A Chronically Implanted System for Automatic Defibrillation in Active Conscious Dogs

Experimental Model for Treatment of Sudden Death from Ventricular Fibrillation

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SUMMARY Ventricular defibrillation was achieved in active conscious dogs with a chronically implanted automatic system composed of a defibrillator and an alternating current fibrillator. The hermetically sealed defibrillator is encased in titanium, weighs 250 g and has a volume of 145 ml. The sensor continuously monitors ventricular electrical activity and recognizes fibrillation by the absence of isoelectric potential segments. Fibrillation is induced by placing a magnet over the implanted fibrillator. The resulting syncope closely resembles the clinical entity of sudden death, while the defibrillator automatically restores normal rhythm with a truncated exponential pulse of 30 J, 15 seconds after the onset of the arrhythmia. The operational status of the defibrillator can be tested in vitro and noninvasively in vivo with an external analyzer. This experimental model allows for the first time a long-term study of the automatic implantable defibrillator approach to prevent sudden death from ventricular fibrillation under a variety of physiopathologic conditions.

BECAUSE THE EFFECTIVENESS of electrical countershock for ventricular fibrillation depends entirely on the prompt availability of specialized personnel and equipment, limited progress is being made in the management of patients who develop this arrhythmia outside the hospital. It has been suggested, therefore, that an implantable device programmed to monitor the heart continuously, identify ventricular fibrillation and automatically deliver corrective defibrillatory shocks when indicated, could be one of the solutions to the problem of sudden arrhythmic death. Such an automatic defibrillator might provide patients with protection from lethal arrhythmia wherever it occurs. Conceptually, the device might also be viewed as analogous to an implantable demand pacemaker, except that ventricular fibrillation instead of asystole is sensed, and the delivered shock is of defibrillating magnitude.

The development of an automatic implantable defibrillator has permitted us to report the first successful automatic defibrillations in active conscious dogs with chronically implanted defibrillators. Together with a miniaturized implanted fibrillator, the implanted defibrillator forms a chronic automatic defibrillating system designed to serve as an experimental model for evaluation of this approach to the prevention of sudden death from ventricular fibrillation under a variety of physiopathologic conditions.

Equipment and Procedures

The automatic defibrillating system (fig. 1)* is composed of two implantable devices: 1) the automatic defibrillator and 2) the alternating current fibrillator. The system is supplemented by a defibrillator analyzer.

The automatic implantable defibrillator is encased in titanium and hermetically sealed with an electron beam weld; it weighs 250 g and has a volume of 145 ml. All materials in contact with body tissue are biocompatible. The defibrillating electrodes are made from titanium mesh and silicone rubber. One of the electrodes is located on an intravascular catheter pervenously introduced into the superior vena cava. The second electrode is placed extrapericardially over the apex of the heart through a left thoracotomy. The outside surface of the apex electrode is insulated to achieve optimum current distribution.

The sensing system continuously monitors a sampled probability density function of the ventricular electrical activity. This function defines the slope fraction of time spent by the differentiated input electrogram between two limits located, in this particular system, near zero. Ventricular fibrillation is recognized by the striking absence of isoelectric potential segments. This approach directly detects fibrillation by identifying a specific characteristic of the arrhythmia, rather than such indirect parameters as the absence of R waves, arterial pressure, electrical impedance, etc. Several backup safety systems are incorporated in the design to minimize the risk of an unnecessary shock. In particular, the capacitor charging cycle will not be initiated unless appropriate voltage levels are present in three critical areas of the cir-

*Developed in conjunction with Medrad, Inc., Pittsburgh, Pennsylvania.
Automatic defibrillation in dogs

The automatic defibrillating system. The implantable defibrillator with apex and superior vena cava electrodes appears at the bottom left, the defibrillator at the bottom right, and the defibrillator analyzer in the upper right half of the photograph. The arrow points toward the electromagnetic transducer.

cuity. Characteristic signal pulses are also required to be present at a fourth point. This sensor has been tested in animals in which only paced rhythms faster than 350 beats/min have been occasionally misinterpreted. In addition, the detector has been challenged by means of a wide range of tape-recorded human arrhythmias derived from surface body leads. Since this is not an entirely adequate test of this system, direct human testing during open heart surgery is being contemplated in the near future. A detailed description of the principles on which this approach is based has been reported elsewhere.4

A truncated exponential pulse was selected for use in the implantable defibrillator. Such pulse is simple to generate, and for a given defibrillation efficacy appears to require less peak voltage and peak current than the damped sine wave and simple capacitor discharges. Because the initial and terminal voltage levels of the pulse are predetermined, its duration ranges between 3–8 msec as a function of the differing heart-electrode resistances.

The device delivers corrective shocks of up to 30 J about 15–20 seconds after the onset of the arrhythmia and can recycle as many as three times if the first shock is ineffective. After the fourth shock, about 35 seconds of normal rhythm are required to reset the counter and to allow a full series of pulses to be delivered again at the next episode. Pacemaking capabilities can be incorporated into the present design. Specially developed lithium batteries have a projected monitoring life of three years or a discharge capability of approximately 100 shocks.

The defibrillator (fig. 1) induces ventricular fibrillation in active, unanesthetized animals. By placing a magnet over the skin in the area where the defibrillator is implanted, 20 mA of 60 Hz current is produced and applied to the heart through a conventional right ventricular pacing catheter.

The defibrillator analyzer (fig. 1) is an instrument designed for testing the operational status of the automatic defibrillator both before and after permanent implantation. The method involves the cycling, in a manner innocuous to the subject, of a built-in test mode. A magnet placed over the skin in the area of the implanted defibrillator first inactivates the device, and it will remain disabled for as long as the magnet is in place. If the defibrillation detection system is functioning properly, removing the magnet triggers a capacitor charging cycle. Special circuits monitor critical areas of the detector and disable both the detector and the test mode circuit should an abnormal operating condition arise. After becoming fully charged, the capacitors are automatically discharged into the built-in test-load resistor. The charge time is monitored by placing a small electromagnetic transducer over the subject's skin near the implanted unit. The transducer is resonant at the defibrillator's inverter frequency and acts as a transformer, detecting an AC signal when the inverter is running. A digital display indicates the time required to charge the capacitors. Progressive increases in the charge time, normally 10 seconds or less, reflect battery depletion, while failure to initiate the cycle indicates abnormal device operation.5

The automatic defibrillating system was implanted in five mongrel dogs weighing from 16–28 kg. A chest x-ray of a dog with all the components of the permanently implanted automatic defibrillating system is shown in figure 2. The apex electrode was positioned first, and the remaining elements were implanted either during the same procedure or later. Correct position of the defibrillating electrodes was radiologically confirmed, ventricular fibrillation induced, and a series of calibrated nonautomatic shocks delivered through temporarily exteriorized leads to determine the defibrillation threshold; it ranged between 4–10 J. The functional status of the defibrillator was tested with the analyzer before implantation and before each subsequent attempt to exercise the automatic defibrillating system. The system was considered to have been exercised when ventricular fibrillation was induced with the implanted fibrillator, and the episode was defined as successful when automatic defibrillation was accomplished.

The automatic defibrillating system was first exer-
cised immediately after implantation of the system, while the animals were still under anesthesia. There were 18 such episodes in this series. Seventeen shocks were successful on the first attempt. In one instance the initial shock was ineffective, but the unit recycled as programmed and terminated the arrhythmia.

Maintaining these animals to ensure an appropriate chronic test preparation was hampered by numerous difficulties. In this early series, infection was a frequent complication as was extrusion of the fibrillating and defibrillating modules, migration of the right ventricular fibrillating catheter, and damage to the electrode catheters by the animals. Subsequent access to the venous system for catheter reimplantation was through the azygous vein. When this approach was not feasible, epicardial fibrillating electrodes were used.

With the dogs awake, the automatic defibrillating system was exercised in three dogs on seven occasions. The experiments were performed four and one-half to nine and one-half months after insertion of the apex electrode and one week to four months after implantation of the defibrillator. Five successful episodes of automatic defibrillation, all after a single shock, were observed in two dogs. Figure 3 shows a typical electrocardiographic sequence of such a fibrillation-defibrillation episode. During the sixth episode, the delivered shock failed to defibrillate the animal; at autopsy, a damaged electrode lead was found. In the third dog the shock was not delivered as expected due to a subsequently corrected design problem; the animal was defibrillated externally but was later sacrificed because of chronic infection and the inability to induce fibrillation. One animal was sacrificed for similar reasons before receiving any shocks in the awake state, and another is being treated for infection and has not yet been tested in the awake state.

Discussion

The inability to deal effectively with ventricular fibrillation outside the hospital is generally recognized. The few strategies proposed to deal with this major public health problem have been unsatisfactory. Primary prevention of arteriosclerotic heart disease does not seem attainable in the near future, and secondary prevention with prophylactic antiarrhythmic therapy will not be possible until the development of effective long-term medication. While mobile coronary care units can save a number of patients, their logistics preclude a broad application of the approach. This drawback is compounded by the tendency of the resuscitated patients to fibrillate again, with a mortality in this clinically well-defined group of about 30% in the first year alone.

With these factors in mind, efforts have been made to study the numerous facets of the automatic implantable defibrillator. The purpose of this
approach is to provide patients with a particularly high risk of developing ventricular fibrillation the kind of critical services available today almost exclusively in a coronary care unit. The goal is to create conditions for prompt defibrillation of patients struck by ventricular fibrillation before a rescue system can come into play.

Over the past few years, several prototypes of the device have been designed and tested by our group. A continuous set of improvements has been incorporated into these successively models. The version described in the present report is of interest because it has the size and operating characteristics suitable for permanent implantation in man.

When used together with the implanted fibrillator in active conscious dogs, a fibrillating-defibrillating system is formed, allowing long-term study of the effectiveness, reliability and safety of the automatic defibrillator. The value and significance of data obtained during bench testing and acute animal experimentation are greatly increased by information collected through periodic exercising of the system. Ventricular fibrillation induced with the technique used in the present investigation leads to effects closely resembling the clinical entity of sudden death, while the automatic defibrillator provides a means of restoring effective cardiac rhythm within seconds, with each animal serving as his own control under closely comparable experimental conditions. It is expected that this chronic model will help expose potential defects and limitations of the automatic defibrillator so they can be eliminated by improvements in the design and/or in the quality of the material used. The experience gained could then be extrapolated to human subjects with relative safety.

While automatic defibrillation during acute experiments has been reported in the past, this study is the first to demonstrate the long-term feasibility of such a method using a chronically implanted defibrillator. The crucial problems related to the miniaturization of the device, determination of effective energy levels, selection of an appropriate waveform and electrode configuration, development of special power sources and creation of a reliable sensing system have been essentially overcome. The clinical implications are even more significant, since evidence of long-term effectiveness of the device represents the precondition for an eventual application of this approach in humans. At the same time, the current work on automatic defibrillation parallels an increasing ability to identify subsets of patients at high risk of sudden death for whom only limited prophylactic or therapeutic options are available.

The applicability of automatic defibrillation to man has been greatly enhanced by the development of a method for testing the operational readiness of the device in vivo. Significantly, such an assessment is noninvasive, simple and requires little time to perform. Since the implanted defibrillator is expected to exhibit long periods of inactivity, information regarding its functional and structural condition is particularly important.

It appears from the above considerations that the implementation of the automatic defibrillator approach to prevention of sudden death from ventricular fibrillation has become a practical possibility. The bioengineering feasibility has been demonstrated, and the gap between early experimental prototypes and a clinical device has been virtually closed. If additional studies confirm our preliminary data, and if progress in identification of high risk patients continues, a new therapeutic modality for dealing with lethal arrhythmias outside the hospital could become available.

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