Efficacy of Automatic Multimodal Device Therapy for Ventricular Tachyarrhythmias as Delivered by a New Implantable Pacing Cardioverter-Defibrillator

Results of a European Multicenter Study of 102 Implants

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Background. Third-generation implantable cardioverter-defibrillators are devices designed to treat ventricular tachycardia (VT) and ventricular fibrillation (VF) by means of overdrive pacing, cardioversion, or defibrillation. So far, the efficacy of tiered therapy has been documented only in small series. Therefore, a European multicenter clinical evaluation study of a new tachyarrhythmia control device, the Medtronic PCD pacemaker-cardioverter-defibrillator with epicardial patch-lead configuration, was undertaken.

Methods and Results. We report on 102 patients (mean age, 55±13 years) from 11 European centers. PCD devices implanted between May 1989 and February 1991 were included. The patients suffered from hemodynamically significant ventricular tachyarrhythmias not suppressed by antiarrhythmic drug therapy and unrelated to acute myocardial infarction; one patient had nonsustained VT and severely depressed left ventricular function. Seventy patients had coronary artery disease with old myocardial infarctions, 23 had cardiomyopathies of various etiologies, and nine patients had no detectable heart disease. Mean ejection fraction was 36±14% (range, 10–76%). Mean intraoperative defibrillation threshold (51 patients) was 10.6±5.1 J (range, 2–18 J). The documented follow-up ranged from 1 to 21 months (mean, 9.4±5.8 months), or 79.9 cumulative patient-years. Perioperative mortality was 3.9%. The actuarial survival rate at 12 months was 91%. One sudden arrhythmic death occurred. Sixty patients (58%) received device therapy. Seventeen patients had therapies only for “VF” episodes, 16 patients only for VT, and 28 patients for VT and “VF” episodes. Based on device memory data, 1,235 spontaneous VT episodes were detected and treated in 43 patients. Twelve hundred four of these VT episodes received painless initial antitachycardia pacing therapy, restoring sinus rhythm in 91%. The 108 ongoing episodes received 209 multiple therapeutic attempts. Eighty-five additional overdrive pacing therapies restored sinus rhythm in 30%. Initial ineffective antitachycardia pacing therapies received 51 cardioversion pulses. The success rate was 61%. Seventy-three additional cardioversion pulses were delivered to backup ineffective pacing therapy as well as ineffective secondary cardioversion pulses. Their success rate was only 40%. Two hundred eighty-six spontaneous episodes were detected in 44 patients as “VF.” Overall defibrillation efficacy was 97.6%.

Conclusions. The implanted device nearly eliminates sudden arrhythmic death in patients with documented, potentially fatal ventricular tachyarrhythmias. Automatic tiered therapy is highly effective to restore sinus rhythm, provided that an integrated two-zone tachycardia detection algorithm is used, assigning lower tachycardia rates to overdrive pacing and/or cardioversion and higher tachycardia rates to defibrillation. In general, spontaneous VTs can be terminated by automatic overdrive pacing, and painful or disturbing countershock therapies are not required to terminate the majority of spontaneous VT episodes. (Circulation 1992;86:363–374)

Key Words • pacing • automatic implantable defibrillator • ventricular tachycardia • sudden cardiac death • ventricular fibrillation

Implantable cardioverter-defibrillators (ICD) are used to terminate ventricular fibrillation (VF) or ventricular tachycardia (VT) by the automatic discharge of countershock pulses.1 Several studies doc-

umented the favorable outcome of patients at high risk of sudden cardiac death treated with an ICD.2–4 Third-generation devices integrate automatic antitachycardia pacing, cardioversion, and defibrillation therapies; on-demand ventricular pacing; memory functions for sensed and therapeutic events; selectable current pathways; and noninvasive programmed electrical stimulation. Reports with a representative number of implants of such a third-generation automatic implantable pacin-
TABLE 1. Clinical Data of the Patients Receiving a PCD Implantation

<table>
<thead>
<tr>
<th>No. of patients</th>
<th>102</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age (years)</td>
<td>55±13</td>
</tr>
<tr>
<td>Male (No.)</td>
<td>84</td>
</tr>
<tr>
<td>Female (No.)</td>
<td>18</td>
</tr>
<tr>
<td>Survivors of SCD (%)</td>
<td>65 (63%)</td>
</tr>
<tr>
<td>Documented sustained VT (%)</td>
<td>60 (58%)</td>
</tr>
<tr>
<td>Mean ejection fraction (%)</td>
<td>36±14%</td>
</tr>
<tr>
<td>Previous myocardial infarction (%)</td>
<td>68 (66%)</td>
</tr>
<tr>
<td>Cardiomyopathy (%)</td>
<td>25 (24%)</td>
</tr>
</tbody>
</table>

SCD, sudden cardiac death; sustained VT, sustained ventricular tachycardia.

VT, and 3) the appropriateness of automatic device therapy.

Methods

The ethical committee of each participating center approved the clinical trial of this device. The patients were finally selected for a PCD implantation if they 1) had spontaneously occurring sustained VT or VF or a history of aborted sudden cardiac death and inducible sustained ventricular tachyarrhythmias, 2) did not respond to either conventional antiarrhythmic drug therapy or amiodarone therapy as indexed by persistent inducibility using a standard ventricular stimulation protocol or spontaneous ventricular tachyarrhythmia recurrence, 3) were not considered suitable candidates for surgical or catheter-ablative procedures or refused such a procedure, 4) were considered compliant to participate in the study, and 5) gave their informed, written consent.

Eleven European centers, using at least five device implants, participated in this report. The study population, summarized in Table 1, consisted of 102 patients (84 men and 18 women; mean age, 55±13 years) who received the device between May 1989 and February 1991. Seventy patients had coronary artery disease. Old myocardial infarctions were present in 68 patients. Previous coronary artery bypass surgery was done in seven patients combined with left ventricular aneurysmectomy in three patients. Twenty-five patients suffered from cardiomyopathies of various etiologies, including two patients with right ventricular dysplasia. No detectable heart disease was present in seven patients. Left ventricular ejection fraction, as measured by either biplane contrast ventriculography, bidimensional echocardiography, or nuclear ventriculography, ranged from 10% to 76% (mean value, 36±14%). Thirty-six patients had a history of spontaneous, sustained VT; 41 patients had a history of an aborted sudden cardiac death or emergency cardioversion for ventricular tachyarrhythmia; and 24 patients had a history of documented VT and a cardiac arrest. One patient with a left ventricular ejection fraction of 13% had a history of recurrent nonsustained VT and showed reproducible induction of VF during programmed ventricular stimulation. The cycle length of the documented spontaneous VTs ranged from 215 to 580 msec (mean, 333±78 msec).

Electrophysiological Evaluation

Programmed ventricular stimulation studies were done using standard techniques. As many as three ventricular extrastimuli were delivered at the right ventricular apex, either during sinus rhythm or at a basic drive cycle length of 600 and/or 400 msec. Before device implantation, 99 patients underwent programmed ventricular stimulation. One patient with incessant VT and two patients who had survived a cardiac arrest did not undergo programmed ventricular stimulation. In 90 patients, sustained monomorphic VT was induced; in 38 patients, more than one distinct morphology was induced. In 66 patients, the induced VT was accompanied by symptoms such as dyspnea, chest pain, or syncpe. In 15 patients, sustained VT was hemodynamically well tolerated. In nine patients, no data were available. Polymorphous VT exclusively was not induced. Primary VF was induced in nine patients. Before device implantation, 93 patients had experienced an average of 3.6±2.3 antiarrhythmic drug trials.

Device

Two versions of the PCD were used: initially, the model 7216A with a volume of 209 ml and a weight of 281 g was used; later, the model 7217B with a volume of 113 ml and a weight of 197 g was used. Apart from size and weight, the two models only differ in sensing configuration. The model 7216A features integrated bipolar sensing (between one myocardial pacemaker electrode and the negative defibrillation electrode), whereas the model 7217B has conventional bipolar sensing.

The device has been recently described in detail.3 In summary, the PCD provides two separately programmable tachycardia detection zones—one assigned for the detection of VT, and one for VF. To avoid inadvertent triggering of VT therapy by sinus tachycardia or atrial fibrillation, an onset or a stability criterion, respectively, can be activated.

Episodes of VT can be treated by as many as four independently programmable therapies. Three kinds of VT therapies are available: two different types of overdrive pacing (ramp or burst antitachycardia pacing) and a synchronized, energy programmable (0.2–34 J) cardioversion. The progression of VT therapy, e.g., from antitachycardia pacing to cardioversion pulses, can be tailored to the patient’s needs. Detection of VF is based on rate alone, and the shock delivery is committed. Up to a maximum of four defibrillation shocks can be delivered for an ongoing VF episode. Like the cardioversion pulses, they are programmable in energy, pulse width, and current pathway. Shocks can be delivered between two or three epicardial patch electrodes in single, bidirectional simultaneous, or bidirectional sequential current pathways, respectively. Epicardial defibrillator patch leads (model 6921) are available in
three sizes with an electrode surface of 30, 45, or 60 cm², respectively.

The PCD offers memory functions that store the number of detected VT or VF episodes separately as well as the successes or failures of the respective therapies. To help to identify the appropriateness of delivered therapies, 20 RR intervals just prior to the last detected VT/VF episode and 10 intervals after the last VT/VF therapy of the last VT/VF episode are retained in memory. PCD further features multiprogrammable on-demand ventricular pacing, automatic sensitivity control, and noninvasive ventricular stimulation for VT and VF induction. Via telemetry, the ventricular bipolar electrogram, the Marker Channel indicating the categorization of sensed, paced, and therapeutic events; the battery voltage; the last charge time; all programmed parameters; and stored therapy data can be obtained and printed out using the printer that is incorporated in the programmer. One example of an induced episode is given in Figure 1.

**Implantation Procedure**

All implantations were done with the patient under general anesthesia. Implantation of the epicardial sense electrodes and patch leads was accomplished via a median sternotomy in 78 patients, via lateral thoracotomy in four patients, via subcostal thoracotomy in seven patients, and via subxyphoidal approach in 13 patients. Two myocardial screw-in electrodes (Medtronic 6917A) were placed in every patient; however, only one was connected with the PCD device for model 7216A implants. The capped one served as a spare electrode for eventual future replacement with a PCD model 7217B. Two patch electrodes for cardioversion and defibrillation were sutured epicardially or pericardially, ideally one anteriorly over the right ventricle and one posteriorly over the left ventricle. All devices were placed in a subcutaneous abdominal pocket, and the leads were connected by subcutaneous tunneling.

Usually, continuous surface ECG rhythm monitoring was performed for at least 72 hours after surgery.

**Intraoperative Testing**

Intraoperative testing was done according to the manufacturer's study protocol and consisted of analysis of pacing, sensing, and defibrillation functions. At least three surface ECG leads, the local bipolar ventricular ECGs, and the Marker Channel were recorded on paper during testing of VF and VT therapies.

Defibrillation threshold was estimated according to a standardized defibrillation efficacy protocol as previously described. The defibrillation electrodes were interfaced to an external tachyarrhythmia control device (model 5355, Medtronic Inc.). Shocks were delivered manually. Defibrillation threshold testing always started with a two-patch–lead configuration. At least three successful defibrillations with an energy ≤18 J (pulse width of 6.3 msec for single pathway configuration) were required. VF was induced using an external AC-defibrillator or rapid ramp pacing via the implanted electrodes. A triple electrode configuration would be tested only if the defibrillation threshold was >18 J.

VF detection was tested at a programmed sensitivity of 1.2 mV. P or T wave oversensing during sinus rhythm and pacing was tested at a sensitivity of 0.3 mV. If oversensing occurred, the oversensing threshold was determined. If negative, the sensitivity was programmed either at 0.3 or 0.6 mV.

**Postoperative Tests**

Usually, the patients underwent a bicycle exercise test before hospital discharge or at 1-month follow-up to assess sinus rate during physical activity and to exclude oversensing during this physical activity.

Before hospital discharge, radiographs of chest and abdomen were done in every patient to document positions of the implanted electrodes and the device. Before discharge or at 1 month after implantation, patients underwent noninvasive programmed ventricular stimulation to induce VF and VT. VF induction was attempted, at least once, in most patients. One or multiple surface ECG leads and the Marker Channel were recorded during all induction and termination episodes. To test VF or cardioversion therapies, the patients were either sedated or were under neuroleptic anesthesia.

**Programming of the Device at Discharge**

The PCD device was programmed based on the various testing results (preoperative, intraoperative, and postoperative stimulation studies).

The following guidelines for programming of VF therapies were given: 1) set the initial VF therapy defibrillation energy at least twice defibrillation threshold and never <18 J and preferentially to 34 J; 2) set VF detection interval about 30 msec shorter than the cycle length of the fastest VT that should be treated with antitachycardia pacing or low-energy cardioversion; 3) only use VF detection interval shorter 300 msec in patients with hemodynamically stable VTs of more than 200 beats per minute; and 4) use a sensitivity level of 0.3 mV, unless undesirable treatments may be caused by T wave oversensing.

VT therapies were prescribed on a more individual basis. Most centers tried to define an initial antitachycardia pacing therapy if the patient presented sustained monomorphic VT with good to fairly well hemodynamic tolerance. Preference to initial cardioversion was given to patients with rapid, compromising VT.

**Follow-up**

Follow-up of patients and devices was done at each implanting center according to a uniform study protocol. The follow-up visits were scheduled after 1 month and 3 months after surgery and every 3 months thereafter. Each follow-up collected patient-related and device-related data. Two-dimensional echocardiography, chest radiographs, and abdominal radiographs were done at least once during follow-up.

At each follow-up, the device was interrogated to obtain its present programmed status and data on its operation. Noninvasive programmed ventricular stimulation was done when the patient's history required verification of tachyarrhythmia detection or therapy and when antiarrhythmic drug therapy was modified. If indicated, the programming of the unit was altered.

In patients who died, the device status was interrogated, explanted, and then sent to the manufacturer for additional investigation.
Figure 1. Induction of a rapid monomorphic ventricular tachycardia (RR interval 220–290 msec) by burst pacing (pacing stimulus interval, 200 msec) using the noninvasive programmed ventricular stimulation option of an implanted PCD. As soon as the rapid pacing is terminated, “ventricular fibrillation” is detected (according to the programmed detection criteria), and after the charging period a defibrillation (D) shock of 18 J is delivered. One-surface ECG lead and the Marker Channel are recorded on the printer incorporated in the programmer. The real-time Marker Channel indicates the categorization of the detected events by annotation. VP, ventricular pacing; VF, ventricular fibrillation; TS, tachycardia sensing; FS, fibrillation sensing. Before and after this episode, the device was interrogated and the obtained data reports were pasted below the ECG strip. A: Success count before the last delivered therapy. B: Data after the last therapy delivery. For further details, see “Methods.”
Definitions

**Antiarrhythmic pacing:** Overdrive pacing, consisting either of burst pacing or ramp pacing, with a stimulus width and amplitude programmed as for the ventricular on-demand (VVI) pacing mode (usually 5 V amplitude and 0.5–1.0 ms pulse width)

**Antiarrhythmic pacing is adaptive:** The cycle length of the antiarrhythmic pacing is programmed as a percentage of the average cycle length of the last four cycles before ventricular tachycardia detection.

**Burst pacing:** A rate-adaptive, equal-interval set of stimuli; for the subsequent sequence of stimuli, the interval is shortened by a programmable value.

**Ramp pacing:** A rate-adaptive set of pacing stimuli delivered at decreasing intervals similar as in autodecremental pacing; however, each successive sequence adds one impulse to become the shortest interval of the sequence.

**Cardioversion:** Synchronized, uncommitted countershock therapy

**Defibrillation:** Nonsynchronized, committed countershock therapy

**Defibrillation threshold:** Lowest shock energy that defibrillated the heart at least once under the condition that a shock of lesser energy has been demonstrated to fail

**Lowest energy of defibrillation:** Lowest energy that defibrillated the heart during testing, irrespective whether attempts were made to demonstrate a lower energy that failed.

**Problematic therapies:** Ventricular tachycardia or ventricular fibrillation therapies triggered by supraventricular tachycardias like atrial fibrillation, atrial tachycardia, or sinus tachycardia that fulfill a programmed ventricular tachycardia detection interval or ventricular fibrillation detection interval

**Staged or tiered therapy:** Automatic progression from a less aggressive (e.g., overdrive pacing) to a more aggressive (e.g., antitachycardia pacing with shorter stimuli intervals and/or a higher number of stimuli or delivery of cardioversion pulses) and potentially more effective therapy in case the previous therapy was ineffective and an ongoing tachyarrhythmia episode is redetected; if, at any time the detected rhythm satisfies the programmed ventricular fibrillation criteria, ventricular tachycardia therapies are abandoned in favor of ventricular fibrillation therapies

**Complication:** A symptomatic or asymptomatic clinical event with potential adverse effects, which cannot be treated or resolved by programming the device and requires intervention after implantation; complications or death are classified as nondevice or device related. A committee formed by six investigators reviewed and classified the complications and deaths

**Operative death/complication:** Events occurring within 30 days of implantation

**Late in-hospital mortality:** Death occurring >30 days after implantation in a patient who has never left the hospital

**Device-related death or complication:** Event that results from a malfunction in operation that is not according to design specification of a component, or as a result of a device-induced arrhythmia or an interaction between a device component and the patient

**Procedure-related death/complication:** An event occurring as a result of a procedure required to implant, follow, or test a device

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Efficacy of Automatic Multimodal Device Therapy

**Table 2. Summary of the PCD Implantation Data**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best electrode systems (%)</td>
<td>97 (95%)</td>
</tr>
<tr>
<td>Triple-electrode systems (%)</td>
<td>5 (5%)</td>
</tr>
<tr>
<td>Mean DFT (51 patients) (J)</td>
<td>10.6±5.1</td>
</tr>
<tr>
<td>Range (J)</td>
<td>2–18</td>
</tr>
<tr>
<td>Mean patch electrode resistance (Ω)</td>
<td>35.7±12.3</td>
</tr>
<tr>
<td>Mean pacing threshold at 0.5-msc pulse width (V)</td>
<td>0.94±0.47</td>
</tr>
<tr>
<td>Mean slew rate (V/sec)</td>
<td>1.47±0.94</td>
</tr>
</tbody>
</table>

DFT, defibrillation threshold.

Wilcoxon test. Differences were considered significant at p ≤ 0.05.

Results

**Intraoperative Measurements**

The implantation data are summarized in Table 2. Sixty-two patients received a 7216A device, and 40 patients received a 7217B device.

The myocardial screw-in leads had a mean slew rate of 1.47 V/sec, a mean R wave amplitude of 13.6 mV, and a mean pacing threshold of 0.94±0.47 V at 0.5 ms pulse width.

**Defibrillation Threshold**

Five hundred ninety-two VF episodes were induced in 94 patients. VF was not inducible in the remaining patients. In 51 patients, in whom the defibrillation energy was assessed according the protocol until a defibrillation failure occurred or the 5-J level was reached, the mean defibrillation threshold was 10.6±5.1 J. In 34 patients, in whom no systematic effort was undertaken to determine the defibrillation threshold, the lowest defibrillation energy ranged from 10 to 18 J. In six patients, it was impossible to induce more than two VF episodes as required by the protocol. Their mean lowest energy of defibrillation was 16.5 J (range, 15–18 J). Three patients did not meet the implant criteria; had defibrillation failures at >30 J, but received the device nevertheless based on the investigator’s discretion. One of those patients died 15 days after implantation (due to bleeding), and one patient had a sudden cardiac death 407 days after implantation. The remaining patient is still alive. At the 3-month follow-up, ventricular flutter was noninvasively induced and terminated with a 34-J shock. According to the device counters, five episodes were detected and effectively defibrillated (stored RR intervals, 210–290 msec).

Patch electrode impedance ranged from 20 to 103 Ω, and mean total patch electrode surface area was 108.8±17.2 cm². Five patients received a triple electrode lead configuration to achieve a defibrillation threshold ≤ 18 J.

Detection of induced VF episodes was tested at a sensitivity level of 1.2 mV.

**Postoperative Follow-up**

Ninety-seven patients (95%) were discharged from the implanting centers. The mean documented follow-up of these patients is 9.4±5.8 months (range, 1–21 months). Ninety patients reached a follow-up of at least 3 months, 46 patients of at least 12 months. The total documented cumulative follow-up time is 79.9 patient-years.

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Statistical Analysis

Data are reported as mean±SD values; for the survival curves, the standard errors are indicated. The survival probabilities across time intervals were calculated according to Cutler and Ederer,6 and the differences between the curves were analyzed using the...
Programming of the Device at Last Documented Follow-up

In 71 of 97 discharged patients (73%), VT therapies were programmed. Comparing patients who had any kind of VT therapy activated with patients who had no kind of VT therapy programmed, no significant difference concerning left ventricular ejection fraction, type of underlying heart disease, or ventricular tachycardia cycle length was observed. However, for patients with VT therapy activated, the indication for device therapy was significantly more often sustained VT without cardiac arrest (44%), while in the other patients without VT therapy enabled, the indication for device therapy was sustained VT in only 16% (p<0.05).

The programmed VT detection interval ranged from 280 to 590 msec. Antitachycardia pacing was the initial therapy in 49 of 71 patients (69%); cardioversion was the initial therapy in 22 of 71 patients (31%). Cardioversion was part of subsequent VT therapy in 68 of 71 patients (94.4%). In no patient was antitachycardia pacing programmed after cardioversion. Three patients with hemodynamically well-tolerated VT had only antitachycardia pacing enabled. The mean programmed cardioversion energy for the initial cardioversion pulse was 14.3±12.4 J (range, 1–34 J).

In all patients, VF therapy was enabled. The mean programmed initial defibrillation energy was 29±7 J (range, 18–34 J). The programmed VF detection intervals ranged from 240 to 390 msec. Twenty-six patients had only VF therapy programmed.

The VVI pacing mode was programmed to 60 beats per minute or higher in 24 patients; in the remaining patients, it was set at 40–60 beats per minute.

VF Induction Studies During Follow-up

Postoperative induction of VF was attempted in 94 of the 97 discharged patients. As classified by surface ECG criteria, 184 VF episodes were induced in 86 patients. No tachyarrhythmia could be induced in one patient. All episodes were terminated by the implanted device. The delivered energy ranged from 18 to 34 J (mean, 29.4±0.4 J).

Detection and Termination of Spontaneous Episodes

Efficacy of VT therapy. According to the event counters, 1,235 VT episodes (as defined by the device) were detected in 43 of 71 patients (60%) with VT therapy activated. Therapy was delivered for 1,234 episodes, as one episode of VT therapy was disabled. The overall efficacy of the three kind of therapies, i.e., antitachycardia pacing, cardioversion, and defibrillation, is summarized in Figure 2.

Efficacy of tiered therapy starting with antitachycardia pacing. Overdrive pacing therapy was delivered as initial therapy in 38 of 43 patients (88%) for 1,204 episodes. Figure 3 shows that according to the device's data counters, 1,096 episodes (91%) were terminated by initial antitachycardia pacing therapy (ATP 1). One hundred eight episodes that were not terminated with the initial antitachycardia pacing therapy received 209 multiple therapeutic attempts (overdrive pacing and cardioversion). For 57 of these ongoing episodes, VT therapy 2 consisted of antitachycardia pacing as well. Eighteen of these 57 episodes (31%) were terminated by ATP 2. Fourteen ongoing episodes received ATP 3, with zero success; therefore, ATP 4 was delivered, restoring sinus rhythm in only two additional episodes (16%).

A total of 28 episodes in seven patients were not terminated. Fourteen were caused by sinus tachycardia, four by atrial fibrillation, four by incessant VTs, and five during in-hospital fine-tuning of device therapy. One episode remains unclassified.

Efficacy of cardioversion therapy when antitachycardia pacing failed. Fifty-one episodes (4%) in 14 patients (14...
of 38 patients, 37%) received cardioversion pulses after ineffective ATP 1. The mean programmed pulse energy was 13 J. In 31 (61%) instances, sinus rhythm was restored. Therefore, sinus rhythm was restored in 95% after the first backup cardioversion or ATP 2. After the first backup cardioversion, a total of 73 cardioversion pulses were delivered either to terminate ineffective antitachycardia pacing, ineffective backup cardioversion, or newly induced arrhythmias. The overall success rate of backup cardioversion was 40%.

Efficacy of VT therapy starting with cardioversion. Cardioversion was initial therapy in five patients for 30 spontaneous VT episodes. Sinus rhythm was restored in 17 episodes after the first discharge (57%). For an additional seven episodes, sinus rhythm was restored by cardioversion therapies with higher energy, resulting in a cumulative efficacy after cardioversion 1 and 2 of 80%. In six ongoing episodes, sinus rhythm was not restored despite high-energy cardioversion as therapy 3 and 4. Five of these six episodes occurred in one patient in whom atrial tachycardia fulfilling the VT detection interval could be demonstrated by an atrial stimulation study done during follow-up. Adjusting VT detection interval resolved the problem.

Efficacy of defibrillation therapy. According to the data counters, 286 “VF” episodes, as defined by the device, were detected and treated in 47 patients: 29 patients with VT and VF episodes, and 18 with VF episodes only. In the 24 patients, the VF detection interval was programmed at ≤300 msec. The first defibrillation terminated 89.2% of these episodes—16 ongoing episodes were terminated by the second shock, six by the third shock, and two by the fourth shock. Seven episodes (2%) were never terminated. Five of these seven shocks occurred in three patients who died. In no case was there evidence for undersensing of rapid ventricular tachyarrhythmia.

Problematic VT therapies. In 10 patients, there was clinical evidence for problematic therapies. Atrial fibrillation with rapid ventricular response triggered therapies in four patients, and various supraventricular tachycardias were the cause in six patients.

In the subgroup with initial antitachycardia pacing therapy, 18 of 28 episodes not terminated after VT therapy 4 were triggered by supraventricular tachycardia. Of 124 cardioversion pulses that were delivered as backup for antitachycardia pacing as well as for ineffective backup cardioversion pulses, only 60 finally restored sinus rhythm despite the use of high-energy pulses. Therefore, we estimate that most of these discharges were delivered for cardioversion-induced supraventricular tachycardia.

Problematic VF therapies. In one patient, atrial fibrillation with rapid ventricular response was observed during the time period when he received two defibrillation shocks. Based on the clinical circumstances and the memory readouts, the two discharges were classified by the concerned investigator as problematic therapies.

Survival Results

Surgical mortality. Four patients died perioperatively (3.9%) from a nonsudden cardiovascular death, classified as procedure related: low output syndrome in two patients combined with acute myocardial infarction in one of these patients, acute bleeding during removal of a chest drain in one patient, and septicemia in the remaining patient.

Late in-hospital mortality. One patient with heart failure was never dismissed from the hospital and died due to low output syndrome 36 days after implantation.

Outpatient mortality. Seven patients died. A nonsudden cardiovascular death occurred in four patients: three patients died due to a low output syndrome 55, 82, and 455 days after implantation, respectively. One patient died shortly after lead explantation for constrictive pericarditis 392 days after implantation. An arrhythmic, nonsudden death occurred in one patient, who died due to refractory, incessant VT 45 days after implantation. Two other patients died from an arrhythmic death: one patient had a sudden death 407 days after implantation (see “Defibrillation Threshold”), the remaining patient died 99 days after implantation. The patient was found unconscious and was hospitalized with symptoms of cerebral damage. Interrogation of the device showed that unwitnessed defibrillation shocks had been delivered. Later, spontaneous VF was defibrillated by a 34-J shock. It was concluded that as a rather long VF detection interval was programmed, supraventricular arrhythmias might have fulfilled the VF detection criteria and prompted spurious VF therapies. The fourth shock may have induced a rapid, hemodynamically compromising ventricular tachyarrhythmia that was not further treated by the device because of the limitation of the number of shocks to four for an ongoing redetected tachyarrhythmia.

Actuarial survival probability. The actual survival rate is plotted in Figure 4. The actuarial survival rate with SEM values was 96%±2% at 1 month, 92%±3% at 3 months, 91%±3% at 6 months and 12 months, and 84%±5% at 18 months.

One sudden death and three arrhythmia-related deaths occurred. The sudden-death–free survival rate was 100% at 12 months and 97±3% at 18 months. The arrhythmia–free survival rate was 99±1% at 3 months, 98±2% at 12 months, and 95±3% at 18 months.

Comparison between the occurrence of the first VF episode and patient’s death. In Figure 5, the number of patients with the first VF episode and the number of
patients who died are summarized. After the first month, three patients had their first VF episode; after 3 months, another 15 patients; after 6 months, another 13 patients; and after 12 months, another 12 patients. After 12 months, however, only nine patients had died. The occurrence of death is not clustered at the occurrence of first VF episodes.

Hypothetical survival probability. This figure is based on the assumption that if device therapy (only the defibrillation shocks were respected) had not taken place, cardiac arrest, sudden cardiac death, or a potentially fatal arrhythmia would have ensued. Of the 47 patients who received VF therapies, two patients were excluded for the purpose of this analysis: one patient because of evidence that defibrillation occurred only in response to atrial fibrillation, and the other patient because defibrillation occurred only during terminal heart failure. To make the analysis meaningful, only these patients were respected in whom the RR intervals leading to VF detection were not overlaid by later VT episodes. In 28 patients, the VF detection intervals were available. In seven patients, intervals <250 msec were recorded; in the remaining patients the intervals ranged between 250 and 300 msec. The hypothetical survival rate at 6 months was 62±5%, and at 12 months, 45±6%. To illustrate the difference between actual survival rate and hypothetical survival rate, both curves are plotted in Figure 4. The difference between the actual survival rate and the hypothetical survival rate are significant with p<0.0001 after the 3-month interval.

Procedure-Related Complications

Pocket complications. In five patients, seroma or hematoma of the abdominal pocket was observed requiring conventional treatment only. Two 7216A PCDs (the larger model) were removed due to abdominal skin erosion and replaced by the smaller 7217B device.

Lead- or patch-related complications. In one patient, a rethoracotomy was necessary because of excessive bleeding. An erosion of the aorta ascendens by the right ventricular patch lead was found. In two patients, right ventricular patch dislodgments required an intervention. In one patient, crinkling of the right ventricular patch with increase of the defibrillation threshold was observed; therefore, a coronary sinus lead was inserted as second anode. This lead later dislodged and was repositioned in the superior vena cava.

In three patients, an exit block at the myocardial screw-in lead occurred. In two patients, the problem was solved by implanting a transvenous right ventricular lead. In one patient, who had a patch dislodgement as well, a new myocardial screw-in lead was reimplanted.

Component failure. One device did not deliver shocks at implantation because of a technical failure in the device. Another device, available as backup during the implantation procedure, was used instead.

Discussion

This report summarizes the multicenter short-term experience gained with a new ventricular tachyarrhythmia control device, the PCD (models 7216A and 7217B). One hundred two consecutive patients received the device with epicardial lead configuration between May 1989 and February 1991. The total device follow-up period is 79.9 patient-years, a number allowing a first judgment of the reliability of the implanted device and of the safety of automatic staged therapy. Forty-six patients (45%) reached a documented follow-up of >12 months.

Efficacy of Device Therapy to Prevent Sudden Arrhythmic Death

Of primary concern in the use of an ICD is the defibrillation efficacy. For chronic defibrillation, a safety margin >1.5 defibrillation threshold or ≥10 J between the programmed device energy and defibrillation threshold is considered to be sufficient. These requirements were met in 99 of the implants. Three patients received the device, although the acute estimated defibrillation threshold did not meet the study protocol requirements. Nevertheless, the patients are included in the analysis. One of these patients had a sudden arrhythmic death. The other patient might have received problematic shocks inducing a fatal arrhythmia; the remaining patient is still alive.

Defibrillation threshold shows an inverse relation to defibrillation electrode surface area. This was respected by using two large epicardial patches whenever the cardiac geometry allowed. Biphasic pulses provide a moderate decrease in defibrillation threshold; however, this output form is not available in the PCD. Bidirectional pulses lower defibrillation threshold as well but require the implantation of a triple-electrode system. This configuration was used only in five patients who otherwise had a defibrillation threshold >18 J. VF-sensing problems were not observed.

Defibrillation shocks for spontaneous episodes were delivered in 46% of the study population. Comparable incidence of shock therapy was reported by other investigators. The first shock was highly effective, as it terminated 98% of all “VF” episodes. After the fourth shock, only seven of 286 episodes were not terminated (Figure 2). Five of these seven shocks occurred in three patients who ultimately died. A sudden arrhythmic death occurred in one patient, who had an acute defibrillation threshold ≥30 J (see “Mortality”) and received the device in this configuration based on clinical judgments.
A hypothetical death probability is plotted in Figure 4. This information is based on the assumption that had the patients not received device therapy, a fatal arrhythmia would have ensued. Only episodes with the corresponding stored RR intervals not overlaid by a last VT therapy were computed. The actual survival probability was 91% at 6 and 12 months, and the hypothetical survival probability was 62% and 45%, respectively; the differences between the two curves is highly significant. However, these data are not ultimate proof that the device intervention saved lifes, as some of these “VF” episodes may have terminated spontaneously, or the patient may have been successfully resuscitated or hospitalized.

As illustrated in Figure 5, the majority of first VF episodes occurred during the first 6 months after implantation. The question arises as to whether VF therapies occur at or close to the actual time of the patient’s death. If so, it would mean that ICD therapy has no live-saving effect. Of the 12 patients who died, only five experienced spontaneous VF therapies. Three of these patients experienced first VF episodes close to the time of death, one patient during agony, and one patient 1 month before death. In the remaining 41 patients, VF episodes occurred unrelated to death.

Efficacy of Automatic Multimodal VT Therapy

An IPCD provides the opportunity to prescribe electrical therapy tailored to the responsiveness of a drug-refractory VT: either antitachycardia pacing and/or cardioversion. In patients responding usually to antitachycardia pacing, cardioversion can be enabled exclusively to act as backup for ineffective initial antitachycardia pacing or in case of pacing-induced moderate (shortening of cycle length of less than 60 msec) acceleration of VT. However, if VT accelerates to the “VF” detection zone, asynchronous defibrillation shocks will be delivered automatically, preserving the safety of withholding countershock therapy. So far, the efficacy of antitachycardia pacing was assessed mainly during induced VTs. Only in a small but well-selected, number of patients with or without a separate ICD could efficacy of antitachycardia pacing be demonstrated. Our data document a very high efficacy of painless antitachycardia pacing to terminate spontaneous VTs in high-risk patients (Figure 2), although antitachycardia pacing was not evaluated respecting a uniform protocol and it was prescribed mainly empirically. Repetitive efficacy assessment during induced VT episodes was avoided. Despite these limitations, for the first time, representative data due to the significant number of patients with a high number of spontaneous VT episodes treated with automatic antitachycardia pacing are provided. The efficacy of multimodal therapy, starting with antitachycardia pacing and incorporating backup cardioversion for ineffective antitachycardia pacing, is summarized in Figure 3. A spontaneous therapy episode is shown in Figure 6. Ninety-three percent of 1,204 spontaneous VT episodes (as defined by the device based on the programmed VT rate criteria) were terminated by antitachycardia pacing, thus avoiding painful countershock therapies that used to be the only kind of therapy delivered by automatic ICDs. The data also show that repetitious antitachycardia pacing applied to terminate ineffective initial antitachycardia pacing has a low success rate (31%) and that intermediate-energy backup cardioversion pulse terminates ongoing VT. However, the device counters indicate that the success rate of cardioversion pulses delivered as VT therapies 3 and 4 bear a low efficacy (37% and 42%, respectively). This figure may be misleading, as it is more likely that cardioversion has provoked atrial fibrillation with rapid ventricular response meeting a programmed tachycardia detection interval. The absolute numbers given regarding efficacy or failure of device therapy are still to be interpreted with caution. Figure 7 illustrates that the device counters do not distinguish between ongoing and separate episodes if initially the event is detected as VT and then accelerates and is subsequently detected as VF. Once this episode is terminated by VF therapy, the success counters of VT and VF therapy will increase by 1.

Appropriateness of Device Therapy

The appropriateness of device therapy remains an important issue. Rapid atrial fibrillation may induce “inappropriate” VT or VF therapy, i.e., the therapy is delivered because the VT detection interval or VF detection interval is met; however, the arrhythmia is of nonventricular origin. Problematic therapies may have serious proarrhythmic effects, as mainly spurious antitachycardia pacing may induce real VT that ultimately may not be terminated by the device. Inappropriate device therapy may be favored by 1) programming of a too-long VT detection interval or VF detection interval, 2) overlapping between sinus rate and VT detection interval, 3) patients prone to atrial fibrillation with high ventricular response rate, and 4) overdetection of extracardiac signals (muscle noise and electrical interference) or double counting of a normal cardiac depolarization. The study protocol asked for tests to exclude oversensing.
To estimate appropriateness, it has been emphasized that symptoms of hemodynamic compromise must precede shock therapies. However, in our study, preference was given to short intervention times. This may preclude the development of symptoms, and the patient receives therapies while he or she is almost unaware of an arrhythmia. This is without any doubt the case for antitachycardia pacing therapies. The PCD's data counters with stored RR intervals before and after the last therapy and counters of effective and ineffective therapy provide a useful information to judge the appropriateness of device interventions. In conjunction with the patient's history, we concluded that in 10 cases (9%) inappropriate therapy was delivered. In the subgroup of patients who received antitachycardia pacing as initial therapy, 64% of ultimately not terminated "VT" episodes were most likely of supraventricular origin. In the subgroup of patients who had cardioversion as initial therapy, 20% of subsequent pulses were delivered, most likely for cardioversion-induced supraventricular tachycardias. By modification of VT detection criteria like implementing the sudden onset and rate stability criteria in the tachycardia detection algorithm and by modifying VT therapy, further occurrence of inappropriate therapies could be avoided in all patients.

Limitations

A certain nonuniformity in the patient's selection, implantation procedures, and device programming is present. Preferences of device therapy over drug therapy or surgical therapy may have biased the patient's selection. The follow-up period of some patients as well as the mean follow-up of the whole study population is quite short, not allowing any valuable conclusions of long-term lead stability, device reliability, or battery longevity. The incidence of late complications, often related to the epicardial patch electrodes, cannot be addressed in our report. There was no systematic evaluation to define the most effective reproducible antitachycardia pacing mode. This would have even improved the antitachycardia pacing results. Personal preferences and experiences for the programming of VT therapy and a learning curve in the adequate programming of a multimodal tachyarrhythmia control device has to be considered as well.

The PCD incorporates VVI pacemaker functions. The extent to which bradycardiac mortality was prevented by the device has not been analyzed. The necessity to incorporate VVI function in an ICD, however, has been emphasized by others who documented bradycardiac sudden death in their patients treated with an ICD.

Like other presently available devices, the device has several limitations, which must be resolved in the near future, e.g., no dual-chamber antibradycardia pacing, only rate-related tachycardia detection algorithm, and therefore no safe exclusion of rapid atrial fibrillation fulfilling rate-based ventricular tachyarrhythmia criteria. Digital recording of cardiac rhythm is a fundamental limitation. The analysis of spontaneous episodes is limited, as only the RR intervals of the last episode are retrievable.

Conclusions

The device effectively prevents arrhythmic sudden death in a high-risk population. Automatic multimodal therapy is highly effective to restore sinus rhythm without compromising the safety of device therapy. Antitachycardia pacing terminates the majority of spontaneous VT episodes, and, if required, cardioversion pulses are highly effective as backup intervention. In the study group, inappropriate VT or VF therapy was infrequent; however, it may have serious consequences. Rapid supraventricular arrhythmias fulfilling VT detection interval or VF detection interval remain an unsolved and potentially dangerous problem.

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Appendix

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