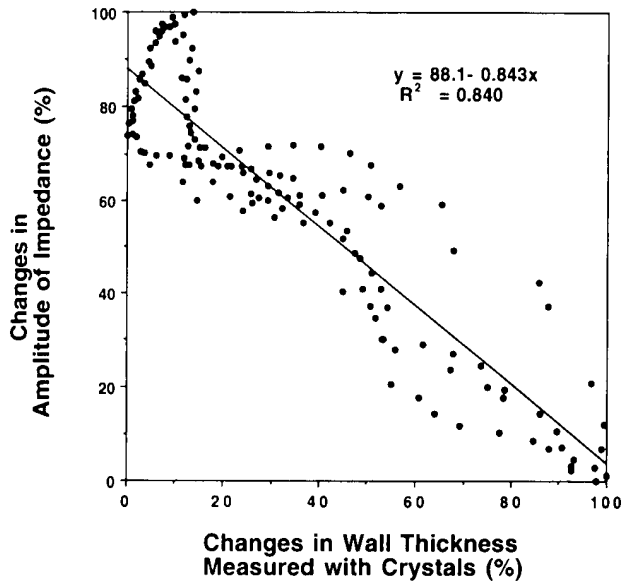


Figure 4. Relationship between changes in amplitude of impedance waveform and changes in wall thickness in normal myocardium (dog, 29 kg).

non of bulging. There was a strong negative correlation between the amplitude of the impedance waveform and wall thickness ($r^2 = 0.735$) **(Figure 5).**

In all dogs, the amplitude of the impedance waveform was highly correlated with wall thickness in normal myocardium ($r^2 > 0.718$) and ischemic myocardium ($r^2 > 0.706$).

During the first 2 hr after coronary ligation in five dogs, the specific resistivity progressively increased, from 254 ± 38 Ω-cm to 329 ± 13 Ω-cm ($P < 0.005$). Significant differences

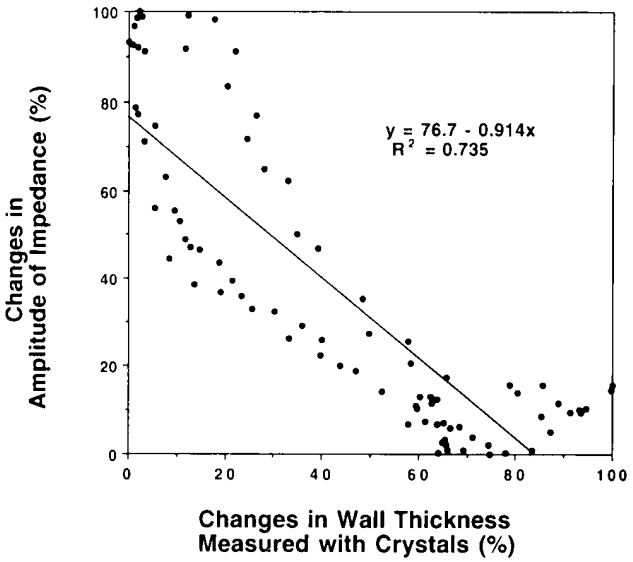


Figure 5. Relationship between changes in amplitude of impedance waveform and changes in wall thickness in ischemic myocardium (dog, 29 kg).

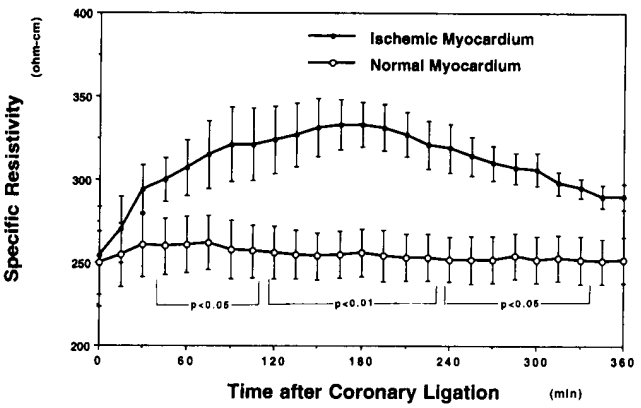


Figure 6. Changes in specific resistivity.

between normal myocardium and ischemic myocardium appeared after 45 min of coronary ligation. After 3 hr, the specific resistivity began to progressively decrease **(Figure 6).**

Discussion

The electrical properties of tissue are determined by various factors, including tissue structure, components and volume of the extracellular and intracellular fluid, the resistivity and capacity of the cell membrane, temperature, and frequency of the charging current. When charged with alternating current, a cell membrane that has high resistivity works as resistance or capacitance, and the extracellular fluid that has low resistance works mainly as conductance. In the myocardium, electrical properties are affected by structural factors, including changes induced by physiologic contraction and changes caused by ischemia. Many investigators have measured the electrical impedance of the myocardium using isolated muscle bundles, isolated hearts, and *in situ* preparations to clarify the electrical properties of the myocardium and to assess the viability of ischemic myocardium.[5-10]

Myocardial ischemia causes intracellular myocardial edema, which enlarges the intracellular space and decreases extracellular space.[1-4,7] When ischemia is induced, resistivity increases. Prolonged ischemia causes malfunction and destruction of the cell membrane and changes in ion concentrations, and the cell bursts. Consequently, decreases in resistivity are correlated with the progression and irreversibility of ischemic injury. We were able to measure these changes clearly by use of a simple two needle electrode probe, and our data agree with previously reported results.[6-8]

We also used myocardial impedance to assess wall motion. The amplitude of the impedance waveform correlated highly with wall thickness, as measured with ultrasonic crystals. Why myocardial impedance reflects wall motion or wall thickness is difficult to establish. In our study, several factors influenced measurement of wall motion with electrical impedance:

1. Changes in the cross section of myocardium between electrodes. As wall thickness increases, the resistance between the needle electrodes may decrease because of the larger cross section through which the electrical current runs.
2. Distance between electrode needles. Electrode needles inserted during systole may be closer to one another, and this shorter distance may reduce resistance.
3. Myocardial blood volume. The volume of blood in the myocardial sinusoids may change during cardiac contractions. During ejection, the volume of blood, which has high conductivity, decreases and, thus, may cause impedance to increase. This theory was not supported by our findings; impedance decreased during systole in our experiments.
4. Changes in direction and shape of muscle fibers. Myocardium consists of muscle fibers. Thus, it has been proposed that the electrical impedance of the heart has anisotropy, according to the direction of electrical current. During cardiac contraction, the orientation of muscle fibers changes, as does the dimension of muscle fiber, which may influence myocardial impedance.

Although we do not know which factors had the most influence on our results, the changes in impedance correlated well with changes in wall thickness. Further studies are necessary to clarify these findings. Some papers have reported that it is impossible to detect changes in specific resistance of myocardium between systole and diastole.[8,10] In those studies, specific resistivity was measured in a small area, such as in an intramural region. Differences in the size of the measured area may be one reason why wall motion can be detected with electrical impedance and, also, that no distinctive differences in impedance were observed when we changed the direction of the electrodes.

Many methods have been investigated to assess ischemic injury and revivability of myocardium in real time function using intramural pH or PCO_2.[11-13] However, these techniques could not assess kinetics in ischemic myocardium. Our simple techniques with needle electrodes allowed us to easily measure myocardial electrical impedance. In addition, the extent of myocardial ischemic injury and changes in wall motion correlated well with changes in wall thickness. Placing the needle electrode was easier than installing a pair of ultrasonic crystals, which required strict control for proper placement. This method may be useful for assessing local myocardial ischemia and for measuring myocardial kinetics during coronary artery bypass surgery.

References

1. Jennings RB: Cell volume regulation in acute myocardial ischemic injury. *Acta Med Scand* 587 (suppl):83-93, 1976.
2. Jennings RB, Ganote CE: Structural changes in myocardium during acute ischemia. *Circ Res* 34:III-156 III-172, 1974.
3. Whalen Jr DA, Hamilton DG, Ganote CE, Jennings RB: Effect of a transient period of ischemia on myocardial cells. *Am J Pathol* 74:381-398, 1974.
4. Tranum-Jensen J, Janse MJ, Fiolet JWT, Krieger WJG, Naumannd'Alnoncourt C, Durrer D: Tissue osmolality, cell swelling, and reperfusion in acute regional myocardial ischemia in the isolated porcine heart. *Circ Res* 49:364-381, 1981.
5. Garrido H, Sueiro J, Rivas J, Vilches J, Romero JM, Garrido F: Bioelectrical tissue resistance during various methods of myocardial preservation. *Ann Thorac Surg* 36:143-151, 1983.
6. Gebhard MM, Gersing E, Brockhoff CJ, Schnabel A, Bretschneider HJ: Impedance spectroscopy: a method for surveillance of ischemia tolerance of the heart. *Thorac Cardiovasc Surg* 35:26-32, 1987.
7. Ellenby MI, Small KW, Wells RM, Hoyt DJ, Lowe JE: On-line detection of reversible myocardial ischemic injury by measurement of myocardial electrical impedance. *Ann Thorac Surg* 44:587-597, 1987.
8. Fallert MA, Mirotznik MS, Downing SW, *et al*: Myocardial electric impedance mapping of ischemic sheep hearts and healing aneurysms. *Circulation* 87:199-207, 1993.
9. Geddes LA, Barker LE: The specific resistance of biological material—a compendium of data for the biomedical engineer and physiologist. *Med Biol Eng* 5:271-293, 1967.
10. van Oosterom A, de Boer RW, van Dam RT: Intramural resistivity of cardiac tissue. *Med Biol Eng Comput* 17:337-343, 1979.
11. Khuri SF, Kloner RA, Hillis D, *et al*: Intramural PCO_2: a reliable index of the severity of myocardial ischemic injury. *Am J Physiol* 237:H253-H259, 1979.
12. Magovern GJ, Flaherty JT, Kanter KR, Schaff HV, Gott VL, Gardner TJ: Assessment of myocardial protection during global ischemia with myocardial gas tension monitoring. *Surgery* 92:373-379, 1982.
13. Lange R, Kloner RA, Zierler M, Carlson N, Seiler M, Khuri SF: Time course of ischemic alterations during normothermic and hypothermic arrest and its reflection by on-line monitoring of tissue pH. *J Thorac Cardiovasc Surg* 86:418-434, 1983.