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Comparison of Initial Detection and Redetection of Ventricular Fibrillation in a Transvenous Defibrillator System With Automatic Gain Control

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Objectives. **The purpose of this study was to prospectively evaluate postshock redetection of ventricular fibrillation by a system that coupled an implantable cardioverter-defibrillator with an automatic gain control sense amplifier and a transvenous lead system.**

Background. **Redetection of ventricular fibrillation after an unsuccessful first shock has not been systematically evaluated. Previous studies have suggested that sensing performance of some lead systems may be adversely affected by the delivery of subthreshold shocks.**

Methods. **The time required for both initial detection and redetection of ventricular fibrillation was compared in 22 patients. These times were estimated by subtracting the capacitor charge time from the total event time.**

Results. **A total of 113 successful and 57 unsuccessful initial shocks were delivered during induced ventricular fibrillation. The mean ± SD initial time to detection of ventricular fibrillation was 5.5 ± 1.7 s (range 2.4 to 10.8); the time to redetection ranged from 1.5 to 18.5 s (mean 4.5 ± 2.8, p = NS vs. detection time). Abnormal redetection episodes, defined as a redetection time >10.2 s (i.e., >2 SD above the mean redetection time), were observed in 4 (18%) of 22 patients.**

Conclusions. **Redetection of ventricular fibrillation after a subthreshold first shock may be delayed. Device testing with intentional delivery of subthreshold shocks to verify successful postshock redetection of ventricular fibrillation should be performed routinely in all patients.**

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The potential advantages of a nonthoracotomy approach to implantation of a cardioverter-defibrillator have been demonstrated by several investigators (1–8). Defibrillation with the use of transvenous lead systems is successful in the majority of patients, and implantation rates are >70% in most studies (6–9). The sensing performance of these lead systems has not been extensively studied. The proximity of the sensing and energy-delivering components of these lead systems may present unique demands on sensing performance. Previous studies (10–14) have demonstrated that the delivery of high energy shocks through some transvenous lead systems can cause transient diminution of the local endocardial signal. Delayed redetection or complete failure to redetect ventricular fibrillation after a failed first shock has been observed (14,15) during testing of several transvenous defibrillator systems.

Redetection of ventricular fibrillation after a failed first shock has not been systematically evaluated. In this study we prospectively evaluated the postshock sensing performance of an integrated bipolar transvenous lead system coupled to an implantable defibrillator with an automatic gain control sense algorithm. Our aim was to compare the time required for initial detection and redetection of ventricular fibrillation induced during routine postoperative testing. In addition, the signal characteristics during ventricular fibrillation and demographic variables in patients with prolonged redetection times were analyzed to identify factors that might influence postshock sensing.

Methods

Study group. Twenty-two consecutive patients who received a Cadence implantable cardioverter-defibrillator (model V-100, Ventritex, Inc.) coupled to an Endotak C (models 0062-0064, Cardiac Pacemakers Inc.) transvenous lead system were studied. All patients had ventricular arrhythmias that were refractory to antiarrhythmic drug therapy. The clinical presentation was syncope in eight patients, tolerated ventricular tachycardia in eight and aborted sudden death in six. Eighty-two percent of the patients were male; the mean age was 63 ± 11 years. Nineteen of the 22 patients had coronary artery disease with previous myocardial infarction; the other 3 had idiopathic dilated cardiomyopathy. The mean ejection fraction was 30 ± 15% (range 7% to 66%). At the time of device

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implantation and testing, five patients were receiving antiarrhythmic medications: *d-l* sotalol, *d-l* sotalol plus mexiletine, *d* sotalol, propafenone and amiodarone in one patient each.

Lead system. The Endotak C 60 series lead is a tripolar pacing/sensing/defibrillation lead. The sensing circuit is composed of the distal tip electrode and the distal defibrillation coil, which is 3.8 cm in length (surface area 295 mm^2) and is separated from the tip electrode by 6 mm. The defibrillation circuit is composed of a distal coil positioned at the right ventricular apex and a proximal coil that typically lies at the junction of the superior vena cava and the right atrium. Thus, one of the energy-delivering leads also serves as the sensing system anode (integrated bipolar sensing). A subcutaneous patch, which was added to the defibrillation lead system if the defibrillation threshold was >550 V at implantation, was implanted in two patients in this study. The polarity of the defibrillation waveform is reversible, but the distal coil was cathodal in all except one patient. Before device implantation, intraoperative lead system testing documented the following specifications in all patients: 1) R wave amplitude ≥5 mV during spontaneous rhythm, 2) pacing threshold ≤1.5 V at a 0.5-ms pulse width, and 3) defibrillation threshold ≤550 V.

Device algorithm and programming. The Cadence V-100 is a third-generation multiprogrammable implantable cardioverter-defibrillator with automatic gain sensing amplifiers used to facilitate detection of low amplitude signals, such as those produced by ventricular fibrillation. The initial detection of ventricular fibrillation is based on a programmable rate criterion. A sensed event is counted toward a diagnosis of ventricular if 1) it follows the last sensed signal by an interval shorter than the fibrillation detection interval, and 2) the average of the last four intervals is also shorter than the fibrillation detection interval. If the device is configured as a two-zone device, (i.e., separate programmable rate cutoffs for ventricular fibrillation and ventricular tachycardia), the interval average can still count toward detection if it is longer than the fibrillation detection interval but shorter than the tachycardia detection interval. Once a programmable number of individual events (nominal = 12) satisfy these criteria, fibrillation is detected. Events that do not meet these criteria 1) are counted toward "redetection" of sinus rhythm (if both the interval and a continuous interval average are >50 ms above the fibrillation detection interval, or 2) are not counted (if one criterion but not the other is satisfied). If a programmable number of events (nominal = 5, "slow" = 7) satisfy the criteria for redetection of sinus rhythm, the fibrillation detection event counter is reset to 0. Programming for detection of fibrillation was nominal and that for redetection of sinus rhythm was slow except in the first patient of the series, whose original programming for sinus rhythm redetection was nominal.

A similar algorithm applies for redetection of ventricular fibrillation after a failed shock. After shock delivery, there is a postshock refractory period of 1,000 ms. Sensed events are counted toward the diagnosis of ventricular fibrillation as described before, except that only six events need to be counted to satisfy the criteria for redetection of ventricular fibrillation. The postshock fibrillation detection interval (for both interval and interval average) decreases to the level of the tachycardia detection interval in a two-zone configuration. Alternatively, a separate postshock fibrillation detection interval can be programmed; however, this feature was not used in this study.

After successful detection or redetection, the capacitors charge and an R wave synchronous shock is delivered after ventricular fibrillation is reconfirmed. After a sequence of therapy delivery, the device reports the charge time of the last high voltage shock. Thus, for both detection and redetection of ventricular fibrillation, the time required for sensing is approximately equal to the total event time minus the charge time.

Implantable cardioverter-defibrillator evaluation. Within 1 week and again at 6 weeks after device implantation, patients were brought to the electrophysiology laboratory for testing of the device under intravenous sedation. Ventricular fibrillation was induced by burst ventricular pacing. Episodes of ventricular fibrillation and subsequent therapy sequences were assessed from recordings of three surface electrocardiographic leads on Mingograph paper at a speed of 25 to 50 mm/s. Bipolar telemetered recordings from the sensing lead system are stored by the device after each episode of therapy delivery and are available through interrogation of the Cadence generator. The analog electrogram signal is processed by the device with a filter centered at 30 Hz. After analog to digital conversion and processing by the automatic gain amplifier, the signals available for output represent information identical to that presented to the device for algorithm-based sensing decisions. Electrograms were recorded on a strip recorder at a speed of 25 mm/s. Defibrillation threshold testing was performed, starting at a first shock output 50 V higher than the defibrillation threshold determined during intraoperative testing. If the initial shock was successful, the first shock output was decreased in 50-V steps until the first shock failed to restore sinus rhythm; if the initial shock was unsuccessful, the first shock output was increased in 50-V steps until the first shock resulted in defibrillation. All defibrillation trials were separated by ≥3 min. After a failed first shock, the effect of the shock on redetection of ventricular fibrillation could be assessed. Delivery of the second shock was at maximal energy output (750 V). If ventricular fibrillation persisted after the delivery of two shocks, external defibrillation was performed promptly.

Data analysis. For each successful first shock, the initial detection time was estimated by subtracting the capacitor charge time from the total episode time (initiation of ventricular fibrillation to shock delivery). This estimate ignores the postinduction sensing refractory period (nominal = 350 ms) and the time required at the end of capacitor charging to reconfirm ventricular fibrillation and to ensure synchronous shock delivery. It also does not take into account the effects of pacing induction from an external stimulation source, which was performed in 2 of the 22 patients. Although the device is blind (i.e., sensing capabilities are disabled) during this stimulation, it decreases the gain setting because of the high

amplitude pacing stimuli and is therefore forced to start detection at a relatively insensitive gain setting. For this reason, detection times may have been marginally prolonged in the two patients who underwent pacing induction from an external source. Similarly, after each first shock that failed to terminate ventricular fibrillation, the postshock redetection time was estimated by subtracting the capacitor charge time for the second shock from the total time between the first and second shocks. This estimate ignores the postshock refractory period (1,000 ms) and the time required for reconfirmation and synchronization. Thus, although the algorithms for initial detection and redetection are slightly different, they were compared to put redetection times into perspective. Because redetection requires a smaller number of sensed events—and, typically, a less stringent fibrillation detection interval—redetection times should be consistently shorter than initial detection times if failed first shocks have no effect on sensing.

Abnormal redetection of ventricular fibrillation was defined as either 1) inappropriate redetection of sinus rhythm by the device during continued ventricular fibrillation, requiring external defibrillation; or 2) a redetection time >2 SD above the mean value for redetection time.

Statistical analysis. Data are presented as the mean value ± 1 SD, unless otherwise noted. A comparison of mean initial detection and redetection times for individual patients was performed with the paired Student *t* test. Analysis of variance with Scheffé subgroup testing when appropriate was used to examine the effect of clinical variables on redetection time. The relation between first shock voltage and redetection time was determined by using least squares linear regression. A p value < 0.05 was considered statistically significant.

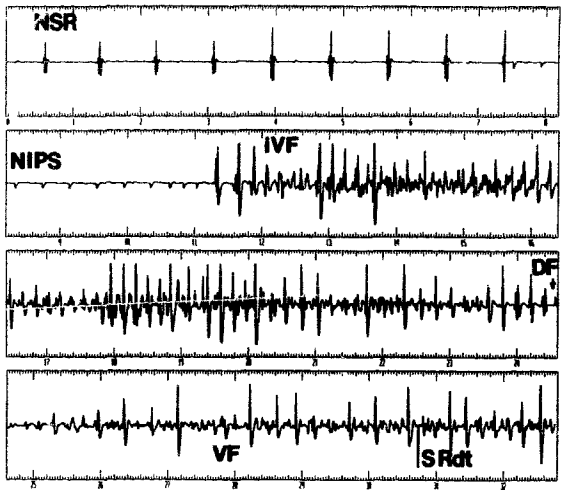

Figure 1. Redetection of sinus rhythm during ventricular fibrillation after a failed first shock. This sequence of stored electrograms begins in sinus rhythm (NSR). Noninvasive programmed stimulation (NIPS) is performed through the device, resulting in the induction of ventricular fibrillation (iVF). Ventricular fibrillation is detected, and a defibrillation shock (DF) of 600 V is delivered. The timing of the shock on the tracing is recognized by the blanking of the sense amplifier (isoelectric line) that occurs in anticipation of energy delivery. Ventricular fibrillation continues after the first shock; however, the device falsely redetects sinus rhythm, which is signified by the sinus redetection marker (**downward vertical line,** S Rdt), preventing the delivery of further device therapy. There is a high degree of signal amplitude variability in the last 3.5 s before the first shock and an even greater degree of variability after shock delivery. An external shock was delivered, restoring sinus rhythm (not shown).

Results

A total of 113 successful initial defibrillation shocks and 57 failed first shocks were delivered during routine postoperative device testing. The mean defibrillation threshold was 435 ± 102 V, and the mean voltage of the failed first shock was 390 ± 109 V (range 200 to 600). The initial detection time was 5.5 ± 1.7 s, (range 2.4 to 10.8); the mean redetection time was 4.5 ± 2.8 s (range 1.5 to 18.5, p = NS). The mean redetection time was 0.5 ± 3.5 s less than the mean detection time in individual patients (p = NS).

Failure to redetect ventricular fibrillation (redetection of sinus rhythm) after an unsuccessful first shock was observed in two episodes in a single patient (Fig. 1). In this patient, sinus rhythm redetection was initially programmed to nominal but the setting was changed to slow after failure of redetection was observed.

A prolonged redetection time (>10.2 s, mean redetection time +2 SD) was observed in 3 of 57 episodes in three patients. An example of the stored electrogram sequence from an episode of delayed redetection is shown in Figure 2. In all abnormal redetection episodes, there was marked variability in the amplitude of the signals recorded from the integrated bipolar sensing system. All patients with such abnormal episodes underwent additional testing of postshock redetection of ventricular fibrillation. In one patient, complete failure of redetection was reproduced in a second trial, but normal postshock sensing was observed in two other episodes. In the remaining patients, prolonged redetection times were not reproducible with additional testing.

Comparison of patients with normal redetection times and those with one or more episodes of abnormal redetection showed no difference in the R wave amplitude measured during spontaneous rhythm, defibrillation threshold, ejection fraction or the programmed postshock fibrillation detection interval. Redetection time did not correlate with the voltage of the failed first shock when the entire group was considered ($r^2 = 0.03$, p = NS). In addition, a voltage-dependent effect on redetection time was not observed in individual patients who had multiple (range two to six) redetection episodes. Redetection time did not correlate with the number of previous defibrillation attempts. The number of defibrillation trials preceding normal and abnormal redetection episodes was not different (3.1 ± 2.5 vs. 2.0 ± 2.0 trials, p = NS). The mean initial detection time was not longer in patients with at least one episode of delayed redetection (>10.2 s) than in those with consistently normal redetection times (6.2 ± 1.5 vs. 5.2 ± 1.2 s, p = NS).

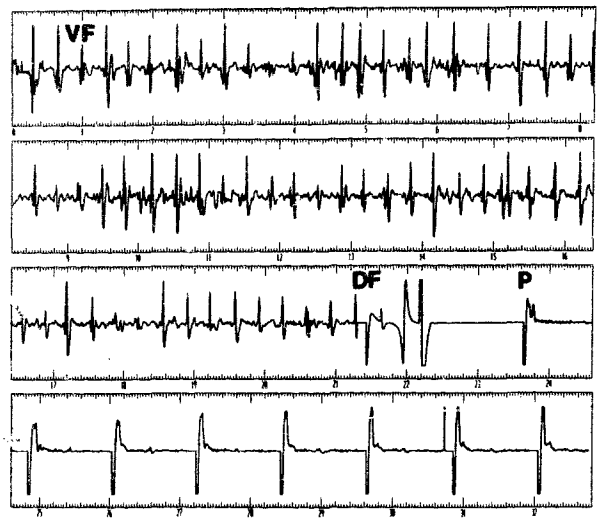

Figure 2. Delayed redetection of ventricular fibrillation after a failed first shock. This sequence of stored electrograms begins just after the initial failed shock for an episode of induced ventricular fibrillation (VF). Note the considerable degree of variability in the amplitude of the electrogram signal. After a redetection time of 18.5 s and a capacitor charge time of 9.9 s, a second defibrillation shock (DF) terminates ventricular fibrillation to a paced rhythm (P).

Over a follow-up period of 5.1 ± 2.5 months (range 1.5 to 9), three patients have had a total of 12 spontaneous episodes of ventricular fibrillation. Ten episodes were terminated with the first shock; in two episodes in one patient, the first shock was unsuccessful, but adequate redetection and defibrillation were demonstrated with a rescue shock.

Discussion

Detection and redetection of ventricular fibrillation. The major finding in this study was that at least one episode of delayed redetection (>10.2 s, 3 patients) or failure of redetection (1 patient) was observed in 4 (18%) of 22 patients. Analysis of the bipolar recordings from the sensing lead of the Endotak-Cadence system demonstrated marked variation in signal amplitude during all episodes of abnormal redetection (Fig. 1 and 2). In the Cadence sensing algorithm, the amplifier gain setting is adjusted for optimal sensing of the predominant signal amplitude. The large amplitude signals presumably prevent the automatic gain amplifier from increasing to the gain setting necessary to detect the low amplitude signals in the sequence. This intermittent signal dropout causes significant variation in the detected RR interval—and thus in the interval average determination—potentially resulting in delayed redetection or failure to redetect ventricular fibrillation.

Potential causes of postshock sensing dysfunction. The basis for the seemingly exaggerated delay noted for redetection as opposed to detection of ventricular fibrillation observed in this study is unknown. Preliminary data from Herre and coworkers (15) suggest that redetection problems are much more frequent with integrated bipolar lead systems, at least when these systems are coupled with Ventak series devices (models 1500, 1550 and 1600, Cardiac Pacemakers Inc.). The deleterious effect of high energy shocks on subsequent sensing performance in integrated bipolar systems has been previously demonstrated. Using a slightly different integrated bipolar lead system (interelectrode distance 5 mm), Yee et al. observed a significant decrease in R wave amplitude after shock delivery in animals (10) and in humans (11). Studies of the Endotak 60 series lead system coupled to pulse generators manufactured by CPI (Ventak P, PRx) (12–14) have also shown a significant decrease in R wave amplitude during sinus rhythm after a successful defibrillation shock.

Jung et al. (14) reported similar changes in signal amplitude during ventricular fibrillation after failed first shocks. They (14) also observed a delayed redetection time or failure to redetect ventricular fibrillation after a failed first shock in two of five patients.

Possible explanations for diminished signal amplitude after shock delivery. Among previously suggested causes of the decreased signal amplitude after shock delivery is polarization of the electrode or the electrode-tissue interface, or both, by the electrochemical effects of the shock (10,11). Transient cellular injury and an increase in membrane permeability resulting in alteration of rest membrane potential and the ionic currents that generate local action potentials may also play a role (10,11,16–18). In any case, the effect appears to be confined to the immediate region of the high energy shock field. Yee et al. (11) observed no change in bipolar signal amplitude recorded from sites in the right ventricle distant from the catheter used for shock delivery. Bardy et al. (19) found no measurable effect of shocks delivered with an epicardial patch-patch system on bipolar electrographic amplitude during ventricular fibrillation recorded with epicardial screw-in electrodes. Finally, preliminary studies with the Endotak model 0072 (interelectrode distance 12 mm) (20,21) have suggested that moving the distal defibrillating coil slightly may diminish the negative effect of energy delivery on signal amplitude.

Role of enhanced variation in electrogram amplitude. It is not clear from this or previous studies whether the decrease in signal amplitude caused by high energy shock delivery is related to the observed delays in postshock redetection of ventricular fibrillation. Several factors suggest that the two phenomena might not be related. 1) The diminution in signal amplitude is a reproducible phenomenon and is probably voltage dependent (11). In contrast, delays in redetection of ventricular fibrillation were typically not reproducible and did not correlate with the voltage of the failed first shock. 2) Delays in redetection were not caused by a uniform reduction in signal amplitude to a level below the threshold for detection (Fig. 1 and 2). In the absence of sensed events, the Cadence delivers pacing stimuli before additional amplifier gain steps; this sequence was not observed in any of our study patients. Delayed redetection was uniformly associated with variation in signal amplitude, such that the large amplitude signals prevented the gain amplifier from performing addi-

tional gain steps. 3) Failure of redetection due to variability in electrogram amplitude has been observed (22) in sensing lead systems that were physically removed from the energy-delivering lead system and thus should have been shielded from effect on signal amplitude. Furthermore, signal amplitude variability was noted during some initial detection episodes of ventricular fibrillation before the delivery of the first shock; in these episodes, the delivery of a subthreshold shock appeared to increase the magnitude of this variability (Fig. 1). It thus appears that in selected patients, failed first shocks may predispose to enhanced cyclic variation in electrographic signal amplitude. It is unclear whether this effect is limited to the field of view of the sensing system or if subthreshold shocks alter the character of ventricular fibrillation throughout the entire myocardium.

Clinical relevance of abnormal redetection. The clinical relevance of these observations during induced ventricular fibrillation is unclear. Failure to redetect ventricular fibrillation with inappropriate redetection of sinus rhythm was observed in a single patient. After the sinus redetection feature was reprogrammed to slow in this patient, no failure to redetect was observed with additional testing. In all subsequent patients with the Cadence implantable cardioverter-defibrillator, redetection of sinus rhythm was programmed to slow at the time of testing. The effect of small increases in redetection time on clinical efficacy is difficult to determine. The effect of duration of fibrillation on defibrillation threshold remains controversial. Bardy et al. (23) found no significant difference in the defibrillation energy requirement after 10 versus 20 s of ventricular fibrillation. Whether prolonged redetection times may sufficiently increase the duration of fibrillation to increase the energy required for defibrillation was not addressed by the present study. In short-term follow-up, all spontaneous episodes of ventricular fibrillation were successfully treated, and there were no episodes of sudden cardiac death.

Summary and recommendations. The specific details of signal acquisition and the sensing algorithms used in different defibrillator systems almost certainly affect postshock sensing performance; however, delayed redetection times have now been observed with integrated bipolar lead systems and true bipolar systems coupled to several different pulse generators. To minimize redetection problems, several recommendations seem appropriate. Formal defibrillation threshold testing should be performed in all patients who receive an implantable cardioverter-defibrillator. To decrease the likelihood of a failed first shock, the first shock energy should be programmed at a value that is at least 10 J greater than the determined defibrillation threshold (24). To decrease the likelihood of signal dropout, the postshock fibrillation detection interval, if programmable, should be set to the longest possible value that will not overlap with cycle lengths of supraventricular rhythms. The sinus redetection should be programmed to slow if this option is available. Redetection of ventricular fibrillation after failed first shocks should be documented in all patients before hospital discharge. However, given the intermittent nature of this phenomenon, documentation of successful redetection does not guarantee that sensing dysfunction will not occur in the future. Finally, effective termination of ventricular fibrillation with backup shocks from the device should be confirmed even if the redetection time is prolonged.

Postshock redetection problems have been observed with true bipolar sensing systems, and it is not known whether prolonged redetection is more likely to be observed with integrated bipolar systems. More investigation is required to determine the specific mechanism or mechanisms of postshock sensing delays. Such investigation may establish preferred sensing lead systems and algorithms for improving the safety and efficacy of implantable defibrillators.

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