Potential Proarrhythmic Effects of Implantable Cardioverter-Defibrillators

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Summary: Implantable cardioverter-defibrillator (ICD) interventions have the potential to be proarrhythmogenic. New arrhythmias can occur in the setting of clinically appropriate therapies, as well as during a cardiac rhythm for which therapy is not intended. Cardioversion/defibrillation therapies, anti-tachycardia pacing, and antibradycardia pacing are potential triggers for the development of new arrhythmias. Newer ICDs allow better recognition and interpretation of the arrhythmias that are induced by delivered therapies. Two cases of ICD-induced proarrhythmias are described. Based on the course of these patients and review of previous reports, proarrhythmic effects of ICD interventions along with prevention and management strategies are discussed.

Key words: proarrhythmia, implantable cardioverter-defibrillator, ventricular arrhythmia, detection enhancement

Introduction

Implantable cardioverter-defibrillator (ICD) interventions, intended to terminate life-threatening ventricular tachyarrhythmias, can be proarrhythmogenic.¹ On the other hand, clinically inappropriate ICD therapies for sinus tachycardia, atrial fibrillation, and other supraventricular tachyarrhythmias are also potential triggers for the development of new arrhythmias. Although ICD-induced proarrhythmias can be associat-

ed with morbidity and even mortality, they are less well recognized than the proarrhythmic effects of *antiarrhythmic* agents. Newer devices with intracardiac electrogram (EGM) storage capability provide documentation of the preceding rhythm and the consequences of delivered therapies, thereby improving our understanding of the proarrhythmic potential of ICDs.

We describe two cases of ICD-induced proarrhythmias. Based on the course of these patients and review of previously published reports, prevention and management strategies are discussed.

Case No. 1

A 63-year-old woman with coronary artery disease had sustained monomorphic ventricular tachycardia (VT) with an average cycle length of 330 ms, which was also inducible at electrophysiologic study. Therapy with metoprolol, sotalol, and amiodarone proved ineffective, therefore an ICD (Micro Jewel™ II 7223 Cx pulse generator and model 6932 electrode, Medtronic, Inc., Minneapolis, Minn., USA) was implanted. Pacing parameters at implantation included EGM amplitude = 7 mV, pacing threshold = 0.4 V/0.5 ms, and pacing lead impedance = 545 Ohm. The defibrillation threshold (DFT) was ± 12 J. Ventricular tachycardia therapy was programmed empirically for a heart rate of 150–200 beats/min, which included several antitachycardia pacing sequences as well as low- and high-energy cardioversion. Defibrillation shocks of 30 J were programmed for the therapy of ventricular fibrillation (VF).

One month after implantation, several ICD shocks occurred shortly after the patient was climbing stairs. Tracings after EGM revealed tachycardia with an average cycle length of 380 ms. The EGM width criterion, which was set “passive,” showed narrow QRS complexes prior to detection, suggesting that the tachycardia was of supraventricular origin. The morphology of the tachycardia was identical to real-time measurements recorded during sinus rhythm, and the stored RR-interval data provided further evidence of sinus tachycardia with a warming-up phase prior to detection. As the tachycardia exceeded the programmed cutoff rate, the episode was detected as VT, followed by delivery of programmed sequence of therapies.

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FIG. 1 Proarrhythmic effects of inappropriate implantable cardioverter-defibrillator therapies in a 63-year-old female patient. (A) Antitachycardia pacing attempts during sinus tachycardia induced nonsustained ventricular arrhythmias. (B) Low-energy cardioversion (0.8 J) induced nonsustained ventricular tachyarrhythmia, fulfilling ventricular fibrillation (VF) detection, followed by spontaneous restoration of sinus rhythm. (C) After the delivery of a committed high-energy shock (30 J) as the first programmed VF therapy, a sustained monomorphic ventricular tachycardia (VT) was induced. (D) The last high-energy shock VT therapy induced a faster, sustained monomorphic VT with a distinctly different electrogram morphology. (E) After the delivery of 30 J defibrillation, another VT was induced. Ventricular tachycardia detection continued while there was no remaining VT therapy to be delivered. VS = ventricle sense, TS = tachycardia sense, TD = VT detection, TP = antitachycardia pacing, FS = fibrillation sense, FD = VF detection, CD = delivery of ICD shock.

The first antitachycardia therapy attempt was burst pacing, which induced a nonsustained arrhythmia (Fig. 1A). The following burst and ramp pacing sequences had similar effects. The next programmed VT therapy was low-energy cardioversion. The delivery of a 0.8 J shock induced a nonsustained arrhythmia that resulted in VF detection (Fig. 1B); however, just after detection, there was spontaneous restoration to sinus rhythm. Since the device responds with committed therapy to a VF episode detected within a VT therapy sequence, a high-energy shock (30 J) was delivered during sinus rhythm (Fig. 1C). A monomorphic VT was induced with a rate and morphology similar to that observed at predischARGE testing, followed by appropriate VT detection. The induced VT was nonsustained, and the delivery of a 30 J shock as final VT therapy during sinus rhythm resulted in faster monomorphic VT with altered EGM morphology (Fig. 1D). After delivery of the

second defibrillation, another VT was induced (Fig. 1E). The detection of VT was appropriate, but there was no other remaining therapy to be delivered. Fortunately, the final EGM recording revealed spontaneous restoration to sinus rhythm.

Case No. 2

A previously healthy 39-year-old man presented with VT (170 beats/min) and left ventricular systolic dysfunction. Ventricular noncompaction was diagnosed by transthoracic echocardiography. This rare disease, characterized by numerous, prominent ventricular trabeculations and deep intertrabecular recesses, is caused by a disorder of endomyocardial morphogenesis that involves a premature arrest of the compaction process of the loose interwoven meshwork of myo-

FIG. 2 Proarrhythmic effects of appropriate implantable cardioverter-defibrillator therapies in a 39-year-old male patient. (A) At implantation, delivery of high-energy defibrillation during ventricular fibrillation (VF) induced ventricular tachycardia (VT). (B) At follow-up, delivery of ramp pacing during a VT episode with a cycle length of 370 ms induced a faster VT (cycle length 290 ms) with a different electrogram morphology. (C) Next programmed VT therapy was 5 J cardioversion which induced VF. This episode was later terminated with backup defibrillation. (D) One h later, the patient developed another VT episode with a cycle length of 390 ms. Ramp pacing decelerated the VT to 410 ms, which was no longer detected. The patient presented with persistent palpitation.

cardial fibers.² Since this unique entity may be associated with frequent occurrence of ventricular tachyarrhythmias and sudden cardiac death, the patient underwent implantation of an ICD (Medtronic Micro Jewel™ 7221 Cx pulse generator and model 6942 electrode). Implantation parameters were EGM amplitude = 7 mV, pacing threshold = 0.6 V/0.5 ms, and pacing lead impedance = 480 Ohm. During DFT testing, delivery of defibrillation shock induced VT (Fig. 2A). Similarly, during implantation and predischARGE-testing, as many as eight VTs with different rates and morphologies were induced, which were difficult to terminate with the device therapies (antitachycardia pacing, low- and high-energy cardioversion), sometimes necessitating external cardioversion. Ventricular tachycardia therapy was programmed for a heart rate of 150–200 beats/min with antitachycardia pacing and low- and high-energy cardioversion. Therapy for VF was 34 J defibrillation.

Two months later, the patient experienced delivery of several ICD therapies, brief loss of consciousness, and later presented with persistent palpitation. Interrogation of the device

showed sustained VT with an average cycle length of 370 ms. Ramp pacing accelerated VT to 290 ms (Fig. 2B). The next programmed VT therapy was 5.0 J cardioversion that resulted in VF induction (Fig. 2C). Fortunately, this arrhythmia was terminated by backup defibrillation (34 J). One h later, the patient developed another VT episode with a cycle length of 390 ms. This time, ramp pacing decelerated the VT to 410 ms (10 ms slower than VT detection interval), so that there was no VT redetection and the patient presented to the hospital with this arrhythmia (Fig. 2D).

Discussion

Implantable cardioverter-defibrillators are widely accepted to be very effective in preventing sudden cardiac death in high-risk patients,³ but any of the delivered therapies have the potential for inducing new arrhythmias.¹ Hemodynamically significant tachyarrhythmias and bradyarrhythmias may be induced with potentially life-threatening consequences.

Stored ventricular EGMs in today's ICDs allow identification of the arrhythmias leading to ICD therapies. Alterations in EGM morphology during a regular tachycardia relative to the baseline sinus rhythm is mostly indicative of VT or, less frequently, of supraventricular tachycardia with ipsilateral bundle-branch block.^{4,5} Based on stored EGMs and clinical judgment, ICD therapy can be classified as being appropriate or inappropriate. Proarrhythmic effects of ICDs may occur as a consequence of clinically inappropriate as well as appropriate therapies.

Proarrhythmic Potential of Inappropriate Implantable Cardioverter-Defibrillator Therapies

Previous reports have documented the potential proarrhythmic effects of inappropriate ICD therapies.⁶⁻¹⁸ By definition, ICD therapy is inappropriate if it is unintentionally delivered (i.e., for rhythms other than sustained VT, VF, or bradycardia below the programmed pacing rate),¹ and is of particular concern because of its rather frequent incidence. Criteria for arrhythmia diagnosis using stored intracardiac ventricular EGMs have been published previously.¹⁹ Based on stored EGM data, the most frequent ICD complication after hospital discharge is inappropriate therapy.²⁰ The report of a patient with an ICD who had an unexpected high sinus rate triggering VT therapy during Holter monitoring, which induced atrial fibrillation with eventual degeneration into VT and death, illustrates the proarrhythmic risks of these devices.¹¹ There are other case reports of patients with ICDs who received inappropriate shock therapies during atrial fibrillation and supraventricular tachycardias resulting in death of the patients as the final outcome.^{15,16} Apart from the associated mortality risks, many ICD-induced proarrhythmias have been reported, which have terminated spontaneously or by the device therapies.^{7,13,21}

Inappropriate Antitachycardia Therapies

Proarrhythmias resulting from clinically inappropriate antitachycardia therapies in properly functioning devices are usually due to inadequacy of detection algorithms.¹ The most common cause of inappropriate antitachycardia therapy is sinus tachycardia and supraventricular tachyarrhythmias, particularly atrial fibrillation with a rapid ventricular response.²⁰ In a study by Grimm *et al.*, 54 of 241 patients (22%) received a total of 132 inappropriate ICD discharges during a mean follow-up of 2 years.²² In five patients, antitachycardia pacing was triggered by atrial fibrillation or regular supraventricular tachycardia resulting in VT induction. Two patients had VT induced by an ICD shock delivered during atrial fibrillation. In all episodes, VT was ultimately terminated by ICD shocks. In addition, seven patients received inappropriate therapies because of oversensing of electrical noise.

Antitachycardia pacing: Antitachycardia pacing may induce arrhythmias by acting like a ventricular stimulation pro-

ocol, especially in the setting of a fast basic rhythm. The increased susceptibility to arrhythmogenesis in fast rhythms can be attributed to associated high sympathetic discharge and/or myocardial ischemia.¹ Since there is no optimal pacing algorithm that terminates VT reliably without causing proarrhythmias, programming is usually performed empirically or based on observations during predischarge testing.

Cardioversion or defibrillation shocks: The delivery of shock therapies during the vulnerable period of ventricular repolarization may result in induction of ventricular tachyarrhythmias. In the absence of risk factors, such as myocardial ischemia, high-energy shocks delivered inappropriately during sinus rhythm are rarely arrhythmogenic.¹ This can be explained by the "upper limit of vulnerability" hypothesis,²³ which states that an electrical shock delivered during the vulnerable period of ventricular depolarization may induce VF only if the delivered energy level is less than the upper limit of vulnerability. During supraventricular tachycardia, however, dispersion of repolarization may be greater with the potential for a reciprocal decrease in VF thresholds.²⁴

Inappropriate Antibradycardia Pacing

In addition to antitachycardia therapies, it is reported that inappropriate antibradycardia pacing resulting from undersensing problems can initiate ventricular tachyarrhythmias.^{17,18} Transient inability to sense sinus beats resulting from variations in signal amplitude can cause asynchronous pacing that may capture the ventricle during its vulnerable period and induce ventricular tachyarrhythmias.

Proarrhythmic Potential of Appropriate Implantable Cardioverter-Defibrillator Therapies

New arrhythmias induced by ICDs can occur in the setting of clinically appropriate therapies. The proarrhythmic effects of clinically appropriate ICD therapies are manifestations of the inherent property of these therapies.

Appropriate Antitachycardia Therapies

Acceleration of VT or degeneration of VT into VF, deceleration of VT, induction of supraventricular tachyarrhythmias, and post-shock bradyarrhythmias are among the well-recognized proarrhythmic complications of appropriate antitachycardia therapies.¹ Induction of VTs with the delivery of defibrillation shocks may also be considered as a proarrhythmic effect of ICDs. As we have observed during the implantation in Case No. 2, VTs with different rate and morphologies (Fig. 2A) were induced which were difficult to terminate, necessitating external cardioversion for some episodes.

Antitachycardia pacing: Overdrive pacing with short coupling intervals can terminate some monomorphic VT episodes, but carries along the risk of acceleration/deceleration of VT or degeneration of VT into VF. In general, aggressive anti-

tachycardia pacing protocols are more likely to be successful than less aggressive ones, at the cost of increased proarrhythmia rate.²⁵ Incidence of acceleration is higher for induced than for spontaneous VTs.^{26, 27} Comparison of fixed burst versus decremental pacing yielded a similar incidence of acceleration between the two algorithms.^{28–30}

Cardioversion or defibrillation shocks: The risk of proarrhythmia induction is relatively high for low-energy shocks.³¹ Although low-energy cardioversion may decrease patient discomfort and provide less myocardial damage, its efficacy is similar to that of antitachycardia pacing for VT termination³² and may be associated with a high risk of VF induction, especially in patients with coronary artery disease.³³ Acceleration of VT or degeneration into VF by low-energy shocks are more common in patients with depressed left ventricular function and high DFTs.³³ The mechanism of proarrhythmia induction by appropriate shocks synchronized with the QRS complex is unclear. However, the possible presence of vulnerable areas of myocardium in hearts with a wide dispersion of refractoriness and nonuniform conduction properties induced by shock delivery has been proposed as an explanation.¹

Some ICDs respond to acceleration of VT with subsequent delivery of appropriately more aggressive therapies if the tachycardia rate falls in a faster zone, or if the rate increase is detected with the acceleration feature of some devices. In Case No. 1, VF was detected after low-energy cardioversion (Fig. 1B); therefore, subsequent programmed VT therapies were interrupted and high-energy shock was delivered as the first VF therapy (Fig. 1C). In Case No. 2, acceleration of VT (Fig. 2B) caused delivery of cardioversion therapy (Fig. 2C), thus unnecessary delay with antitachycardia pacing was avoided. However, if VT decelerates below the detection rate, it is not detected and thus not terminated by the device (Fig. 2D). On the other hand, if the VT rate falls in a slower zone, programmed sequence of therapies are interrupted and the device “steps down” to the slower therapeutic zone. In Case No. 1, after the delivery of first VF therapy during sinus tachycardia (Fig. 1C), VT was detected followed by the delivery of subsequent VT therapies (Fig. 1D). This step-down feature prevents inappropriate delivery of aggressive therapies for decelerated VTs or new-onset VTs induced by defibrillation therapies. The drawback of this feature is delay in redetection, as VT detection (real VT in our case) was suspended for 17 sensed events after defibrillation therapy.

Appropriate Antibradycardia Pacing

New ventricular tachyarrhythmias may as well be induced by appropriately paced beats. Nunain *et al.* reported 25 episodes of VT in five patients with coronary artery disease that were initiated by ventricular paced beats terminating prolonged pauses.²⁰ The paced beats were all appropriately timed and did not result from sensing failure, as documented by stored intracardiac EGMs. There is a recently published report of two cases of patients with nonischemic cardiomyopathy who had VF induced by appropriately paced beats.³⁴

Bradyarrhythmic Effects of Implantable Cardioverter-Defibrillator Therapies

Proarrhythmic effects of ICDs are not limited to induction of tachyarrhythmias. Implantable cardioverter-defibrillator shocks may result in marked bradycardias or prolonged asystole that makes back-up pacing a desirable feature. It has been reported that a single appropriate ICD shock may result in bradyarrhythmic death;³⁵ however, ICD shocks delivered inappropriately during sinus rhythm are less likely to induce bradyarrhythmias.¹ Defibrillation shocks may be associated with transient increases in pacing thresholds and loss of ventricular capture. Other potential proarrhythmic effects of ICDs include inhibition of bradycardia pacing due to oversensing of T waves after paced beats³⁶ and the resetting of a separate pacemaker by shock therapies.³⁷

Prevention and Management Strategies

Optimization of Detection

Proarrhythmias induced by clinically inappropriate ICD therapies can be prevented if detection strategies are improved. Although a detection specificity of 100% is theoretically possible, it can only be accomplished at the cost of decreased sensitivity. Such a compromise would be undesirable, since the primary goal of ICD therapies is to terminate all ventricular tachyarrhythmia episodes.

To improve discrimination between supraventricular and ventricular arrhythmias and reduce the incidence of inappropriate shocks, some detection enhancement algorithms, such as “sudden onset,” “stability,” and “sustained high rate,” have been incorporated into ICDs. With careful evaluation of the clinical picture of the patients, as well as increased knowledge and utilization of device features, the number of false detections may be decreased. The recent introduction of ICDs capable of dual-chamber sensing may facilitate discrimination between supraventricular and ventricular tachyarrhythmias.

Detection Algorithms

Rate-only detection: Inappropriate detection of VT during sinus tachycardia may be avoided by programming the cutoff rate for tachycardia detection above the patient’s maximal sinus rate during exercise testing. In Case No. 1, a symptom-limited exercise test yielded a maximum heart rate of 135 beats/min and all her clinical VTs were 175 beats/min; therefore, the VT detection rate was set at 150 beats/min. However, as demonstrated in our case, this approach is not completely reliable since sinus rate may reach unexpected high levels in some patients. On the other hand, in many patients with ICDs the sinus and VT rates overlap. This is more frequently observed in patients on antiarrhythmic drugs, especially combination regimens, which tend to slow the VT rates. Therefore, the use of rate-alone VT detection is far from ideal in arrhythmia diagnosis.

Onset and stability criteria: Improvements in tachyarrhythmia detection algorithms have enabled increased accuracy of automatic arrhythmia diagnosis.³⁸ The sudden onset criterion can be useful for discriminating between sinus tachycardia and VT, and the rate stability criterion helps to discriminate between atrial fibrillation with a fast ventricular response and monomorphic VT. The incorporation of these additional criteria represents a compromise between sensitivity and specificity.³⁹ In Case No. 1, analysis of the RR intervals prior to detection demonstrated that the sudden onset criterion could have prevented inappropriate detection of VT if it was activated with a threshold of 81%. However, this criterion should not be used routinely because of potential failures. The stability criterion may have a better performance to differentiate rapid ventricular rhythms with irregular intervals, such as atrial fibrillation.³⁹ In any case, it must be used with caution, since VT may be associated with variability in cycle length, making reliable discrimination between the two arrhythmias difficult in some patients.

Intracardiac electrogram width: The EGM width criterion can also be used to complement rate-based VT detection.⁴⁰⁻⁴³ It works by measuring the width of the EGMs and classifying the QRS complexes as wide or narrow by comparing the width measurement with the programmed threshold value. The EGM width criterion may provide greater discrimination against all supraventricular tachyarrhythmias, including atrial flutter and atrial tachycardia, when the ventricular rates overlap. In Case No. 1, this algorithm revealed EGMs with widths narrower than the tested threshold; therefore it could have prevented inappropriate detection if it had been activated. The EGM width criterion can be particularly useful in patients with slow VTs who have a greater likelihood of overlap of sinus and VT rates.

Non-Committed Response

Implantable cardioverter-defibrillators with a committed response deliver programmed therapies once detection criteria are met. This feature may result in the delivery of shocks when the sinus rhythm is restored after nonsustained ventricular tachyarrhythmias. Induction of new arrhythmias by committed shocks during nonsustained rhythms have been reported.¹² Third-generation ICDs have the possibility of reconfirming the tachycardia before therapy delivery. On the other hand, when a VF episode is detected during VT therapy sequence, the shock is delivered without a "second look." This feature designed to facilitate therapy delivery without delay can sometimes be disadvantageous, as demonstrated in Case No. 1 (Figs. 1B and C). In general, ICD therapies should be programmed to a noncommitted mode if the device has this property. Another option is to increase detection time at the cost of delay in therapy delivery.

Sensing Problems

Oversensing and undersensing of signals may cause delivery of inappropriate antitachycardia and antibradycardia therapies, respectively. Oversensing of electrical noise requires in-

vestigation for structural defects (e.g., insulation failure) or connection problems (e.g., loose screws). T-wave oversensing may sometimes be prevented by adjusting the sensitivity. Oversensing of pacing stimulus from a separate pacemaker may be prevented by positioning the pacemaker lead far apart from the ICD lead.

Optimization of Therapies

Proarrhythmic risks of clinically appropriate ICD therapies can be partially decreased by optimal programming of the therapies.

Antitachycardia pacing: While antitachycardia pacing with ramp and burst pacing algorithms with similar degree of aggression have yielded a comparable incidence of acceleration in randomized trials,²⁸⁻³⁰ antitachycardia attempts with many extrastimuli and at short coupling intervals are more likely to induce new arrhythmias. Therefore, in general, very aggressive antitachycardia pacing protocols should be avoided. However, less aggressive antitachycardia pacing protocols are likely to result in a compromise in the efficacy of delivered therapies. Electrophysiologic studies can provide valuable information and can guide optimal programming of antitachycardia therapies. Inactivation of antitachycardia pacing may be reserved as an option if proarrhythmias are suspected or documented.

Cardioversion shocks: Proarrhythmic risks of ICD therapies are relatively common for low-energy shocks. Therefore, such attempts should be limited in number and should always be followed by high-energy shocks. In general, electrophysiologic testing may be recommended for maximum efficacy and safety in each patient.

Antibradycardia pacing: Ventricular tachyarrhythmias induced by appropriately timed ventricular paced beats terminating prolonged pauses may be prevented by increasing the backup bradycardia pacing rate. If changing the pacing rate is ineffective, then turning off the pacemaker function or use of antiarrhythmic drugs may solve the problem. Implantation of a separate pacemaker with its electrode in a different ventricular location can be reserved as an option. Since defibrillation shocks may be associated with transient increases in pacing thresholds, backup pacing should have high outputs to avoid loss of ventricular capture.

Conclusions

The cases presented illustrate that several appropriate and inappropriate ICD therapies can potentially provoke new arrhythmias in the same patient, even in the course of a single episode. The assumption that induced arrhythmias can be corrected by the device may not always be valid if the device simply runs out of available therapies or if the induced arrhythmia is slower than the programmed detection rate. Fortunately, in Case No. 1, sinus rhythm was restored spontaneously, and in Case No. 2, the induced but undetected arrhythmia was hemodynamically tolerated. The expanded

memory capacity and diagnostic capabilities of today's ICDs enable the clinician to better evaluate the nature of potential proarrhythmic effects of these devices and to individualize therapy. Undoubtedly, awareness of the extent and consequences of inappropriate ICD therapies will enhance the use of programmable options for detection enhancement, and will reduce the number of inappropriate therapies. The introduction of more complex ICDs will solve some of the problems of the present technology, but will certainly carry along the potential for new proarrhythmias.

References

1. Pinski SL, Fahy GJ: The proarrhythmic potential of implantable cardioverter-defibrillators. *Circulation* 1995;92:1651-1664
2. Ritter M, Oechslin E, Sütsch G, Attenhofer C, Schneider J, Jenni R: Isolated noncompaction of the myocardium in adults. *Mayo Clin Proc* 1997;72:26-31
3. Winkle RA, Mead RH, Ruder MA, Gaudiani VA, Smith NA, Buch WS, Schmidt P, Shipman T: Long-term outcome with the automatic implantable cardioverter-defibrillator. *J Am Coll Cardiol* 1989; 13:1353-1361
4. Callans DJ, Hook BG, Marchlinski FE: Use of bipolar recordings from patch-patch and rate sensing leads to distinguish ventricular tachycardia from supraventricular rhythms in patients with implantable cardioverter defibrillators. *PACE* 1991;14:1917-1922
5. Sarter BH, Hook BG, Callans DJ, Marchlinski FE: Effect of bundle branch block on local electrogram morphologic features: Implications for arrhythmia diagnosis by stored electrogram analysis. *Am Heart J* 1996;131(5):947-952
6. Leitch JW, Gillis AM, Wyse G, Yee R, Klein GJ, Guiraudon G, Sheldon RS, Duff HJ, Kieser TM, Mitchell LM: Reduction in defibrillator shocks with an implantable device combining anti-tachycardia pacing and shock therapy. *J Am Coll Cardiol* 1991; 18:145-151
7. Weber M, Block M, Brunn J, Baensch D, Castrucci M, Böcker D, Breithardt G: Proarrhythmic effects of inappropriate implantable cardioverter/defibrillator therapies: Incidence, causes and prevention (abstr). *Eur Heart J* 1995;16(suppl):221
8. Johnson NJ, Marchlinski FE: Arrhythmias induced by device anti-tachycardia therapy due to diagnostic nonspecificity. *J Am Coll Cardiol* 1991;18:1418-1425
9. Schmitt C, Montero M, Melichercik J: Significance of supraventricular tachyarrhythmias in patients with implanted pacing cardioverter defibrillators. *PACE* 1994;17:295-302
10. Köhlkamp V, Dörnberger V, Mermi J, Mewis C, Seipel L: Schockinduzierte, aber nicht terminierte Kamertachykardie bei einem Patienten mit implantierbarem Defibrillator. *Z Kardiol* 1996;85: 306-311
11. Birgersdotter-Green U, Rosenqvist M, Lindemans FW, Ryden L, Radegran K: Holter documented sudden death in a patient with an implanted defibrillator. *PACE* 1992;15:1008-1014
12. Kou WH, Kirsh MM, Stirling MC, Kadish AH, Orringer CE, Morady F: Provocation of ventricular tachycardia by an automatic implantable cardioverter defibrillator. *Am Heart J* 1990;120: 208-210
13. Maloney J, Masterson M, Khoury D, Trohman R, Wilkoff B, Simmons T, Morant V, Castle L: Clinical performance of the implantable cardioverter defibrillator: Electrocardiographic documentation of 101 spontaneous discharges. *PACE* 1991;14:280-285
14. Winkle RA, Mead RH, Ruder MA, Gaudiani VA, Smith NA, Buch WS, Schmidt P, Shipman T: Long-term outcome with the automatic implantable cardioverter-defibrillator. *J Am Coll Cardiol* 1989; 13:1353-1361
15. Fromer M, Brachmann J, Block M, Siebels J, Hoffmann E, Almen-dral J, Ohm OJ, den Dulk K, Coumel P, Camm AJ, Touboul P: Efficacy of automatic multi-modal device therapy for ventricular tachyarrhythmias as delivered by a new implantable pacing cardioverter-defibrillator. *Circulation* 1992;86:363-374
16. Cohen TJ, Liem LB: A hemodynamically responsive antitachycardia system: Development and design in humans. *Circulation* 1990; 82:394-406
17. Callans DJ, Hook BG, Marchlinski FE: Paced beats following single nonsensed complexes in a "codependent" cardioverter defibril-lator and bradycardia pacing system: Potential for ventricular tachycardia induction. *PACE* 1991;14:1281-1287
18. Pinski SL, Simmons TW, Maloney JD: Troubleshooting anti-tachycardia pacing in patients with implantable defibrillators. In *Implantable Cardioverter Defibrillators: A Comprehensive Text-book* (Eds. Estes NAM III, Manolis AS, Wang PJ) p. 445-477. New York: Marcel Dekker Inc., 1994
19. Hook BG, Callans DJ, Kleiman RB, Flores BT, Marchlinski FE: Implantable cardioverter-defibrillator therapy in the absence of significant symptoms: Rhythm diagnosis and management aided by stored electrogram analysis. *Circulation* 1993;87:1897-1906
20. Nunain SO, Roelke M, Trouton T, Osswald S, Kim YH, Sosa-Suarez G, Brooks DR, McGovern B, Guy M, Torchiana DF, Vlahakes GJ, Garson H, Ruskin JR: Limitations and late complications of third generation automatic cardioverter defibrillators. *Circulation* 1995;91:2204-2213
21. Kelly PA, Cannom DS, Garan H, Mirabal GS, Harthorne JW, Hurvitz RJ, Vlahakes GJ, Jacobs ML, Ilvento JP, Buckley MJ, Ruskin JR: The automatic implantable cardioverter defibrillator: Efficacy, complications and survival in patients with malignant ventricular arrhythmias. *J Am Coll Cardiol* 1988;11:1278-1286
22. Grimm W, Flores BF, Marchlinski FE: Electrocardiographically documented unnecessary, spontaneous shocks in 241 patients with implantable cardioverter defibrillators. *PACE* 1992;15(1): 1667-1673
23. Chen PS, Shibata N, Dixon EG, Martin RO, Ideker RE: Comparison of the defibrillation threshold and the upper limit of vulnerability. *Circulation* 1986;73:1022-1028
24. Cohen TJ, Chien WW, Lurie KG, Lee MA, Lesh MD, Scheinman MM, Griffin JC: Implantable cardioverter defibrillator proarrhythmia: Case report and review of the literature. *PACE* 1991;14:1326-1329
25. Waldecker B, Brugada P, Zehender M, Stevenson W, den Dulk K, Wellens HJ: Importance of modes of electrical termination of ventricular tachycardia for the selection of implantable antitachycardia devices. *Am J Cardiol* 1986;57:150-155
26. Ip JH, Winters SL, Schweitzer P, Lotvin A, Tepper D, Gomes AJ: Determinants of pace-terminable ventricular tachycardia: Implications for implantable antitachycardia devices. *PACE* 1991;14: 1777-1781
27. Bardy GH, Hofer B, Johnson G, Kudenchuk PJ, Poole JE, Dolack GL, Gleva M, Mitchell R, Kelso D: Implantable transvenous cardioverter-defibrillators. *Circulation* 1993;87:1152-1168
28. Calkins H, el-Atassi R, Kalbfleisch S, Langberg J, Morady F: Comparison of fixed burst versus decremental burst pacing for termination of ventricular tachycardia. *PACE* 1993;16:26-32
29. Gillis AM, Leitch JW, Sheldon RS, Morillo CA, Wyse DG, Yee R, Klein GJ, Mitchell LB: A prospective randomized comparison of autodecremental pacing to burst pacing in device therapy for chronic ventricular tachycardia secondary to coronary artery disease. *Am J Cardiol* 1993;72:311-315
30. Newman D, Dorian P, Hardy J: Randomized controlled comparison of anti-tachycardia pacing algorithms for termination of ventricular tachycardia. *J Am Coll Cardiol* 1993;21:1413-1418
31. Bardy GH, Troutman C, Poole JE, Kudenchuk PJ, Dolack GL, Johnson G, Hofer B: Clinical experience with a tiered-therapy, multiprogrammable antiarrhythmia device. *Circulation* 1992;85: 1689-1698

32. Estes NA III, Haugh CJ, Wang PJ, Manolis AS: Antitachycardia pacing and low-energy cardioversion for ventricular tachycardia termination: A clinical perspective. *Am Heart J* 1994;127(4 Pt 2): 1038–1046
33. Lauer MR, Young C, Liem LB, Ottoboni L, Peterson J, Goold P, Sung RJ: Ventricular fibrillation induced by low-energy shocks from programmable implantable cardioverter-defibrillators in patients with coronary artery disease. *Am J Cardiol* 1994;73(8): 559–563
34. Vlay LC, Vlay SC: Pacing induced ventricular fibrillation in internal cardioverter defibrillator patients: A new form of proarrhythmia. *PACE* 1997;20(Pt.I):132–133
35. Khastgir T, Aarons D, Veltri E: Sudden bradyarrhythmic death in patients with the implantable cardioverter-defibrillator: Report of two cases. *PACE* 1991;14:395–398
36. Callans DJ, Hook BG, Kleiman RB, Mitra RL, Flores BT, Marchlinski FE: Unique sensing errors in third-generation implantable cardioverter-defibrillators. *J Am Coll Cardiol* 1993;22:1135–1140
37. Calkins H, Brinker J, Veltri EP, Guarnieri EPT, Levine JH: Clinical interactions between pacemakers and automatic implantable cardioverter-defibrillators. *J Am Coll Cardiol* 1990;16:666–673
38. Olson WH, Bardy GH, Mehra R, Keimel JG, Huberty KP, Almquist C, Biallas RM: Onset and stability for ventricular tachyarrhythmia detection in an implantable pacer cardioverter-defibrillator. In *Computers in Cardiology*, p. 167–170. New York: IEEE Press, 1987
39. Swerdlow CD, Chen PS, Kass RM, Allard JR, Peter CT: Discrimination of ventricular tachycardia from sinus tachycardia and atrial fibrillation in a tiered-therapy cardioverter-defibrillator. *J Am Coll Cardiol* 1994;23:1342–1355
40. Ruetz LL, Bardy GH, Mitchell LB, Swerdlow CD, Gillberg JM, Gunderson BD, Olson WH: Clinical evaluation of electrogram width measurements for automatic detection of ventricular tachycardia (abstr). *PACE* 1996;19:582
41. Brachman J, Seidl K, Hauer B, Hilbel T, Lighezan D, Schoels W, Beyer T, Ruf-Richter J, Schwink N, Senges J, Kübler W: Intracardiac electrogram width measurement for improved tachycardia discrimination: Initial results of a new ICD (abstr). *J Am Coll Cardiol* 1996;27:96A
42. Gillberg JM, Olson WH, Bardy GH, Mader SJ: Electrogram width algorithm for discrimination of supraventricular from ventricular tachycardia (abstr). *PACE* 1994;17:866
43. Barold HS, Newby KH, Tomasoni G, Kearney M, Brandon J, Natale A: Prospective evaluation of new and old criteria to discriminate between supraventricular and ventricular tachycardia in implantable defibrillators. *PACE* 1998;21:1347–1355