Effect of Epicardial Patch Electrodes on Transthoracic Defibrillation

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To improve survival rates in patients undergoing surgical ablative procedures for malignant ventricular tachycardia (VT), a frequent practice is to implant epicardial patch electrodes at the time of map-guided surgery. After operation, patients with inducible VT often receive an automatic internal cardioverter/defibrillator (AICD) implant, whereas patients with noninducible VT usually do not. In the event that spontaneous, hypotensive VT or ventricular fibrillation should subsequently occur in the patient with noninducible VT, however, transthoracic defibrillation and resuscitation may prove difficult, because the patch electrodes are insulated with silicone rubber that can reduce the amount of current traversing the myocardium and thus can increase transthoracic defibrillation threshold (DFT). In this study, DFT was determined in mongrel dogs to test the hypothesis that epicardial patch electrodes elevate threshold. This study was also designed to assess the effect of patch electrode orientation and size on DFT. In the first protocol (perpendicular orientation), small epicardial patch electrodes (surface area, 30 cm²) were sutured to the epicardial surfaces of the anterior right and posterior left ventricles in 15 dogs so that the center axes of the patch electrodes were coincident and perpendicular to the coincident center axes of the transthoracic electrodes. The effect of two large epicardial patch electrodes (surface area, 53 cm²) on transthoracic DFT was also examined in eight of these dogs. In the second protocol (parallel orientation), small patch electrodes were sutured to the lateral surfaces of the right and left ventricles in seven dogs. In this orientation, the center axes of the epicardial and transthoracic electrodes were coincident and passed through the center of the heart. In protocol 1, small epicardial patch electrodes increased DFT from $100\pm38$ J (control) to $141\pm73$ J ($p=0.01$). Large patch electrodes increased DFT from $77\pm48$ J (control) to $186\pm106$ J ($p<0.01$). Three of the eight dogs could not be defibrillated after the large patches were implanted. In protocol 2, small patch electrodes increased DFT from $117\pm69$ J (control) to $190\pm98$ J ($p<0.01$). The mean percent increment in DFT due to small epicardial patches for each dog in protocol 1 was $46\pm16\%$, and in protocol 2, the increment was $80\pm16\%$. Therefore, AICD epicardial patch electrodes, regardless of orientation or size, can alter or block current flow through the heart during transthoracic defibrillation, thereby markedly increasing defibrillation energy. (Circulation 1990;81:1409–1414)

The development of the automatic implantable cardioverter/defibrillator (AICD) has had a major impact on the treatment and survival of patients with medically refractory ventricular tachycardia (VT) and ventricular fibrillation (VF). Sudden cardiac arrest survival rates at 1 year approach 98%. The most frequently implanted AICD electrode system consists of two epicardial patch electrodes sutured to the surfaces of the right and left ventricles. The AICD is often considered a primary therapeutic modality for patients with atherosclerotic heart disease and medically refractory hypotensive VT who are not suitable candidates for map-guided subendocardial resection. Recently studies have proposed that AICD epicardial patch electrodes should also be routinely implanted in patients at the time of surgical ablative procedures for VT. This recommendation is based on the rationale that if VT remains inducible after operation, a generator can then be implanted without subjecting the patient to an additional thoracotomy. In the event that VT is noninducible after operation, a generator would not be required. Should VF sub-
successively occur in patients with noninducible VT, however, an event that may occur in 10–15% of such patients,

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The tensionpressive was by calibrated with a silicone rubber sheath, their presence theoretically can alter or in some instances block the flow of current through the myocardium during transthoracic defibrillation. The purpose of this study was to test the hypothesis that epicardial patch electrodes significantly elevate transthoracic defibrillation threshold (DFT).

Methods

All studies were performed in accordance with the guidelines of the American Physiological Society. Mongrel dogs weighing 18–34 kg were anesthetized with 30 mg/kg sodium pentobarbital and with supplemental doses as required. The animals were ventilated with a respirator (Harvard Apparatus, South Natick, Massachusetts). Electrocardiographic surface lead II and arterial pressure (Statham Instruments, Oxnard, California) were continuously monitored on an electrostatic recorder (model ES-1000, Gould, Houston, Texas). Arterial blood gases were monitored at 30-minute intervals, and the ventilation volume rate and bicarbonate levels were adjusted to maintain physiologic conditions. VF was induced by introducing alternating current through a percutaneous quadripolar catheter (6F, USCI, Billerica, Massachusetts) positioned in either the right or left ventricle.

Method of Defibrillation

Shocks were delivered by a modified and commercially available defibrillator (LifePak 6, Physio-Control, Redmond, Washington). The defibrillator was calibrated in units of current and was discharged through a precision control system that regulated electrode force. Electrode area (60 cm², circular stainless steel) and force (50 N) were held constant. A fresh, thin film of electrode paste (Redux Paste, Hewlett-Packard, Palo Alto, California) covered the surfaces of the electrodes and was maintained throughout the protocol.

The current-based defibrillator utilized a constant-load current divider circuit that has been previously described. Briefly, the defibrillator is calibrated to deliver 3,000 V at 400 J across a 50-Ω load. The transthoracic resistance in each dog was determined with a single 20 A shock delivered during sinus rhythm before initiating the experimental protocol. During the protocol, variable parallel and series resistors were adjusted to deliver the desired current and simultaneously maintain a 50-Ω load to the defibrillator.

The system to control electrode force was adjusted by changing precision weights on a pair of levers. The tension of the weights was changed to a compressive force on the electrodes (located over the shaven right and left lateral chest walls at the transverse level of the heart) by a statically balanced pair of levers, each having one horizontal and one diagonal arm. All forces due to the weight of the levers and electrodes were cancelled by adjusting counterweights until the horizontal beams were statically balanced with no applied weight. Therefore, the net force at the electrodes was equal in magnitude to that supplied by the precision weights.

Transthoracic DFT was determined by a method previously described. After induction of VF, the endotracheal tube was clamped at peak inspiration before balancing the electrode system and delivering the shock. Ten seconds after induction of VF, a subthreshold shock was delivered, and the current was increased in 2 A steps until defibrillation occurred. Although DFT may not be a constant, the current-based method has shown small variability between successive trials. To facilitate the experimental protocol and reduce the number of DFT trials, thresholds in each phase of the protocol were determined during two or three consecutive trials (5-minute intervals) and were averaged. Thresholds for consecutive trials varied by approximately ±2 A.

Voltage delivered across the thorax was measured with a 1,000:1 voltage divider in parallel with the defibrillator output, and the delivered current was measured with a 0.10-Ω resistor in series with the defibrillator output. Voltage and current waveforms were displayed on a triggered-sweep storage oscilloscope (model 5113, Tektronix, Beaverton, Oregon) with a frequency response from direct current to 1 MHz.

Experimental Protocol

Protocol IA. Small epicardial patches perpendicular to transthoracic electrodes

Step 1. Control transthoracic DFT (control 1) was determined in 15 dogs. DFT was measured after a median sternotomy and pericardiotomy were first performed, followed by closure of the pericardium and chest.

Step 2. Transthoracic DFT was determined after small epicardial patch electrodes were implanted and the pericardium and sternum were closed. The patch electrodes were composed of a titanium mesh, with the outer surface insulated with silicone rubber (model 0040, Cardiac Pacemakers, St. Paul, Minnesota). The electrode surface area including insulation is 30 cm². The patch electrodes were sutured to the surfaces of the anterior right and the left posterior ventricles and were oriented longitudinal to the long axis of the heart (Figure 1A). As a result, the center axes of the epicardial and transthoracic electrodes passed through the center of the heart and were approximately perpendicular to each other. In this orientation, the epicardial patch electrodes presented minimal interference to current flow through the myocardium. The distal ends of the patch electrodes were insulated and thus did not provide a path for current flow away from the heart.
Step 3. A recontrol DFT (control 2) was determined after the epicardial patch electrodes were removed and the pericardium and chest were closed.

Protocol 1B. Large epicardial patches perpendicular to transthoracic electrodes

Step 4. In eight of the 15 dogs studied in protocol 1A, the effect of two large epicardial patch electrodes (model 0041, Cardiac Pacemakers) on transthoracic DFT was also examined. The total surface area of the electrodes including insulation was 53 cm². DFT was determined after large epicardial patches were implanted and the pericardium and chest were closed.

Step 5. A control DFT (control 3) was again determined after the large patch electrodes were removed and the pericardium and chest were closed.

Protocol 2. Small epicardial patches parallel to transthoracic electrodes

An identical protocol to protocol 1A (steps 1–3), except for the orientation of the epicardial patch electrodes, was performed in a separate group of seven dogs. Small patches were sutured to the lateral surfaces of the right and left ventricles and were oriented longitudinal to the long axis of the heart (Figure 1B). In this configuration, the center axes of the epicardial and transthoracic electrodes were approximately coincident and passed through the center of the heart.

Data Analysis

The effect of patch electrodes on DFT was analyzed with the Student’s paired t test. For the small patch protocols, control DFT was determined by averaging the mean DFT obtained in steps 1 and 3. In step 1, DFT was determined by averaging the threshold obtained in two or three consecutive defibrillation trials. DFT was determined in a similar manner in step 3. The mean control DFT was then compared with DFT obtained with the implanted epicardial patches. This value was also obtained by averaging two or three consecutive defibrillation trials. To compare the effect of perpendicular and parallel orientation of small epicardial patches on DFT, we determined the percent change in DFT in each dog in the respective protocols and then analyzed the data with a t test for unpaired samples. For analysis of the large patch electrode protocol (1B), control DFT was determined by averaging the mean DFT calculated in steps 3 and 5. If the dog could not be defibrillated with the large patch electrodes, then control DFT was considered the mean obtained from step 3. For purposes of analysis, if a dog could not be defibrillated with the implanted patches, the last unsuccessful shock dose was considered the “DFT.” Data are mean±SD. Differences were considered significant at a p value less than 0.05.

Results

Protocol 1A. Small Epicardial Patches Perpendicular to Transthoracic Electrodes

Data for DFT are expressed in units of energy and current. Fifteen dogs were studied in this protocol. Control DFT was 100±38 J. Transthoracic DFT increased to 141±73 J (p<0.01) when small patch electrodes were implanted (Figure 2A). When analyzed according to current, DFT was significantly greater with the patch electrodes: 27±5 (control) vs. 33±9 A (patch electrodes), p<0.01 (Figure 2B). DFT between the two control periods showed little variability: 27±4 (step 1) vs. 27±6 A (step 3), p=NS. Transthoracic resistance was slightly greater without the patch electrodes: 61±9 (control) vs. 56±8 Ω (patch electrodes), p=0.01.

Protocol 1B. Large Epicardial Patches Perpendicular to Transthoracic Electrodes

This protocol was performed in eight of the 15 dogs studied in protocol 1A. DFT was 77±48 (control) vs. 186±106 J (patch electrodes), p<0.01 (Figure 3A), and 24±7 (control) vs. 40±12 A (patch electrodes), p<0.01 (Figure 3B). Control DFT before and after removal of the large patches was equivalent: 25±8 (step 3) vs. 23±7 A (step 5). Three of the eight dogs studied in this protocol could not be
FIGURE 2. Plots of transthoracic defibrillation threshold (DFT) determined during protocol 1A (perpendicular orientation of small epicardial patches). Panel A: DFT calibrated in units of energy. Panel B: DFT calibrated in units of current.

defibrillated after the large patch electrodes were implanted. There was no change in transthoracic resistance due to the presence of large epicardial patch electrodes: 53±13 (control) vs. 49±10 Ω (patch electrodes), p=NS.

Protocol 2. Small Patch Electrodes Parallel to Transthoracic Electrodes

Control DFT was 117±69 J in seven dogs. The addition of the patch electrodes increased threshold to 190±98 J, p<0.01 (Figure 4A). Similarly, DFT analyzed according to current was 29±8 A during control and increased to 42±13 A after implantation of the epicardial patches, p<0.01 (Figure 4B). There was no significant difference between control DFT before or after removal of the epicardial patches: 28±12 (step 1) vs. 30±15 A (step 3). Comparison of the percent increment in DFT between the two electrode configurations (calculated for each individual animal) showed a trend toward a higher DFT when the patch electrodes were oriented parallel to and coincident with the axes of the transthoracic electrodes. This difference approached but did not reach statistical significance: 46±16% (perpendicular orientation) vs. 81±16% (parallel orientation), p=0.1. Transthoracic resistance did not significantly differ between control (50±7 Ω) and after epicardial patch implantation (48±6 Ω).

Discussion

The major finding in this study is that AICD epicardial patch electrodes can significantly elevate transthoracic defibrillation requirements or in some cases even preclude defibrillation. In addition, variables such as orientation and size of patch electrodes may also increase transthoracic threshold.

The clinical success of the AICD in reducing the rate of sudden cardiac death has encouraged some investigators to consider this device as the treatment of choice for survivors of sudden cardiac arrest.13,14 Standard practice has been to implant the patch electrodes at the same time as the pulse generator. More recently another trend has emerged: staged implantation in patients who are undergoing cardiac surgery for other indications. For instance, patch electrodes may be implanted at the time of map-guided subendocardial resection for VT3-7 or in those who are survivors of sudden cardiac arrest undergoing coronary revascularization or valve re-
myocardial field distortion created by the patches was primarily due to the blocking effect of the electrode’s insulation rather than the shunting effect of its conducting surface. For example, if the center axes of the patch electrodes are coincident and are perpendicular to the coincident center axes of the transthoracic electrodes, then there should be minimal distortion of the electric field through the myocardium during transthoracic defibrillation. This condition was approximated (though not duplicated) in protocol 1 (perpendicular patch orientation). If we assume standard anterolateral positioning of transthoracic electrodes in the clinical setting, implantation of patch electrodes on the surfaces of the posterolateral right and the anterolateral left ventricles would approach a perpendicular epicardial-transthoracic electrode configuration. An alternative patch electrode configuration examined in this study (protocol 2, parallel patch configuration) is the condition in which the center axes of the epicardial and transthoracic electrodes are approximately coincident and pass through the center of the heart. This electrode configuration resulted in a trend toward a higher DFT compared with the perpendicular configuration but was not significant.

**Limitations**

This study has several potential limitations. The relation of patch electrode surface area to heart surface area is not identical for humans and mongrel dogs. Consequently, patch electrode insulation may have a greater effect on DFT in dogs than humans. This difference in effect is probably relatively small, however, because the ratio of patch electrode surface area to myocardial surface area is nearly identical in dogs and humans when two small patch electrodes are implanted in dogs and when one small and one large patch electrode are implanted in humans.

Of concern, because large patch DFT was determined after small patch DFT was determined in eight of the 15 dogs studied in protocol 1, the increase in DFT associated with large patches may have been due to deterioration of the animal. Although this factor cannot be dismissed, it is worth noting that in the initial phase of protocol 1A (with small patches), control DFT was greater than that determined in the final phase of protocol 1B (with large patches).

Finally, although these were short-term studies, there are data to suggest that these results would also be similar under long-term conditions. Transmyocardial thresholds with implanted epicardial patch electrodes have been shown to remain stable for as long as 17 months. Under these conditions, transthoracic DFT would also be expected to remain stable or even possibly increase. For instance, the presence of pericardial fibrosis may have the effect of adding an additional insulator around the heart.

**Figure 4.** Plots of transthoracic defibrillation threshold (DFT) determined during protocol 2 (parallel orientation of small epicardial patches). Panel A: DFT calibrated in units of energy. Panel B: DFT calibrated in units of current.

placement. If hypotensive VT or VF should recur spontaneously during the follow-up period, because of either failure of antiarrhythmic drug therapy or inadequate surgical resection or is induced by programmed stimulation during postoperative electrophysiologic study, an AICD pulse generator could then be implanted in the paraumbilical area, which would obviate the need for thoracotomy.

Although the above approach has some merit, approximately 75–85% of patients who undergo map-guided resection will have a surgical cure of their arrhythmia and therefore do not require an AICD system. Furthermore, the presence of epicardial patch electrodes alone may have adverse consequences, because the patch electrodes are insulated on the noncontact or free surface. The results of the present study indicate that this factor may prevent sufficient current from traversing the heart if the need for transthoracic defibrillation should occur. Of particular concern is the finding that nearly 40% of dogs with large patches could not be defibrillated. In contrast, all dogs with small patches, without regard to orientation, were successfully defibrillated.

One hypothesis of this study was that the orientation of the epicardial patch electrodes would affect transthoracic DFT. Another hypothesis was that
Implications

The results of this study suggest that the need for external defibrillation arise in a patient with epicardial patch electrodes, careful consideration should be given to the orientation of thoracic electrodes with respect to patch electrodes. When implanting patch electrodes without a generator, it is perhaps preferable to choose the smallest-sized patch electrodes that effectively defibrillate the heart and to orient them (if anatomic conditions permit) as perpendicular as possible to the conventional trans-thoracic electrode axis.

References


Key Words: • cardiac death, sudden • ventricular fibrillation • automatic internal cardioverter/defibrillator
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