Myocardial Necrosis from Direct Current Countershock

Effect of Paddle Electrode Size and Time Interval Between Discharges

By Charles F. Dahl, Gordon A. Ewy, M.D., E. D. Warner, M.D., and Evan D. Thomas

SUMMARY

The effect of varying both paddle electrode size and the time interval between direct current countershocks on myocardial necrosis was studied. Forty-two dogs were divided into seven groups of six dogs each. All dogs were given ten consecutive, 240 watt-second countershocks (delivered energy into a 50 ohm load). Three groups were shocked with paddle electrode diameters of 8.0 cm (standard electrodes), two groups with paddle electrode diameters of 12.8 cm (large electrodes), and two groups with paddle electrode diameters of 4.3 cm (small electrodes). The time intervals between discharges in the groups shocked with the standard electrodes were 15 seconds, one minute, and three minutes. The time interval between discharges in the groups shocked with small and large electrodes was 15 seconds and three minutes. Myocardial necrosis was quantitated by precordial electrocardiographic mapping recorded minutes after, and by gross and microscopic examination of the hearts four days after direct current countershock.

When the time interval between discharges was shorter, myocardial necrosis was greater. When the time interval between discharges was constant, more necrosis was produced with smaller-sized paddle electrodes. It is concluded that large paddle electrodes should be used for delivering direct current countershocks, and that during elective cardioversion, consecutive discharges should be delivered at time intervals greater than three minutes.

Additional Indexing Words:
Cardioversion Defibrillation Precordial electrocardiographic mapping

Following the development of direct current (DC) defibrillators, a study comparing myocardial necrosis from alternating current (AC) and direct current (DC) discharges showed the relative safety of the DC discharges. The transient increase in serum enzyme levels that occasionally occur in man following DC cardioversion have been attributed to chest wall muscle and not cardiac muscle damage. A recent study in which isoenzymes of creatinine phosphokinase (CPK) were measured following elective cardioversion suggests that, at times, some of the elevation of CPK is contributed by enzymes from the myocardium.

During a study of the determinants of canine transthoracic resistance to DC discharge in this laboratory, electrocardiographic ST-segment elevation and gross myocardial lesions were frequently observed after ten consecutive DC countershocks. Similar studies by Patel and Galash suggested that gross pathological lesions were more frequent at higher levels of delivered energy. Our pilot studies suggested that the myocardial necrosis was related not only to the amount of delivered energy but also to the paddle electrode size and the time interval between DC discharges.

Since this observation could be of significant clinical import, the following experiments were devised to determine the effect of paddle electrode size and time interval between DC discharges on myocardial necrosis from DC defibrillator or cardioverter discharge.

Methods

Forty-two mongrel dogs weighing between 14.2 and 27.0 kg were divided into seven groups of six dogs each. The
MYOCARDIAL NECROSIS FROM DC SHOCK

Protocol within each group varied only in the time interval between discharges and/or the diameter of the paddle electrode used to deliver the discharge. Each dog was anesthetized with pentobarbitol sodium, 25 mg/kg. The thoracic hair was removed with electric clippers. Electrode paste* was generously applied to the paddle electrodes which were then applied to the chest wall. In all experiments, one paddle electrode was placed on the left precordium with its center over the point of maximal cardiac impulse. The second was placed on the opposite lateral chest wall at the same thoracic level. Ten consecutive direct current discharges were delivered to each animal from a Hewlett-Packard 7502C defibrillator at a dial setting of 400 watt-seconds. At this setting this unit delivers 240 watt-seconds across a 50 ohm resistance.

Three groups were shocked with paddle electrodes with diameters of 8.0 cm (standard electrodes), two groups with paddle electrodes with diameters of 12.8 cm (large electrodes), and two groups with paddle electrodes with diameters of 4.3 cm (small electrodes). The time intervals between discharges in the groups shocked with standard electrodes were 15 seconds, one minute, and three minutes. The time intervals between shocks in the groups shocked with the small and large electrodes were 15 seconds and three minutes.

Electrocardiographic and morphologic means were utilized to assess the degree of myocardial injury and/or necrosis. A standard 12-lead electrocardiogram was taken on each dog before and after the discharges were delivered. Electrocardiographic precordial mapping was then done. A grid of 25 points, each two centimeters apart, was painted on the left chest wall with the center of the grid at the point of maximal cardiac impulse (fig. 1). Electrocardiographic recordings were made from each point using the unipolar precordial lead. Any electrocardiographic ST-segment elevation which differed from the baseline recording was measured in millimeters, at a point 0.08 second after the onset of the QRS complex. The ST-segment changes of each of the 25 points on each animal were added. The mean, in millimeters, was recorded for each animal.

Four days after the direct current discharges were delivered, the dogs were anesthetized and then sacrificed. The hearts were examined grossly and microscopically. The area of gross discoloration of each heart was estimated in square centimeters. Blocks were taken in buffered 10% formalin and in 4% gluteraldehyde for light and electron microscopic (E.M.) study, respectively. The hearts were then placed in 10% formalin. After fixation for several weeks, the hearts were sectioned parallel to the atrioventricular sulus. The depth of the gross lesions was noted. Tissue blocks for light microscopy were processed in paraffin and those for E.M. in epon. Microscopic sections from the area of damage were graded as negligible, grades I, II, or III. The microscopical grading was done by the pathologist (E.W.) on the basis of a combination of the severity and the depth of the lesions. The smaller and milder lesions tended to be quite superficial, i.e., subepicardial. The larger and more severe lesions tended to be full thickness. Grade I lesions were patchy in that many apparently intact muscle fibers were interspersed with the necrotic area and/or the lesion was very superficial. Grade III lesions contained large areas where essentially all fibers were degenerating and the depth of the lesions was full thickness. Grade II lesions were intermediate between Grades I and III, intermediate in both the extent of destruction of cell fibers and in depth. Samples of myocardium which appeared normal grossly showed no microscopical lesions.

To quantitate the amount of necrosis in each heart, the gross area of discoloration in square centimeters was multiplied by the microscopic severity to obtain a myocardial damage index. For example, if the animal’s heart showed a gross lesion with an area of two square centimeters, and the microscopic severity was judged to be Grade II, a myocardial necrosis index of four was given. The pathologist evaluated the morphologic lesions without knowledge of the protocol used on the animal until after the myocardial necrosis score was obtained.

**Results**

The results are tabulated in tables 1, 2, and 3. There was more electrocardiographic ST-segment elevation

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**Table 1**

<table>
<thead>
<tr>
<th>Time interval: 15 sec</th>
<th>Small electrodes</th>
<th>Standard electrodes</th>
<th>Large electrodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.6 ± 7.6</td>
<td>2.3 ± 2.8</td>
<td>0.1 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>Time interval: 1 min</td>
<td>1.2 ± 3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time interval: 3 min</td>
<td>0.2 ± 0.4</td>
<td>0 ± 0</td>
<td></td>
</tr>
</tbody>
</table>

ST segment elevation in millimeters per precordial lead per dog, expressed as mean ± one SD.

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**Table 2**

<table>
<thead>
<tr>
<th>Time interval: 15 sec</th>
<th>Small electrodes</th>
<th>Standard electrodes</th>
<th>Large electrodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.2 ± 45.7</td>
<td>4.4 ± 1.8</td>
<td>3.0 ± 4.5</td>
<td></td>
</tr>
<tr>
<td>Time interval: 1 min</td>
<td>15.0 ± 29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time interval: 3 min</td>
<td>4.0 ± 5.4</td>
<td>1.1 ± 1.8</td>
<td>0.5 ± 0.9</td>
</tr>
</tbody>
</table>

Mean ± one SD.

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*Redux Paste, Hewlett-Packard part number 651-1008.*

**Figure 1**

Left) Grid showing 25 positions for precordial electrocardiographic mapping. Right) Example of grid marked on shaved canine chest.

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when the same amount of direct current electrical energy was discharged transthoracically with the small electrodes and at shorter time intervals (Table 1, 15 seconds versus three minute intervals, $P < 0.025$). An example of precordial electrocardiographic mapping is shown in figure 2.

As shown in Table 2, there was more myocardial necrosis when equal amounts of energy were discharged transthoracically at 15 seconds rather than three minutes ($P < 0.25$). When the time interval between discharges was held constant, there was more myocardial necrosis with smaller diameter electrodes (small versus standard and small versus large electrodes, $P < .025$). Table 3 shows the relation between pathologic myocardial necrosis and the mean ST elevation (per precordial lead) for each of the 42 dogs used in the study. The over-all correlation coefficient was high ($r = 0.89$).

Figure 3 illustrates the typical appearance of the gross morphologic lesions observed four days post-direct current discharge. As shown in the illustrations, most specimens had lesions that were on opposite sides of the heart like entrance and exit wounds. In some, the lesions were more confluent on the anterior surface of the heart. Examples of the microscopic lesions are shown in figures 4 and 5. The microscopic lesions were characterized by necrosis of myocardial fibers which were replaced by proliferating large mononuclear cells. Although the animals were all sacrificed four days after the DC discharges, there was considerable variation in the extent of the replacement of necrotic myocardial fibers. Some necrotic fibers retained their morphologic characteristics, with cross striation visible. At times, the striations were exaggerated in prominence by dark staining material. The dark staining material was positive for calcium by the von Kossa stain and was electron dense in unstained electron microscopy studies. On electron microscopical examination, this material appeared to be deposited in the mitochondria. Other necrotic fibers were extensively fragmented, with loss of staining intensity, and still others were replaced by large mononuclear cells, many containing mitotic figures. Considerable variability in the amount of destruction was found, not only from animal to animal, but from field to field in the same specimen.

![Figure 3](http://circ.ahajournals.org/)

**Figure 3**

Examples of gross myocardial appearance four days after ten direct current defibrillator discharges. Top) Necrosis produced with small (4.5 cm diameter) electrodes with discharges at 15 second intervals. Note the large whitish discolored area on each side of the heart. Their size is similar to the paddle electrode size used, even though the electrodes were applied to the intact chest skin. Bottom) Necrosis produced by electrodes of 8.0 cm diameter. Note white areas on the lateral aspects of the heart. One lesion is lateral to the left anterior descending coronary artery and the other larger one is on the infero-lateral surface of the right ventricle. Their area is much smaller than that of the electrode used.
Discussion

The advantages of treating certain cardiac arrhythmias with electrical cardioversion are well known and widely accepted. Possible adverse effects on the myocardium have been suggested by the appearance of arrhythmias, electrocardiographic ST-segment elevation, serum enzyme elevations, development of pulmonary edema, and acute left ventricular decompensation following elective cardioversion. Arrhythmias such as the transient appearance of a premature ventricular contraction are recognized as commonly occurring after this treatment, but most severe arrhythmias that develop have been attributed to concomitant administration of toxic or near toxic doses of quinidine and/or digitalis, or the advanced stage of the underlying cardiac disease. There is reason to doubt these conclusions. Russian authors have reported "marked changes in the myocardium" in five of 220 patients who had acute left ventricular insufficiency following elective cardioversion. Transient electrocardiographic ST-segment elevation has been reported in the English

Table 3

Relation Between Myocardial Necrosis and Mean Electrocardiographic ST-Elevation in Millimeters for Each Paddle Electrode Size at Each Time Interval of Countershock

<table>
<thead>
<tr>
<th>Time (Secs)</th>
<th>Small (4.3 cm)</th>
<th>Standard (8.0 cm)</th>
<th>Large (12.8 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Myocardial necrosis</td>
<td>Myocardial necrosis</td>
<td>Myocardial necrosis</td>
</tr>
<tr>
<td>15 secs</td>
<td>16 105 6 8 0 2</td>
<td>17 106 6 5 0 0</td>
<td>0 20 0 2 0 2</td>
</tr>
<tr>
<td></td>
<td>0 0 1 3 0 2</td>
<td>12 42 0 5 1 12</td>
<td>7 88 2 5 0 2</td>
</tr>
<tr>
<td>60 secs</td>
<td>0 0 0 0</td>
<td>8 74 0 0</td>
<td>0 0</td>
</tr>
<tr>
<td></td>
<td>0 0 0 0</td>
<td>14 0 0 0</td>
<td>0 2 0 0</td>
</tr>
<tr>
<td>180 secs</td>
<td>0 2 0 0</td>
<td>0 0 0 0</td>
<td>0 8 0 0</td>
</tr>
</tbody>
</table>

*Myocardial damage index determined by multiplying the area of discoloration on gross examination in square centimeters by a grade assigned for the severity of the lesion examined microscopically.

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Figure 4

Microscopic section from a grossly discolored area. Beginning at the top of the figure, note the following: the epicardium and subepicardial adipose tissue are intact. The subepicardial myocardial fibers have been destroyed. Note sharp line of demarcation between the lesion and deeper myocardium which is intact. Hematoxylin and eosin stain, × 70.

Figure 5

Microscopic section from a grossly discolored area. Degenerating myocardial fibers undergoing mineralization with exaggerated prominence of cross markings. Hematoxylin and eosin stain, × 500.
literature following elective cardioversion.\textsuperscript{8-11} Both good correlation found between the mean ST-segment elevation and the amount of myocardial necrosis (table 3, \( r = 0.89 \)) and the finding that all animals with ST-segment elevation had myocardial necrosis suggest that any electrocardiographic ST-segment elevation seen following transthoracic DC discharge is indicative of myocardial necrosis. Sixteen animals had myocardial necrosis without ST-segment elevation, indicating that ST-segment elevation is a specific but relatively insensitive indicator of myocardial necrosis. Serial electrocardiograms were not done on these animals, but a standard 12-lead electrocardiogram done prior to sacrifice on the fourth day showed no ST-segment elevation.

Although elevated serum enzymes have been reported following elective cardioversion,\textsuperscript{2,4,11} most investigators have concluded that serum enzyme elevation resulted from chest wall muscle and not cardiac muscle damage.\textsuperscript{2,5} A recent study of the effect of cardioversion on the serum isoenzymes of CPK showed that the MB or myocardial fraction of CPK was elevated in a small percent of patients.\textsuperscript{6}

We have produced myocardial necrosis in a dog in our laboratory with one DC discharge delivered with "pediatric-sized" paddle electrodes.\textsuperscript{20} This experience and the present study suggest that larger paddle electrodes should be used for cardioversion and defibrillation. Preliminary studies from this laboratory have shown that 12.8 cm diameter electrodes are as effective as 8.0 cm diameter electrodes in defibrillating the dog.\textsuperscript{21}

Transthoracic impedance to direct current discharge is greatest with small paddle electrodes and progressively decreases with increasing electrode size, even when only one of the two electrodes is increased in size.\textsuperscript{22} In the present study, the mean impedance was 30 ± 1 ohm with the 12.8 cm electrodes and 66 ± 1 ohm for the 4.5 cm electrodes. If damage is less when the transthoracic impedance is less, one should select not only the appropriate paddle electrode size, but also the chest wall interface that results in lowest impedance. Studies have shown that impedance during direct current countershock is less when electrode paste is used and increases progressively with saline soaked gauze pads, electrode creams, and with bare electrodes against the chest wall.\textsuperscript{22}

There were animals in each group (table 3) in which there was no necrosis. This large variation in susceptibility suggests that myocardial necrosis to DC defibrillator discharge is related to other factors besides delivered energy, paddle electrode size, and time interval between discharge.

It is probable that myocardial necrosis can occur in man from DC electroshock delivered during elective cardioversion. Myocardial necrosis also probably occurs in patients who undergo multiple defibrillations. The clinical implications of this study are that myocardial necrosis can be minimized by utilizing large paddle electrodes and/or increasing the time interval between discharges.

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