Feasibility and Effectiveness of Low-Energy Catheter Defibrillation in Man

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SUMMARY
The effectiveness of low energy intraventricular catheter defibrillation was evaluated in 11 patients undergoing coronary artery surgery, in whom ventricular fibrillation occurred after anoxic arrest of 21-42 min. A distal electrode catheter was introduced through an atriotomy into the right ventricular apex. In eight patients the proximal electrode was a saline-soaked sponge placed on the superior vena cava, while in three this electrode formed an integral part of the superior vena cava cannula used in cardiopulmonary bypass. Intravenous catheter defibrillation was accomplished in nine patients using 5-15 w-sec, considerably less energy than required for paddle defibrillation. There were no apparent short or long-term ill effects. Unsuccessful defibrillation in the two remaining patients was ascribed to difficulties in electrode placement. The effectiveness of low energy intraventricular catheter defibrillation in man, in addition to raising basic electrophysiologic questions, provides background for the development of the transvenous automatic defibrillator for protection of selected high-risk patients.

Additional Indexing Words:
Ventricular fibrillation Sudden death

APPLICATION
Ventricular fibrillation is the only reliable method for terminating ventricular fibrillation. When administered transthoracically, the countershock strength is frequently as high as 400 w-sec, while in thoracotomized patients, with the electrode paddles directly applied to the exposed heart, discharges varying from 20 to 100 w-sec may be required.

Recently, however, ventricular defibrillation by means of a totally intravascular catheter electrode system delivering the countershock from inside the heart has been shown feasible in closed-chest animals. Using this system, it was possible to decrease the energy needed for defibrillation from several hundred to 0.5 (Mirowski M, Mower MM, Wolfson SK: Unpublished data) -10 w-sec, a minute fraction of the conventional transthoracic requirements. The endomyocardial effects of this technic were shown to be minimal.

The effectiveness and the potential advantages of low energy intraventricular catheter defibrillation prompted the present study aimed at evaluating the feasibility of this technic in man. Patients undergoing surgery for coronary saphenous vein bypass were thought to be suitable for catheter defibrillation since they often develop ventricular fibrillation as a result of the elective anoxic cardiac arrest routinely used in this institution during the operation. The objective of the present communication is to report the results of this study and to discuss their clinical and electrophysiologic implications.

Materials and Methods
The 11 patients included in this study were selected at random among those who developed ventricular fibrillation during coronary artery bypass grafting in the Johns Hopkins Hospital between November, 1971 and April, 1972. Nine were male and two were female, their ages ranging from 43 to 61 years (mean 57 years). All suffered from advanced and incapacitating coronary artery disease with prior history of myocardial infarction in five. Coronary arteriography documented double-vessel disease in two patients and triple-vessel disease in the remaining nine.

The equipment used for intraventricular defibrillation was specially built for this purpose and consisted of a
catheter electrode system and a countershock pulse generator.

The electrode system was designed to duplicate as closely as possible the one used in our animal studies (fig. 1). In the initial eight patients it was composed of platinum intraventricular electrodes having a total surface area of 2.4 sq cm, incorporated into the distal tip of a silastic catheter, and of a platinum clamp electrode designed to hold a saline-soaked sponge for placement on the superior vena cava (fig. 2). Because of difficulty in consistently passing the flexible silastic catheter into the right ventricular apex, as well as in maintaining the clamp electrode on the superior vena cava, a more convenient electrode system was subsequently developed and used in the last three patients. This new system was composed of a moderately stiff right ventricular electrode probe (fig. 3, left) and of a second electrode incorporated into, and in fact forming an integral part of, the superior vena cava canula used for cardiopulmonary bypass (fig. 3,

Figure 1

Chest X-ray of a dog showing the position of the single intravascular catheter system during ventricular defibrillation. The distal electrode is wedged into the right ventricular apex, while the proximal electrode is in the superior vena cava.
Electrode catheter system used in the first eight patients consisting of a platinum electrode incorporated into the distal tip of a silastic right ventricular catheter (left) and a platinum clamp designed to hold a saline-soaked sponge for placement on the superior vena cava.

The two electrodes were connected to the countershock pulse generator through an interconnecting cable.

The countershock pulse generator (fig. 4) had the capability of delivering calibrated amounts of energy of 5, 10, 15, and 20 w-sec, independently of the resistive load. Truncated exponential capacitor discharges described by Schuder were used in this study (fig. 5), the pulse width of which varied to compensate for differing heart-electrode resistances. At a resistance of 100 ohms, for example, the pulse width was approximately 4 msec. The block diagram and the function of the pulse generator have been described elsewhere.

A battery-powered oscilloscope was used to observe the pulse waveform width prior to and during the procedure so as to grossly determine the interelectrode resistance and pulse generator performance.

The studies were performed during normothermic cardiopulmonary bypass, achieved by means of a roller pump with a disposable bubble oxygenator and a standard heat exchanger for temperature maintenance. A hemodilution priming solution was used, and the left ventricle was vented during the operative procedure. Normothermic ischemic arrest of the heart was induced by occluding the ascending aorta for a period exceeding 20 min. On release of the clamp ventricular fibrillation was frequently present and in these cases catheter defibrillation was used.

In addition to the usual surgical team, a cardiologist and a qualified electronic technician were present during the procedure. The pulse generator was tested with the battery-powered oscilloscope for its conformity to predetermined specifications. When defibrillation

Electrode catheter system used in the three last patients of the series. The right ventricular electrode (left) is incorporated into the distal tip of a moderately stiff probe. The second electrode (right) forms an integral part of the superior vena cava cannula routinely used during cardiopulmonary bypass.

The countershock pulse generator. Discharges of 20 w-sec were not used in this study.

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was needed the distal electrode catheter was introduced through a 2-mm atriotomy as low as possible into the right ventricle. However, precise determination of its position by palpation was frequently hampered by the thickness of the right ventricular wall. The proximal electrode was placed on the superior vena cava near its junction with the right atrium in eight patients, and was entirely intravascular in the remaining three, as described above.

Shocks of 5 or 10 w-sec were first administered and if sinus rhythm was not restored, additional shocks of 5 or 10 w-sec were applied. If these were unsuccessful, shocks of 15 w-sec were then delivered to the heart. Catheter discharges of 20 w-sec were not used in this study. At times, when the initial shocks were unsuccessful, attempts were made to redetermine the electrode positions, to readjust the catheter or the clamp electrode if found displaced from its intended location, and the shocks repeated. Following defibrillation, the clamp electrode and the right ventricular electrode catheter were removed and the atriotomy closed. The standard internal paddle defibrillator was available in the event that the catheter intraventricular approach would be unsuccessful. Paddles were also used for defibrillation if such was needed following subsequent anoxic arrests for additional grafts.

Results

The results of this study are summarized in table 1. Successful intraventricular catheter defibrillation was achieved in nine of the 11 patients studied: two on the first attempt at 5 w-sec (patients 1 and 2), four were defibrillated with 10 w-sec (patients 3, 5, 8, and 11), and the remaining three patients (patients 4, 6, and 9) with 15 w-sec (figs. 6 and 7). Correct placement of both electrodes was critical for success of the technic. In the two patients who did not respond even to shocks of 15 w-sec the catheter position was clearly uncertain. This was also the case in two patients defibrillated with 15 w-sec and in three others converted with 10 w-sec. In one initially unsuccessful case (no. 5) the clamp electrode was found not to lie in good contact with the superior vena cava, but after repositioning it the shock was immediately effective (fig. 7).

Successful shocks were characterized by pulse widths of 3.5-4.5 msec, indicating an interelectrode impedance similar to that produced by a 100-ohm test load. During unsuccessful shocks pulse widths below these values were interpreted as meaning inadequate electrode separation, while pulse widths of more than 4.5 msec were thought to indicate inadequate electrode-tissue contact.

The duration of anoxic arrest in this series varied between 21 and 42 min, with a mean of 27 min. The two patients defibrillated with 5 w-sec had the shortest periods of anoxic arrest (21 min), while the two who did not respond to the catheter technic had anoxic arrests of 28 and 42 min, respectively. One patient (patient 1) who reverted to sinus rhythm with a shock of 5 w-sec, required two 20-w-sec shocks with internal paddles following a second bypass procedure. No undue short or long-term effects which could be related to the catheter

**Figure 5**

The truncated exponential waveform delivered by the countershock pulse generator.

**Figure 6**

Ventricular fibrillation developed after 23 min of anoxic arrest (pt 3). Conversion to normal sinus rhythm after a single catheter discharge of 10 w-sec (arrow).

**Figure 7**

Ventricular fibrillation after 32 min of anoxic arrest (pt 5). (A) Initial 10-w-sec shock (arrow) does not terminate the arrhythmia. (B) After repositioning the clamp electrode on the superior vena cava, a second countershock (arrow) using the same energy defibrillates the heart.
defibrillation were noted. Specifically, our patients did not demonstrate unusual arrhythmias during or following the procedure, there were no difficulties in weaning them from the pump oxygenator, and they did not develop myocardial infarction, thromboembolic phenomena, or congestive heart failure during an average 3-month follow-up period so far. The only operative death in this series occurred in the patient who underwent a triple graft procedure requiring four separate periods of anoxic arrest; catheter defibrillation was attempted following two of these periods without success. The autopsy did not show any lesions which could be attributable to the defibrillation technic.

Discussion

Defibrillation using an intravascular electrode catheter system appeared to be a logical approach for the implementation of the automatic defibrillator concept. Such an implantable device for automatic recognition and treatment of ventricular fibrillation was seen as a partial solution to the problem of lethal arrhythmias occurring outside the hospital setting. It was soon realized that in the present stage of capacitor technology, miniaturization of a defibrillator to a size small enough to allow its implantation in man could only be accomplished through a significant decrease in the amount of energy required for defibrillation. Since most of the current applied transthoracically is dissipated in the surrounding tissues before reaching the heart, countershock delivery through a catheter from within the ventricular cavity was considered to be a possible and even an attractive way to achieve defibrillation with low energy levels.

This working hypothesis was tested in animals and demonstrated as being correct. The right ventricular electrode catheter used for intravenous defibrillation was initially paired with a subcutaneous precordial plate, but subsequently it was found possible to incorporate the two defibrillatory electrodes into a single intravascular catheter.
system in which the distal electrode was wedged into the right ventricular apex and the proximal one located in the superior vena cava (fig. 1).

The present study demonstrates that intraventricular catheter defibrillation is also feasible in man. The energy levels of 5–15 w-sec which terminated the arrhythmia compare favorably to those used in the experimental animal. The rate of successful reversions in this admittedly small series was high (nine of 11). In the two unsuccessful attempts (patients 7 and 10) there were acknowledged difficulties in placing and maintaining the electrodes correctly. In one of these cases, however, unusually long periods of anoxic arrest were present and might have prejudiced the ability to achieve defibrillation.

In discussing the significance of the above results one should note that they were obtained under adverse metabolic conditions, markedly different from those present in patients with primary ventricular fibrillation in whom catheter defibrillation is mainly intended to be used. It is well documented that patients on cardiopulmonary bypass whose hearts are submitted to anoxic cardiac arrest in excess of 20 min rapidly develop profound lactic acidosis12 which decreases myocardial contractility13 and the responsiveness of the myocardium to catecholamines,14 thus making defibrillation relatively difficult.15 On the other hand, patients who develop primary ventricular fibrillation resulting from electrical instability of the heart have by definition very little, if any, important metabolic changes. It is thus conceivable that in this latter group the catheter technic of defibrillation could yield an even higher rate of success as well as a further decrease in the amount of energy required for terminating the arrhythmia.

The very feasibility of catheter defibrillation raises intriguing questions regarding its basic mechanism and that of ventricular fibrillation and defibrillation in general. It has hitherto been assumed that an extrinsic electrical discharge terminates arrhythmias by instantaneously depolarizing all cardiac fibers,16,17 thus allowing the pacemaker having the highest degree of automaticity to assume control of the heart. While satisfactorily explaining defibrillation by means of transthoracic and internal paddles, this concept does not seem applicable to defibrillation through a catheter, the geometry and electrode distribution of which are unlikely to achieve sufficient current density to depolarize the entire myocardium. This issue is of considerable interest in view of the long-standing controversy regarding the nature of ventricular fibrillation. If indeed depolarization of only a group of fibers can terminate the arrhythmia, then fibrillation is most probably due to a "circus movement,"18 defibrillation reflecting interruption of one or several of the "reentry" pathways. It is evident that clarification of this fundamental electrophysiologic problem is mandatory.

At this stage, the full clinical significance of our results can only be surmised. Although catheter defibrillation as performed in the present study involved thoracotomy, the nature of the technic allows transplantation of our data to closed-chest patients. Should this assumption prove correct, the energies required for defibrillation of intact patients would thus be decreased from a few hundred to 15 w-sec or less. This amount can readily be packaged in a clinical device sufficiently small for semiimplantable or even completely implantable use. It appears then that the most important long-term implication of our data is the thrust they provide for the development of the transvenous automatic defibrillator.3–5 While considerable work on various levels is still required, this demonstration of the feasibility and effectiveness of low energy catheter defibrillation in man, even under conditions of extreme ischemia, clearly justifies further efforts in pursuit of such a concept.

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