Increasing catheter ablation lesion size by simultaneous application of radiofrequency current to two adjacent sites

Treatment of ventricular tachycardia by radiofrequency current application can be difficult, partly because of the larger size of the reentry circuit in relation to the lesion generated. Larger lesions than those currently achieved with single radiofrequency applications are desirable. This study evaluated simultaneous radiofrequency application to two adjacent electrodes to determine the effects of interelectrode distance and configuration (bipolar serial vs parallel) on lesion size and tissue temperature. Two 6F electrodes were placed, with the tips facing each other, on bovine myocardium in a saline bath at 37°C. Radiofrequency current was applied to a single electrode, or simultaneously to two electrodes connected either in series or in parallel. Tissue temperature, power, and lesion size were measured. Lesions produced by simultaneous radiofrequency delivery to both electrodes were more than twice the size of those produced by a single electrode alone (>100 mm³ vs 33.2 mm³, p < 0.01). Temperatures between electrodes were greater than those temperatures at the same distances from a single electrode (p < 0.001). The size of the lesions decreased as interelectrode distance decreased below 3.5 mm (p < 0.030) because of the increasing depth of the lesion between the electrodes. Two electrodes placed in a bipolar as opposed to a parallel configuration were most efficient, as this configuration produced greater lesion sizes for a given level of power delivery (p < 0.0001). The bipolar lesion size decreased by >50% if one electrode was not in contact with the tissue (p < 0.0004). Thus in this in vitro model, simultaneous application of radiofrequency current to two adjacent sites synergistically increases lesion size more than twice that of a single lesion, in part as a result of an increase in lesion depth between electrodes at areas of overlap. Bipolar radiofrequency ablation using two large, closely spaced electrodes may provide a convenient method to increase lesion size for ablation of ventricular reentry circuits. (Am Heart J 1993;125:1276.)

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Catheter ablation has been used successfully to treat a variety of arrhythmias. Treatment of ventricular tachycardia arising from chronic infarct scars, however, has been more difficult than the treatment of supraventricular tachyarrhythmias. In part this is because of the size of the area that must be ablated to successfully prevent ventricular tachycardia, which often arises from relatively large reentry circuits that may be subendocardial, intramural, or epicardial. Radiofrequency catheter ablation produces relatively small, focal lesions, and a method for increasing radiofrequency lesion size is desirable for ventricular tachycardia catheter ablation.

The size of radiofrequency lesions is closely related to the temperature achieved in the tissue, which is determined by the delivered power. A tissue temperature of >48°C seems to be required to produce a lesion. Prolonging the radiofrequency current duration or increasing the power often increases temperature to >100°C such that boiling occurs, with formation of a coagulum on the electrode, causing a rise in impedance and preventing further current delivery and limiting lesion size. Increasing the electrode size increases lesion volume to a point, but also necessitates greater power delivery to generate a sufficiently high temperature to produce a lesion, which potentially decreases efficiency. We hypothesized that simultaneous radiofrequency delivery to two adjacent electrodes would increase tissue temperature over a greater distance between the two sites, producing larger lesions than expected by repeated radiofrequency delivery to a single electrode moved to adjacent sites. Using an in vitro
preparation, we also investigated various configurations for radiofrequency current delivery to two separate electrodes to determine configurations that optimize lesion size and radiofrequency efficiency.

**METHODS**

Radiofrequency lesions were produced in vitro on bovine myocardium. Strips of bovine myocardium were placed in a circular aluminum chamber. The tissue was immersed in normal saline (0.9%), and the entire chamber was heated to 37.0°C by a Corning P-320 heater/stirrer (Dow Corning, Waynesboro, Va.). Temperatures in the bath and tissue were measured via a nickel/chromium temperature probe (Model 821; Tegem, Inc., Madison, Ohio). The stir rate was adjusted to maintain a flow rate of roughly 70 cm³/min over the surface of the tissue. The flow rate was calculated by observing the time required for a 1 mm particle to traverse the length of the bath over the tissue. All measurements of distance were made by a digital micrometer (Jocal, CE Johnasson Products, Inc., Sweden).

Two custom-designed radiofrequency generators were used in this experiment. Both devices delivered 500 kHz square wave current at preset voltages ranging from 10 to 60 V. Both devices incorporated displays that indicated actual voltage and current. Voltage and current were recorded at onset, at 15 seconds, and at 30 seconds during the pulse durations. By Ohm’s law, impedance was calculated as the ratio of voltage over current. The actual delivered power was estimated as the product of voltage and current. The total energy was estimated as the product of power and time. In all experiments, radiofrequency current was delivered for 30 seconds.

Radiofrequency energy was delivered to the 4 mm tip electrode of one or two 6F electrode catheters (EP Technologies, Inc., Mountain View, Calif.). The catheters were placed horizontally on the myocardium, with two 10 gm weights placed 2 cm from each tip (Fig. 1). Radiofrequency generators were connected to the two electrodes in one of three configurations: (1) In the “two-device” configuration, two catheters were connected to two separate radiofrequency devices. The ground for each catheter was placed in the saline bath, not in contact with the aluminum sides of the bath (Fig. 1, A). (2) In the “unipolar” configuration, tip electrodes from both catheters were connected in parallel to the same radiofrequency device, and the sides of the aluminum bath served as the common ground (Fig. 1, B). (3) In the “bipolar” configuration, one tip electrode was connected to the radiofrequency device at the output terminal, and the other tip electrode was connected to the ground reference terminal of the radiofrequency device (Fig. 1, C). Temperatures were recorded at a point equidistant between the two electrodes.

Lesion size was assessed from the dimensions of the visibly coagulated myocardium. To measure lesion volumes, the lesion sizes were traced using a clear plastic sheet placed over the lesion. The length (L) and width (W) of the traced areas were recorded. The depth (D) of the lesion was then assessed by sectioning the center of the lesion and recording the cross-sectional depth of the lesion. Lesion area was calculated using the formula for a hemiellipse [volume = (1/2) × (4/3) × π × (L/2) × (D) × (W/2)] = 0.524 × L × W × H].

To measure the volumes of confluent lesions made by two tip electrodes, we assumed that the ends of each lesion (in a “peanut” configuration) were hemispheres (volume formula as stated above), connected to each other by a hemicylinder (volume = L × π × W × H/8 = 0.393 × L × W × D). The total lesion volume = 0.524 × L × W × D1 (end volume number 1) + 0.524 × L × W × D2 (end volume number 2) + 0.393 × L × W × H3 (the hemicylinder). When the lesions made by the two catheters did not overlap, the area of the central connecting cylinder was assumed to be zero.

**Statistical analysis.** Data were analyzed using linear regression analysis and the Student’s t test. Slopes of the regression lines from linear regression were compared using the Student’s t test. Significance was set at p < 0.05.

**RESULTS**

Simultaneous radiofrequency application to two adjacent electrodes. Fig. 2 compares lesions made from one electrode (at the far right) with lesions made by simultaneous application of radiofrequency current to two adjacent electrodes in the “two-device” configuration. The distance between the two electrodes varied from 2.0 to 7.0 mm. All lesions were made at a preset voltage of 30 V, yielding delivered power and energy of 18 ± 2.3 W and 541 ± 68 joules for the single lesion produced; in the two-device configuration, power and energy of 17.5 ± 0.7 W and 526 ± 21 joules for radiofrequency device No. 1 and 18.5 ± 1.8 W and 554 ± 55 joules for radiofrequency device No. 2 were delivered. These energies were not significantly different (p = NS). At all interelectrode distances tested, lesions produced from two radiofrequency tip electrodes were more than twice the volume of lesions produced from only one electrode (p < 0.01). The average lesion size from one electrode was 33.2 ± 34 mm³, whereas lesions made by two devices were greater than 100 mm³.

As shown in Fig. 2, lesion size diminished as interelectrode distance increased beyond 3.5 mm (p = 0.03). A possible reason for this is suggested by the data in Fig. 3, which graphs interelectrode distance versus the lesion depth measured at the midpoint between the two electrodes and also shows the fraction of experiments in which lesions from the two electrodes overlapped. The depths of the lesions (solid bars) made at interelectrode distances of 2 to 3.4 mm were significantly greater than those made at interelectrode distances ≥3.5 mm. Similarly, for interelectrode distances less than 3.5 mm, all lesions overlapped (hatched bars), while less than one half of the lesions overlapped at interelectrode distances ≥4.5 mm.
Fig. 1. A, Orientation of the two electrodes connected to two independent devices for simultaneous radiofrequency (radiofrecuency) delivery. The electrode tips are shown facing each other, resting on the myocardium (stippled box). The temperature probe is inserted in tissue midway between the two electrodes. Each electrode tip is connected to independent radiofrequency outputs, with each ground immersed in the saline bath. B, Orientation of the two electrodes connected in parallel in a unipolar configuration. The electrode tips are shown facing each other, resting on the myocardium (stippled box). The temperature probe is inserted midway between the two electrodes. Each electrode tip is connected to a common radiofrequency output, with a common ground connected to the aluminum sides of the saline bath. C, Orientation of the two electrodes connected in series in a bipolar configuration. The electrode tips are shown facing each other, resting on the myocardium (stippled box). The temperature probe is inserted midway between the two electrodes. One electrode tip is connected to the radiofrequency output, and the other connected to the radiofrequency “ground” output.

Fig. 4 shows the maximum tissue temperature at the midpoint between the tip electrodes for different interelectrode distances; also shown are the maximum temperatures from single lesions at different distances from the electrode tip. Since tissue temperature is inversely related to the fourth power of the distance from the electrode tip, a log-log scale was used to linearize the relation. Temperatures were greater between two electrodes compared with the temperature at a single electrode. The slope of the regression line for the single electrode was significantly different from the slope for the dual-electrode configuration (p < 0.001).

In summary, simultaneous delivery of radiofrequency energy to two adjacent electrodes produces greater heating in the tissue between the two electrodes, increasing lesion depth between these electrodes, which more than doubles lesion size. This is
Fig. 2. Bar graph of lesion sizes produced by a single electrode (far right) versus those produced by simultaneous current delivery to two electrodes at various interelectrode distances. The y axis presents lesion size in cubic millimeters. The x axis is interelectrode distance. The lesions produced by one electrode were significantly smaller than those produced by two electrodes (p < 0.01). Lesions produced by two electrodes at an interelectrode distance less than 3.5 mm were larger than those at greater interelectrode distances. Vertical lines indicate one standard deviation. The number of experiments (n) is shown below each bar. See text for discussion.

Fig. 3. Bar graph of lesion depth (solid bars) and the fraction of lesions that overlapped (hatched bars) produced by two adjacent electrodes. Lesion depth at the midpoint between electrodes decreased significantly when the interelectrode distance increased to greater than 3.5 mm (p = 0.004). All lesions produced at interelectrode distances <3.5 mm overlapped, and the fraction of lesions with overlap decreased at distances ≥3.5 mm. At interelectrode distances from 5.5 to 7.0 mm, no lesions overlapped, and correspondingly lesion depth at the midpoint was 0. Vertical lines indicate standard deviations. The number of experiments (n) is shown below each bar. See text for discussion.
most pronounced at relatively close electrode spacings where lesions from each electrode overlap.

**Configuration of radiofrequency delivery to two electrodes.** Fig. 5 shows plots of lesion size versus power from lesions produced by simultaneous application of radiofrequency energy to two electrodes 3 mm apart for each of three different configurations. Linear regression analysis was performed for power versus volume for each configuration. The bipolar configuration produced the greatest lesion size for a given power (slope = 3.3 mm³/W), followed by the unipolar configuration (slope = 3.8 mm³/W). The two-device configuration produced the smallest lesions (slope = 0.93 mm³/W). The slope of the bipolar configuration was significantly greater than that of the unipolar (p < 0.0001) and two-device configurations (p < 0.0001). The slope of the unipolar configuration was greater than that of the two-device configuration (p < 0.0001).

Analysis of temperature at the midpoint between the two electrodes versus power yielded similar results (Fig. 6). The temperature generated between lesions was greatest for the bipolar configuration (slope = 0.90 °C/W), which was greater than that of the unipolar configuration (slope = 0.36 °C/W, p < 0.0001) or that of the two-device configuration (slope = 0.15 °C/W, p < 0.0001).

Fig. 7 shows the impedance for the bipolar and unipolar configurations. The bipolar configuration had a greater impedance (60.2 ± 10 Ω) than the unipolar configuration (23.8 ± 6.8 Ω, p < 0.0001). Impedance did not vary with power for either configuration.

**Effects of tissue contact on bipolar lesion size.** Although simultaneous delivery of radiofrequency energy to two electrodes in a bipolar configuration produces larger lesions than delivery of such energy to a single electrode, maintaining tissue contact at two electrodes may sometimes be difficult in the beating heart. To determine the effects of poor tissue contact at one electrode on lesion size, we placed one electrode on the tissue and the other electrode either on the tissue or 1 or 3 mm above the tissue. Delivered voltage was constant, yielding similar power levels for each trial (19.6 ± 1.5 W at 0 mm, 20.6 ± 1.9 W at 1 mm, and 20.8 ± 0.8 W at 3 mm) (p = NS). The interelectrode distance was held constant at 3 mm. Lesion sizes and impedance are shown in Fig. 8. Lesions in which both catheters were in contact with the tissue (average size = 123.6 ± 28.0 mm³) were greater than twice the size of lesions with one of the catheters 1 mm above (average size = 53.0 ± 23.5 mm³) (p = 0.0004) or 3 mm above the tissue (average size = 48.9 ± 31.6 mm³) (p = 0.0009). There was no significant difference in lesion size between the 1 and 3 mm elevations. The impedance with both elec-
Fig. 5. Plot of lesion size (y axis) versus power (x axis) for three different radiofrequency electrode configurations for current application to two adjacent electrodes at an interelectrode of 3 mm. Radiofrequency configurations are bipolar (squares), unipolar (crosses), and two-device (stars). Correlation coefficients (r) for each regression line are shown. See text for discussion.

Fig. 6. Plot of temperature (y axis) at the midpoint between two adjacent electrodes at an interelectrode distance of 3 mm versus power (x axis) for three different configurations. Radiofrequency configurations are bipolar (squares), unipolar (crosses), and two-device (stars). Correlation coefficients (r) for each regression line are shown. See text for discussion.

trodes in contact (57.6 ± 3.5 ohm) was significantly less than the impedance with one electrode at 1 mm (71.5 ± 5.5 ohm) or at 3 mm (72.9 ± 0.9 ohm) above the tissue (p < 0.0001).

DISCUSSION

It is evident that a lesion made by radiofrequency application to two electrode catheters would be considerably larger than a lesion made by a single elec-
trode. Others have investigated bipolar application of radiofrequency to electrodes positioned on either side of the ventricular septum, in the coronary sinus and at the left ventricular side of the mitral annulus and in the ventricle. These studies were performed in beating canine hearts with conventional small electrodes and did not investigate the effects of varying the distance between electrodes.

A major finding of the present study is that lesions produced by simultaneous application to two adjacent electrodes are greater than twice the size of the lesions produced by a single radiofrequency application to a single electrode, consistent with a synergistic effect. Lesion size is determined at least in part by the temperature generated by the radiofrequency pulse. The greatest temperature is at the electrode tip, and temperature decreases inversely with increasing distance from the tip. Simultaneous radiofrequency delivery to two adjacent sites increases temperatures in tissue between the two electrodes, generating a bridging area of necrosis between the two electrodes. We expected that the largest lesions would occur with the largest interelectrode distance that still produced bridging necrosis between electrodes. We observed, however, that the smaller the distance, the larger the lesion. This was a result of the increased depth of the bridging necrosis between electrodes at the smallest interelectrode distances. Thus penetration of radiofrequency effects is increased by using closely spaced electrodes.

Simultaneous radiofrequency current delivery to two separate electrodes can be achieved in a variety of ways, with electrodes in series (bipolar), in parallel, or connected to two separate radiofrequency generators. Bipolar radiofrequency current delivery has the greatest efficiency, producing the largest lesions and the greatest temperatures for a given energy. This is consistent with the dissipation of the entire energy output at the tissue, rather than partially at a remote ground electrode. Both the unipolar and the two-device configurations were connected to large grounding plates that were in contact with the entire bath. In the bipolar configuration, the electrodes were electrically in series, yielding the highest load impedance (R). In the unipolar configuration, the two electrodes were in parallel, and the impedance of the entire circuit was less than the impedance of each individual electrode itself (1/2 R). However, because of the low resistance ground, this lower impedance was not associated with greater lesion size or energy efficiency.

A practical limitation of bipolar current delivery is the possibility that one electrode could be in poor contact with the myocardium. This reduces lesion size to a size similar to that produced by a single electrode. If the two electrodes do not have identical surface areas, greater heating would be expected at the smaller electrode during bipolar energy delivery because of the higher current density around that electrode. New catheter designs or simultaneous use
Lesion Size (mm³) \ Impedance (Ohms)

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<th>Distance of Electrode From Tissue</th>
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Fig. 8. Bar graph illustrating the effects of tissue contact on lesion size produced by two adjacent electrodes in the bipolar configuration. Lesion sizes (solid bars) and impedance (hatched bars) are on the y axis in cubic millimeters and ohms, respectively. One electrode was on the myocardium while the second electrode was 0 mm, 1 mm, or 3 mm above the myocardium. The number of experiments (n) is shown below each bar. See text for discussion.

of two catheters may be required for successful application of bipolar current delivery during catheter ablation procedures.

Limitations. Although saline flowed over the surface of the tissue, our in vitro preparation did not take into account the effects of additional heat sinking from blood flowing through the tissue, which may reduce lesion size. It is possible that our results would be quantitatively different in vivo. The determination of lesion size from the measurement of visibly coagulated areas did not assess the possible microscopic tissue damage that may extend beyond the visual areas of tissue coagulation. In the two-device configuration, the radiofrequency currents of the two devices were not necessarily in phase with each other. This could theoretically have reduced effective current delivery.

Conclusions. Simultaneous bipolar radiofrequency current delivery can increase lesion size with currently available power sources. This could potentially facilitate the success of catheter ablation of large reentry circuits that cause ventricular tachycardia after myocardial infarction.

REFERENCES
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Effects of diltiazem on concealed atrioventricular nodal conduction in relation to ventricular response during atrial fibrillation in anesthetized dogs

By means of a new quantitative index for concealed conduction, we evaluated the effects of diltiazem on atrioventricular (AV) node concealment and correlated this index with the variability of the ventricular response during atrial fibrillation in 16 anesthetized mongrel dogs. After determination of the atrial effective refractory period (ERP), AV nodal ERP (AVNERP), concealment zone, and concealment index (AVNERP of blocked atrial extrasystole/AVNERP of conducted atrial extrasystole), the R-R intervals during atrial fibrillation induced by electrical stimulation were measured. Both low (0.1 mg/kg) and medium (0.2 to 0.4 mg/kg) doses of diltiazem prolonged the AVNERP and increased the mean R-R interval during atrial fibrillation. Only medium doses of diltiazem increased the degree of concealed conduction in the AV node and accentuated the variability of R-R intervals. There was a good positive correlation between the variability of the ventricular response during atrial fibrillation and the concealment index. In conclusion, medium doses of diltiazem are more effective in reducing heart rate during atrial fibrillation than a low dose. However, medium doses also increase the degree of concealed conduction in the AV node and enhance the irregularity of the ventricular response during atrial fibrillation. Measurement of the concealment index is useful for quantitating the degree of concealed conduction in the AV node, which is actually an important determinant of the ventricular response during atrial fibrillation. (AM HEART J 1993;125:1264.)

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