Transesophageal Low-Energy Cardioversion in an Animal Model of Life-Threatening Tachyarrhythmias

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The purpose of this study was to determine the feasibility and efficacy of terminating life-threatening ventricular tachyarrhythmia by low-energy synchronous or asynchronous shocks delivered through a transesophageal catheter that had both an anode and a cathode. Forty-three episodes of ventricular fibrillation or flutter (VF or VF) were provoked by transesophageal asynchronous random shocks occurring during the vulnerable period of the ventricular cycle in seven dogs and seven pigs that were healthy adults. The 43 episodes of VF or VF were terminated by the transesophageal technique. The defibrillation energy thresholds were 23.11±6.28 J (range, 5–30 J). Seven episodes of ventricular tachycardia (VT) with a cycle length of 360 msec or less (330±27 msec) were provoked by ventricular pacing stimuli during acute myocardial ischemia resulting from delayed resuscitation in two dogs and three pigs. Five of the seven VTs had a duration of 31 seconds or more, and they were all terminated by transesophageal asynchronous shocks, the cardioversion thresholds being 1.71±2.25 J (range, 0.25–5 J). Fourteen episodes of idioventricular tachycardia (IVT) with a cycle length of 400 msec or more (445±33.5 msec) spontaneously occurred after the use of adrenaline and after defibrillation in four dogs and five pigs. We also succeeded in terminating seven episodes of IVT with a duration of 34 seconds or more by the same means of treating VT, although IVT is not an indication for cardioversion in the clinical setting. The cardioversion thresholds were 1.45±2.2 J (range, 0.25–5 J). The difference between the mean energy levels required for cardioversion of VT and IVT were not significant (t=0.20, p>0.5). The remaining two VTs and IVTs had a duration less than 30 seconds and were not tested. There was no significant difference of threshold energy of cardioversion for VT or IVT and VF or VF between dogs and pigs and between animals that weighed more than 12.5 kg and less than 12.5 kg. There were no apparent functional or histologic ill effects in the esophagi that received cumulative shocks of 192±91 J (100–377.5 J). In 246 synchronous or asynchronous shocks (including subthreshold shocks) for cardioversion, acceleration of VT or IVT or degeneration to VF or VF never occurred. We conclude that this new procedure is a safe and effective method for treating life-threatening ventricular tachyarrhythmias. (Circulation 1989;80:1354–1359)

In recent years, transesophageal atrial pacing has been used to diagnose and treat paroxysmal supraventricular tachycardia because it offers some advantages over transvenous cardiac pacing.1-3 However, the method fails to terminate life-threatening ventricular tachyarrhythmias. Inspired by the safety and success of intracardiac low-energy cardioversion with a transvenous electrode catheter,4-7 we reasoned that life-threatening ventricular tachyarrhythmias could be safely and effectively terminated by countershock of very low energy delivered through intraesophageal electrodes. The purpose of this study was to test this hypothesis using canine and porcine models.

Methods

Equipment

The catheter electrode, 9F with six stainless steel electrodes (Figure 1), was specifically designed for cardioversion in this study and for further use in the clinical setting. The distal three electrodes at the tip

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Supported by Guizhou Provincial Cardiovascular Institute.

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Received January 18, 1989; revision accepted June 6, 1989.
are separated from each other by a 3-cm space, each having a surface area of 0.94 cm². The proximal three (with a separating space of 1.2 cm) have a surface area of 0.28 cm² each. The two groups of electrodes are separated by a 1.5-cm space. The catheter can be used for cardioversion, atrial pacing, and monitoring the electrocardiogram (ECG). When shocks are delivered, the most distal two electrodes are coupled together to form the cathode, and the other electrodes, coupled together, form the anode.

The cardiac emergency-monitoring equipment (Model XJJ-I, Shanghai, China) was used to monitor and record ECG and as a cardioverter. The unit was reformed and could deliver a truncated exponential waveform, 6 msec in duration, at 25 energy levels: 0.25, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 20, 25, 30, 40, and 60 J. ECG with standard limb leads was connected to the unit. Synchronous shocks were delivered within the QRS complex for terminating ventricular tachycardia (VT). An initial shock of 0.25 J was used for the first attempt at synchronous cardioversion, and then, this shock was increased stepwise to obtain the cardioversion threshold, which was defined as the minimum energy required to terminate VT. When ventricular fibrillation or flutter (Vf or VF) occurred, an immediate asynchronous shock of 5 J was used for the first attempt at defibrillation, and this was increased stepwise by 5 J to obtain the defibrillation threshold, which was defined as the minimum energy required to terminate Vf or VF.

Study Protocol

Seven adult, healthy mongrel dogs (weight, 13.9±5.4 kg) and seven adult, healthy Guizhou pigs of small type (weight, 13.0±3.14 kg) were anesthetized with sodium pentobarbital (30–40 mg/kg i.v.), intubated, and mechanically ventilated with room air. The catheter was inserted through the mouth and advanced to the esophagus. Transesophageal atrial pacing was performed with the most distal two electrodes connected to an impulse generator (Model CT-1, Guizhou, China). After obtaining the insertion depth associated with two lowest settings of threshold voltage, we advanced the catheter 2 cm farther so that its tip reached the level of the ventricle. Then, the catheter was fixed and connected to the cardioverter in the manner mentioned above. The 14 esophageal electrodes were positioned without fluoroscopic guidance.

VF or VF was provoked by a transesophageal asynchronous random shock during the vulnerable period of the ventricular cycle. Because of the stepwise determination of the thresholds, this procedure could result in a delayed defibrillation followed by acute myocardial ischemia. During the procedure, VT could be induced by ventricular pacing with the percutaneous puncture needle as the anode and the esophageal tip electrode as the cathode.

Fifteen minutes after the sinus rhythm was recovered by transesophageal low-energy cardioversion, VF or VF was repeatedly provoked by the same method in some of the animals. The energy level chosen for each attempt at cardioversion was set one step lower than that used in the previous successful cardioversion. Throughout the procedure, cardiac compression, transesophageal cardiac pacing, resuscitation drugs, and so forth were administered when necessary.

After the procedure was completed, synchronous shocks (1–60 J), which were irrelevant to cardioversion of the ventricular tachyarrhythmias, were
repeatedly delivered with the same method in all animals to determine the level of shock energy tolerated by the esophagus. Esophagi from dead animals and esophagi from the survivors that were killed 3–25 days later were examined by serial histologic sections.

Statistical Analysis

The Student’s t test was used for statistical analysis of the results. Values are expressed as mean±SD.

Results

Animal Model of Ventricular Tachyarrhythmias

All animals had sinus rhythm at the onset of the study. VF or VF was provoked at least once (one to seven times) in each animal by means of transesophageal random asynchronous shock. However, we found that an episode of VF or VF could be provoked only by the shock that occurred about 40 msec before the peak of the T wave on the ECG and only when its energy level was 10 J or more. An average of 7.2 (five to 11) random asynchronous shocks were required for each provocation of VF or VF. Figure 2 presents a record of a successful provocation of VF. Altogether, 43 episodes of VF or VF were provoked, of which 22 episodes occurred in the dogs and 21 in the pigs.

Acute myocardial ischemia with a manifestation of an ST segment depression of 0.25–0.6 mV occurred in all animals after VF or VF was provoked and terminated either once or repeatedly. During that time, the programmed ventricular pacing provoked seven episodes of VT with a cycle length of 360 msec or less (330±27 msec) in two dogs and three pigs. Two of seven episodes spontaneously terminated at 6 and 15 seconds, and were, therefore, not tested by the method; the remainder had a duration of 31 seconds or more. In five pigs and four dogs, adrenaline (1 or 2 mg i.v.) was used to transform fine VF waves to rough VF waves to make defibrillation easier. They had 14 spontaneous episodes of idioventricular tachycardia (IVT) with a cycle length of 400 msec or more (448±33.5 msec) after defibrillation. We also terminated seven episodes of IVT with a duration of 34 msec or more. The reason for terminating these episodes was to test the capability of transesophageal cardioversion, though IVT is not an indication for cardioversion in our clinic. The other seven episodes of IVT spontaneously terminated within 30 seconds.

Efficacy

Altogether, 43 episodes of VF or VF were successfully terminated by the transesophageal technique. The energy levels associated with successful defibrillation varied from 5 to 30 J (23.1±6.28 J). Figure 3 shows the record of a successful transesophageal defibrillation; five episodes of VT were terminated by this method. The energy levels associated with successful cardioversion ranged from 0.25 to 5 J (1.71±2.25 J). Figure 4 shows the record of a successful cardioversion for VT. The energy required for terminating seven episodes of IVT ranged from 0.25 to 5 J (1.45±2.2 J). Figure 5 presents the record of a successful termination of IVT. The difference between the mean energy lev-
els required for cardioversion of VT and IVT was not significant \( t=0.20, p>0.5 \). Thus, we terminated 12 episodes of VT or IVT with a duration between 31 and 146 seconds. There was no significant difference between the threshold energy of cardioversion for VT or IVT andVF or VF in treating pigs and dogs and between animals that weighed more than 12.5 kg and less than 12.5 kg (see Tables 1 and 2).

**Safety**

All animals received cumulative shock energy ranging from 100 to 377.5 J \( (192\pm 91 \text{ J}) \), including shock energy of subthreshold attempts and energy that was irrelevant to cardioversion. There were no apparent histologic effects in their esophagi according to microscopy. Six surviving animals were observed for 3–25 days and were then killed. There was no occurrence of anorexia, hiccup, or symptoms of esophagospasm during the observation period. In 246 synchronous or asynchronous shocks for cardioversion (including subthreshold shocks), acceleration of the VT or IVT or degeneration to VF or VF never occurred. Three hundred ten random asynchronous shocks that failed to provoke VF or VF, and also, 213 synchronous shocks irrelevant to cardioversion of the ventricular tachyarrhythmias never induced unwanted arrhythmias.

**Discussion**

Conventional transthoracic cardioversion is accepted as the most effective and safest form of electrical therapy to terminate life-threatening tachyarrhythmias. However, it has obvious limitations for long-term applications. The purpose of this study was to develop a therapeutic approach that may be as safe and effective as transthoracic cardioversion but that could have some advantages over the conventional method. During counter-shock by the usual surface electrode technique, only a fraction of the energy administered to the patient is usefully consumed within the heart; the greater part of the administered energy is expended in extracardiac tissues where it is wasted because such tissue does not participate in depolarizing the heart. The transesophageal method, as does the transvenous method, allows the electrodes to be placed closer to the heart.\(^5\)\(^-\)\(^9\) Thus, this method can entirely depolarize the heart with fairly low energy.

In 1966, McNally et al\(^10\) placed one electrode that consisted of bars (22-gauge, 7 cm long coil) in the esophagus, and the other electrode was placed on the precordium of eight anesthetized and five unanesthetized patients. With this method, cardioversion energy for atrial fibrillation was reduced to less than half of that when the conventional surface electrode placement was used. Thirteen patients were observed carefully for any symptoms suggestive of esophageal injury or dysfunction. No symptoms occurred, either immediately or within 4 months. The cardioversion energy for ventricular tachyarrhythmias was not researched by McNally et al, and we did not compare the energy requirement of their esophageal technique with that of our technique. However, we are certain that our method has a lower energy requirement than that of McNally et al because the energy was delivered in such a way that it avoided extracardiac tissues.

The present study is the first attempt to place both the anode and the cathode in the esophagus of animals, and it shows that transesophageal cardioversion with small amounts of energy can safely and effectively terminate life-threatening tachyarrhythmias. In animals, the energy levels of successful

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**Figure 4.** Tracing of a synchronous shock of 2 J that terminated ventricular tachycardia.

**Figure 5.** Tracing of a synchronous shock of 0.5 J that terminated idioventricular tachycardia.
cardioversion for Vf or VF decreased to 30 J or less and decreased to 5 J or less for VT. There is no significant difference between the threshold energy for successful cardioversion in treating the dogs and pigs and between the animals that weighed more than 12.5 kg and less than 12.5 kg. In studies of successful cardioversion for VT with a transvenous catheter, the energy levels that were applied in humans (0.025–2 J) were not too different from those applied in dogs (0.008–1 J). Also, when defibrillation was successfully performed, the energy levels applied in humans (≤15 W) were not too different from those applied in animals (≤10 W). At present, the reason for this is not clear. Whether or not this holds true for the transesophageal technique remains to be confirmed by future study. The thresholds of cardioversion could be influenced by the origin of the life-threatening ventricular tachyarrhythmias in relation to the position and arrangement of the electrode and by other factors, though the origin and other factors were not observed in this study. Quite possibly, future development in the design and arrangement of catheter electrodes may further reduce energy requirements.

The observational results of esophageal function and histologic analysis suggest that the esophagus have a strong resistance to transient current. Single shock energy of 60 J or less and cumulative shock energy of 377.5 J or less did not cause obvious injury in the esophagus. We conclude that the transesophageal technique is not only effective but also safe for treating life-threatening ventricular tachyarrhythmias.

Although delayed defibrillation due to the threshold tests caused acute myocardial ischemia and consequently cardiac damage due to an obvious metabolic abnormality, the animals were all healthy before the study. Therefore, we cannot exclude the possibility that the successful rate of cardioversion in our animals is higher than that in patients with chronic organic heart diseases.

In the early 1970s, Mirowski and coworkers documented the feasibility and effectiveness of low-energy transvenous cardiac catheter defibrillation in humans. Since then, successful animal experiments and clinical application have been reported. Recently, an implanted automatic defibrillator was developed based on these previous studies. At present, the esophageal electrode cannot be permanently placed in patients, but the transesophageal technique has some potential applications. For example, the catheter electrode connected to an external unit can be used on a temporary basis for patients who have frequent recurrences of VT or VF for several days, thereby avoiding repeated chest trauma and the need of anesthesia for cardioversion if thresholds are low. The transesophageal technique could also provide some advantages over the transvenous method in patients who are undergoing cardiac surgery.

It is true that some problems should be solved before the transesophageal technique can be widely used in the clinical setting. Of particular importance, the catheter electrode design and arrangement must be further developed, and the energy requirements for treating various tachyarrhythmias in humans and the level of energy that could be tolerated by unanesthetized patients must be determined. We conclude that the transesophageal technique could be one method with a potentially wide application.

Acknowledgments
We thank Jian Zhifang and Cen Tinhui for support, Ye Guiling for histologic examination, and Mu Jiayi, Zhong Zhi, and Jin Dinyan for secretarial help.

References
5. Jackman WM, Zipes DP: Transvenous, low energy cardioversion of ventricular tachycardia using a catheter electrode

Table 1. Threshold Energy for Successful Cardioversion of Animals

<table>
<thead>
<tr>
<th>Animal</th>
<th>Energy (J)</th>
<th>VT or IVT</th>
<th>Vf or VF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig</td>
<td>1.52±1.97</td>
<td>22.8±6.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(n=5)</td>
<td>(n=21)</td>
<td></td>
</tr>
<tr>
<td>Dog</td>
<td>1.70±2.25</td>
<td>23.4±5.96</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(n=7)</td>
<td>(n=22)</td>
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Student’s t test

<table>
<thead>
<tr>
<th>t</th>
<th>p</th>
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<tbody>
<tr>
<td>0.143</td>
<td>&gt;0.5</td>
</tr>
</tbody>
</table>

Data are mean±SD. VT or IVT, ventricular or idioventricular tachycardia; Vf or VF, ventricular fibrillation or flutter.

Table 2. Threshold Energy for Successful Cardioversion of Various Weights of Animals

<table>
<thead>
<tr>
<th>Weight (kg)</th>
<th>Energy (J)</th>
<th>VT or IVT</th>
<th>Vf or VF</th>
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<tbody>
<tr>
<td>&gt;12.5</td>
<td>1.21±1.68</td>
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<td>(n=7)</td>
<td>(n=17)</td>
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<tr>
<td>&lt;12.5</td>
<td>2.20±2.56</td>
<td>22.3±7.34</td>
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<tr>
<td></td>
<td>(n=5)</td>
<td>(n=26)</td>
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Student’s t test

<table>
<thead>
<tr>
<th>t</th>
<th>p</th>
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</thead>
<tbody>
<tr>
<td>0.814</td>
<td>&gt;0.2</td>
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</tbody>
</table>

Data are mean±SD. VT or IVT, ventricular or idioventricular tachycardia; Vf or VF, ventricular fibrillation or flutter.

KEY WORDS • transesophageal cardioversion • tachyarrhythmias
Transesophageal low-energy cardioversion in an animal model of life-threatening tachyarrhythmias.
Y C Cai, S L Fan, D X Feng, S X Gan, J F Feng, Z S Kuang and Z F Li

Circulation. 1989;80:1354-1359
doi: 10.1161/01.CIR.80.5.1354

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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