

REVIEW

Advanced ICD Troubleshooting: Part I

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defibrillation, ICD

Background

This review is organized by clinical problems in troubleshooting implantable cardioverter defibrillators (ICDs). Although aspects of troubleshooting are common to all ICDs, our discussion of technical features is limited (with exceptions) to products of the three major U.S. manufacturers. We assume a basic familiarity with ICD programming, stored electrograms, telemetered marker annotations, discriminators for supraventricular tachycardia (SVT) versus ventricular tachycardia (VT), lead impedance values, and chest radiography of ICDs. However, a few definitions may be helpful as background:

Sensing is the process by which an ICD determines the timing of each atrial or ventricular depolarization from electrogram signals. *Detection* is the algorithm by which an ICD processes sensed signals to classify the rhythm and determine if therapy should be delivered. ICDs have up to three programmable rate detection zones to permit zone-specific therapies for slower VT, faster VT, and ventricular fibrillation (VF). The minimum *duration* of tachycardia required for detection is programmable, either directly (in seconds) or indirectly by setting the number of ventricular intervals required for detection. The specific method used to count ventricular intervals influences the sensitivity and specificity of VT detection (Sections XIB and C). *SVT-VT discriminators* are a programmable subset of the VT/VF detection algorithm that withholds ventricular therapy for SVT to improve specificity. They usually differ from SVT detection algorithms used to mode-switch during bradycardia pacing or to deliver atrial therapy for atrial fibrillation or atrial flutter. *Confirmation* or *reconfirmation* is the brief process by which ICDs determine whether to deliver or abort a shock after the high-voltage capacitor is charged. *Redetection* is the process by which ICDs determine whether VT or VF detection criteria remain satisfied after therapy is delivered. *Termina-*

tion of a VT or VF episode occurs when the ICD reclassifies the rhythm as sinus after VT or VF has been detected.

Evaluating Appropriateness of Delivered Therapy

ICDs detect tachycardias imperfectly: An ICD-detected tachycardia may represent either a tachyarrhythmia (SVT or VT) or oversensing of nonarrhythmic electrical signals. ICDs also classify tachycardias imperfectly: True SVT episodes may be classified as VT or VF; and true VT may be classified as SVT. Stored ICD electrograms from detected SVT, VT, and VF episodes together with corresponding annotated markers (Fig. 1) provide the essential data for interpreting the causes and outcomes of ICD shocks. Figure 2 summarizes the approach to the analysis of delivered ICD therapy. The first step is to determine if therapy was delivered in response to oversensing or a true tachycardia.

Oversensing

Inappropriate therapy occurs in the absence of tachycardias because nonphysiological or nonarrhythmic, physiological signals are oversensed and detected as arrhythmias.^{1,2} Nonphysiological signals usually are extracardiac. Physiological signals may be intracardiac (P, R, or T waves) or extracardiac (myopotentials). Oversensing presents characteristic patterns of stored electrograms and associated markers. See Figure 3.

Intracardiac Signals

Ventricular oversensing of physiologic intracardiac signals results in two detected ventricular electrograms for each cardiac cycle, which may result in inappropriate detection of VT or VF.

T-Wave Oversensing

Oversensing of spontaneous T waves may cause inappropriate detection of either VT or VF, depending on the sensed RT interval and programmed VF detection interval. T-wave oversensing is identified by alternating electrogram morphologies.¹ RR intervals usually alternate, but the magnitude of alternation may be small.

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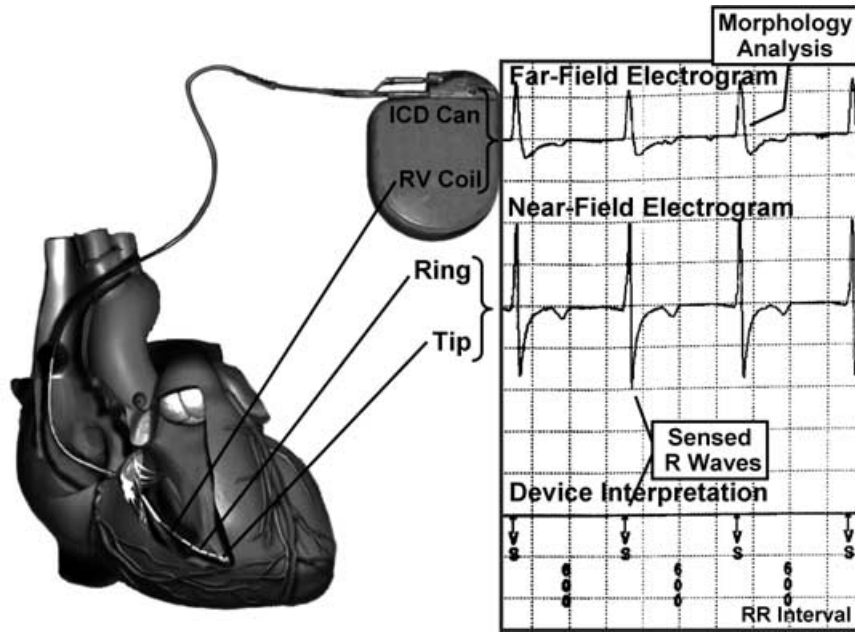


Figure 1. ICD leads and electrograms. The left panel shows an ICD system including left-pectoral active can and RV lead. Right panel shows telemetered electrograms. The dual-coil lead uses true-bipolar sensing between tip and ring electrodes. Right panel shows telemetered high-voltage (shock), far-field (FF-VEGM) and sensing, near-field (NF-VEGM) electrograms with annotated markers. Arrows on Marker Channel denotes timing of R waves sensed from true-bipolar electrogram. ICDs measure all timing intervals from this electrogram and display them on the Marker Channel, which also indicates the ICD’s classification of each atrial and ventricular event by letter symbols. In this figure, VS indicates sensed ventricular events in the sinus rate zone and numbers indicate RR intervals. The stored near-field, rate-sensing electrogram is a wide-band (unfiltered) signal in Medtronic ICDs, but filtered in Guidant and St. Jude ICDs.

R-wave double counting occurs if the duration of the sensing electrogram exceeds the ventricular blanking period of 120–140 ms, which is programmable only in St. Jude ICDs. It may be exacerbated by sodium-channel-blocking drugs, particularly at high heart rates, which increase use-dependent sodium-channel blockade. It is particularly common during VT or conducted supraventricular rhythms in Y-adapted or older biventricular ICDs that use extended bipolar sensing between the tips of the left-ventricular (LV) and right-ventricular (RV) electrodes.³ See Figure 4 and Section IXA. Double counting of R waves results in alternation of ventricular cycle lengths with an isoelectric interval between sensed events, producing a characteristic “railroad track” pattern of ventricular intervals on interval plots. See Figure 4 lower panel and legend.

P-wave oversensing may occur if the distal coil of an integrated bipolar lead is close to the tricuspid valve, and the sensed PR interval exceeds the ventricular blanking period. It is rare in adults with defibrillation leads near the RV apex, but may occur in children or in adults if the RV electrode

dislodges or is positioned in the proximal septum or inflow portion of the RV. If P-wave oversensing occurs during a 1:1 rhythm, the considerations are similar to those for R-wave double counting, provided the sensed PR or RP interval is less than

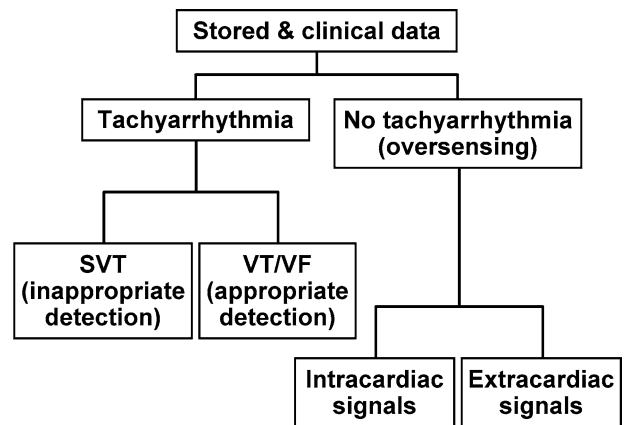


Figure 2. Analysis of ICD shocks. See text.

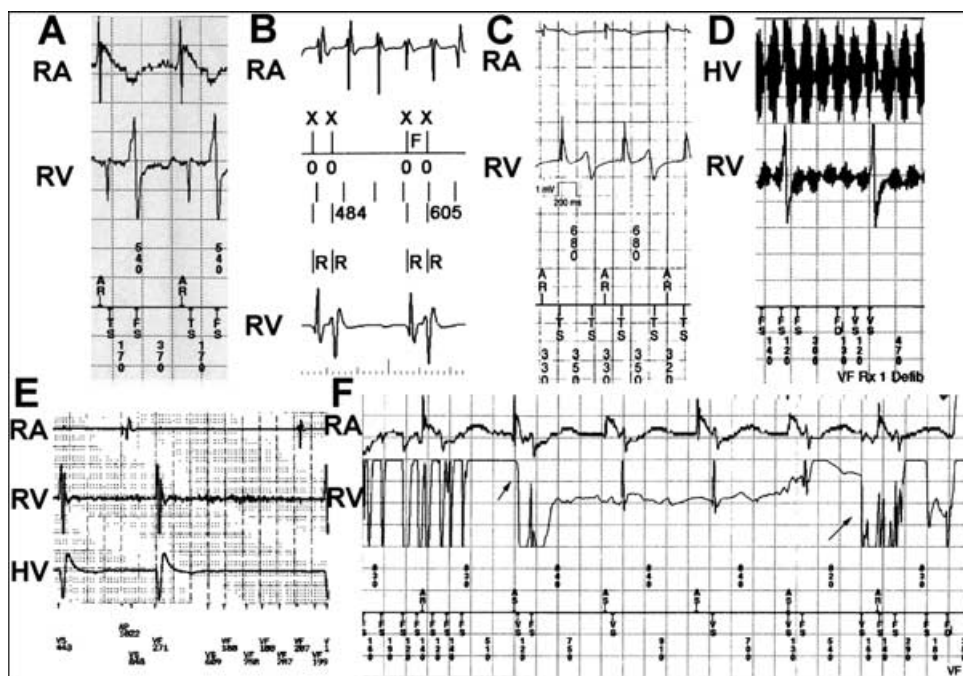


Figure 3. Types of oversensing resulting in inappropriate detection of VT/VF. A–C show oversensing of physiological, intracardiac signals. D–F show oversensing of extracardiac signals. (A) P-wave oversensing in sinus rhythm from integrated bipolar lead with distal coil near the tricuspid valve. (B) R-wave double counting during conducted AF in a biventricular-sensing ICD. (C) T-wave oversensing in patient with low-amplitude R wave (note mV calibration marker). (D) Electromagnetic interference from a power drill has higher amplitude on widely spaced high-voltage electrogram than on closely spaced true bipolar sensing electrogram. (E) Diaphragmatic myopotential oversensing in a patient with an integrated bipolar lead at the RV apex. Note that noise level is constant, but oversensing does not occur until automatic gain control increases the gain sufficiently, about 600 ms after the sensed R waves. (F) Lead fracture noise results in intermittent saturation of amplifier range denoted by arrow. RA = right atrium; RV = right ventricular sensing electrogram; HV = high-voltage electrogram. Reprinted with permission from Swerdlow and Shivkumar.⁵⁸

the VF detection interval. However, oversensing of P waves as R waves can cause inappropriate detection of VF during atrial fibrillation or atrial flutter, independent of the ventricular rate.

Far-field R-wave oversensing on the atrial channel, the analog of P-wave oversensing on the ventricular channel, shows a pattern of alternating atrial cycle lengths with one sense marker close to the ventricular electrogram. If rate and duration criteria for VT are fulfilled, far-field R-wave oversensing may confound SVT-VT discrimination. But it does not cause inappropriate detection of VT if the ventricular rate is in the sinus zone.

Extracardiac Signals

The distinctive feature of oversensing extracardiac signals is replacement of the isoelectric baseline with high-frequency noise that does not have a constant relationship to the cardiac cycle.²

External electromagnetic interference^{1,2} Signal amplitude is greater on the high-voltage electrogram recorded from widely spaced electrodes than on the sensing electrogram recorded from closely spaced electrodes. The interference signal may be continuous. Clinical data may suggest a specific identifiable cause of external electromagnetic interference.

Lead/Connector Problems

Oversensing due to lead or connector (header, adapter, or set-screw) problems is intermittent. Usually it occurs only during a small fraction (<10%) of the cardiac cycle and often saturates the amplifier. It may be limited to the sensing electrogram and may be associated with postural changes. Often, the pacing-lead impedance is abnormal, indicating complete or partial interruption of the pace-sense circuit. However, abnormal impedance measurements may be intermittent.

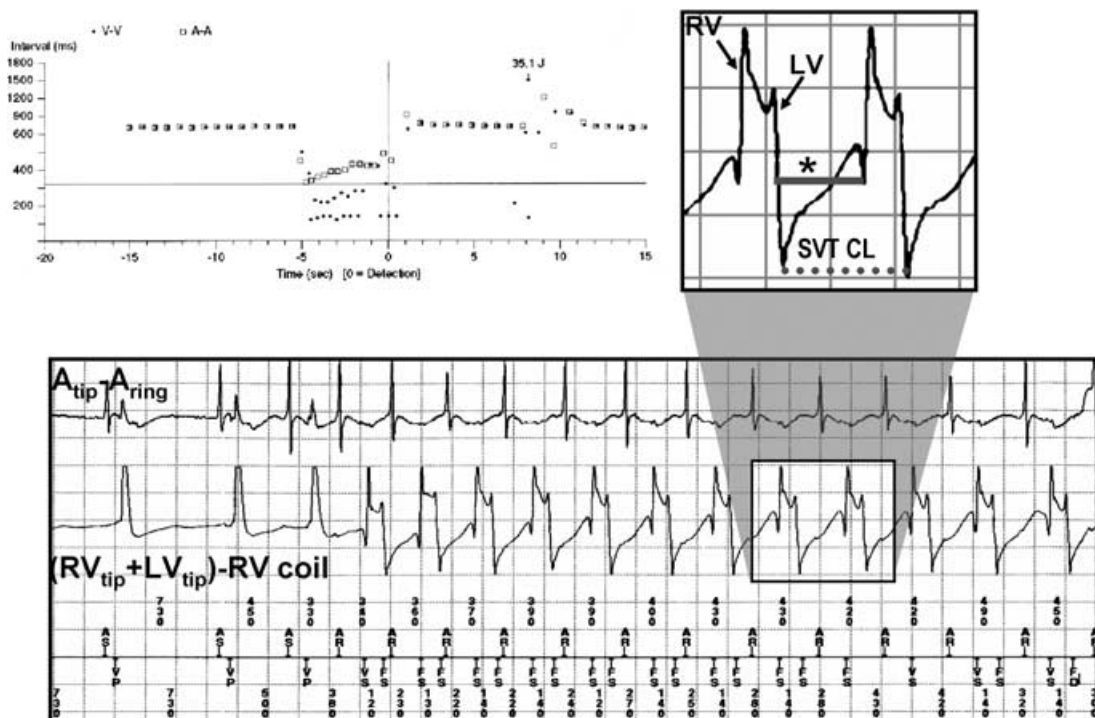


Figure 4. R-wave double counting in a patient with a Y-adapted cardiac resynchronization ICD and LBBB. Main panel: Atrial and extended bipolar ventricular electrograms are shown with Marker Channels. The first two complexes show atrial-sensed, ventricular paced rhythm. The third atrial complex is premature and initiates SVT faster than the programmed upper tracking limit, resulting in intermittent R-wave double counting. Insert shows that the first component of the ventricular electrogram represents RV activation and the second component represents LV activation. Insert also illustrates conditions for inappropriate detection of SVT. The double-counted, RV-LV interval measures within 20 ms of the ventricular blanking period of 120 ms (see Marker Channel) and is always classified in the VF zone. Inappropriate detection occurs when the interval represented by the solid line segment (asterisk) in the upper right insert is less than the VT detection interval. This interval represents the difference between the true SVT cycle length (CL, dotted line segment in upper right insert) and the double-counted RV-LV interval. For example, if the VT detection interval is 400 ms and the double-counted RV-LV interval is 140 ms, inappropriate detection occurs for any tachycardia cycle length less than 540 ms. AS = sensed atrial intervals; AR = atrial intervals in postventricular atrial refractory period; VS = interval sin sinus zone; FS = intervals in VF zone. Upper left panel: Plot shows atrial intervals as open squares and ventricular intervals as closed circles. The initial rhythm is atrial sensed, ventricular paced with a cycle length of ~700 ms. At the onset of SVT, there is an abrupt decrease in atrial intervals. Sensed “ventricular intervals” alternate. Their sum equals the atrial interval. This “railroad track” pattern of ventricular intervals also occurs with P-wave oversensing and may occur with T-wave oversensing. A corresponding “railroad track” pattern of atrial intervals occurs with far-field R-wave oversensing on the atrial channel. See Figure 17.

Myopotential oversensing may persist for variable fractions of the cardiac cycle. Diaphragmatic myopotentials are most prominent on the sensing electrogram. Oversensing usually occurs after long diastolic intervals or after ventricular paced events when amplifier sensitivity or gain is maximal. It often ends with a sensed R wave, which abruptly reduces sensitivity. In pacemaker-dependent patients, diaphragmatic oversensing causes inhibition of pacing, resulting in persistent oversensing and inappropriate detection of VF (Fig. 5). Clinically this may present as syncope from inhibition of pacing followed by an inappropriate shock.

This is an exception to the rule that syncope prior to a shock indicates an appropriate shock. It is most common in male patients who have integrated bipolar leads in the RV apex with Guidant ICDs that utilize Automatic Gain Control™.⁴ Pectoral myopotentials are more prominent on a far-field electrogram that includes the ICD can rather than the near-field electrogram; because ICDs do not use this electrogram for rate-counting, oversensing of pectoral myopotentials does not usually cause inappropriate detection. The most common exception occurs if the morphology of the far-field electrogram is used for SVT-VT

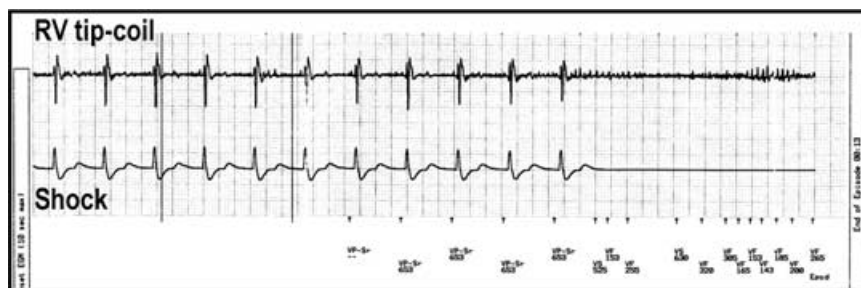


Figure 5. Oversensing of diaphragmatic myopotentials causes inhibition of bradycardia pacing and delivery of an inappropriate shock (not shown) in a pacemaker-dependent patient. High-frequency myopotentials have greater amplitude on integrated-bipolar sensing electrogram (RV tip-coil) than high-voltage electrogram (shock). VP-Sr = paced intervals; VS = intervals in sinus zone; VF = intervals in VF zone; Epsd = episode start/end. Repositioning the lead eliminated the problem.

discrimination during exercise-induced sinus tachycardia.

VT versus SVT: Analysis of Stored Electrograms

If therapy is delivered in response to a tachycardia, the second step is to determine if the initial rhythm detected as VT or VF is true VT/VF or SVT. After the initial tachycardia is diagnosed, posttherapy tachycardias must be diagnosed to determine if they represent continuation of the initial arrhythmia or one of the four different classes of arrhythmia: SVT after therapy of VT, a different VT after therapy of VT, VT after inappropriate therapy of SVT (e.g., device proarrhythmia⁵), or a differ-

ent SVT after inappropriate therapy of SVT (e.g., atrial fibrillation after inappropriate therapy of sinus tachycardia). Figure 6 summarizes methods for analyzing single-chamber and dual-chamber electrograms.

Analysis of Single-Chamber Electrograms

The morphology, abruptness of onset, and regularity of ventricular electrograms form the foundation of single-chamber SVT-VT discrimination.

Morphology

Electrogram morphology should be analyzed from the all recorded channels, ideally including a far-field dipole. SVT cannot be discriminated

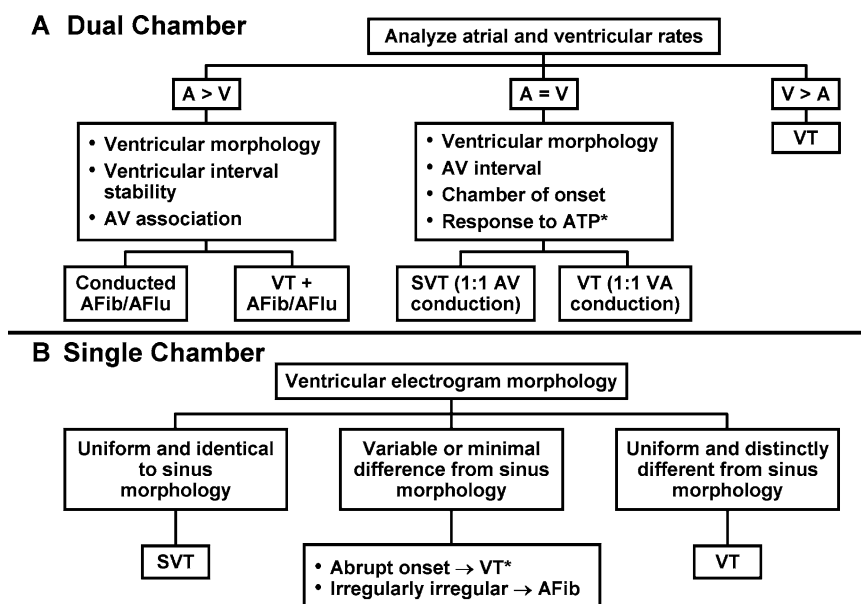


Figure 6. Method for analysis of stored electrograms in dual-chamber ICDs (upper panel) and single-chamber ICDs (lower panel). Asterisks denote weaker criteria. TP = antitachycardia pacing; AFib = atrial fibrillation; AFlu = atrial flutter. See text for details.

from VT unequivocally using near-field electrograms in 5–10% of VTs.^{6,7} A real-time, reference electrogram of conducted baseline rhythm should be recorded to compare morphology with that of the stored electrogram. Ideally, it should be recorded in the posture in which the episode occurred.

The rhythm is classified as SVT if electrogram morphology is uniform and identical to the sinus

morphology. It is classified as VT if morphology is uniform and distinctly different from the sinus morphology. This approach necessarily classifies rate-related bundle branch block during SVT as VT. After shocks, electrogram morphology is distorted by postshock lead polarization and/or local electroperoration. See Figure 7. Morphology cannot be used to discriminate VT from SVT until postshock electrogram distortion resolves.

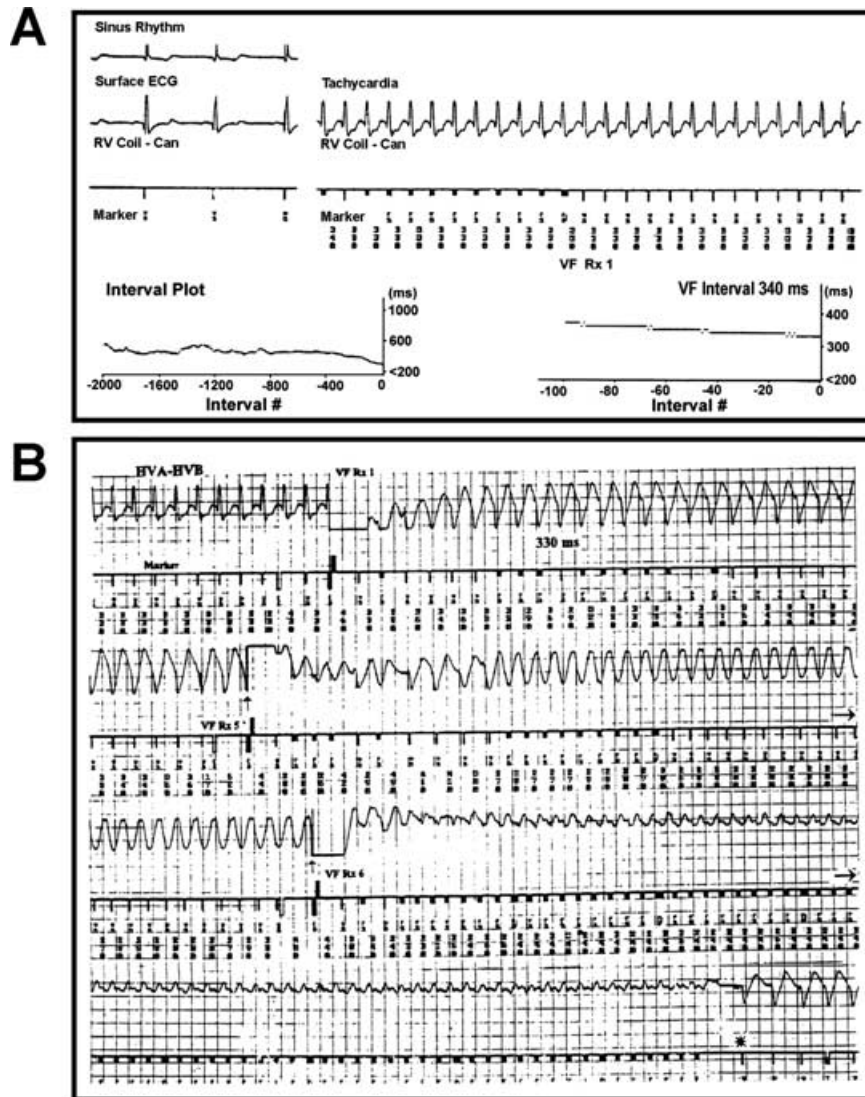


Figure 7. Proarrhythmia caused by inappropriate shock for sinus tachycardia during rate-only detection. (A) The top left tracing shows electrograms recorded from high-voltage leads (HVA-HVB) during sinus rhythm. The top right tracing shows the initial stored electrogram from the treated tachycardia. The electrograms in these two panels are essentially identical, indicating that treated arrhythmia is SVT. The electrogram during tachycardia is clipped at the maximum amplitude of +8 mV. The lower panels are “flashback interval” plots of the RR-interval cycle lengths prior to rate-only detection of VF, which occurs at the right side of each panel.

(continued)

Interval Stability

Characteristically, the ventricular rhythm is irregularly irregular in atrial fibrillation and regular during monomorphic VT, but exceptions are important. Usually, atrial fibrillation is detected inappropriately during ongoing atrial fibrillation when the ventricular rate exceeds the programmed rate criterion. Thus, stored intervals are irregularly irregular prior to and during detection. However, because RR intervals in atrial fibrillation are more regular at faster ventricular rates, interval stability cannot reliably discriminate atrial fibrillation from VT at rates above $\sim 170/\text{min}$.^{8,9} Further, the conducted ventricular rhythm in atrial fibrillation may regularize at slower rates due to transient organization of the atrial rhythm. During rapidly conducted atrial fibrillation, electrograms frequently demonstrate subtle beat-to-beat variation in morphology, the intracardiac correlate of rate-related aberrancy. In contrast, electrograms during VT tend to have a more uniform morphology. However, amiodarone or type IC antiarrhythmic drugs may cause monomorphic VT to become markedly irregular or polymorphic VT to slow, causing irregular intervals during true VT in the VT rate zone.^{10,11}

Onset

Sinus tachycardia accelerates gradually and is always detected at the sinus-VT rate boundary (Fig. 7). In contrast, the onset of VT or paroxysmal SVT is abrupt unless it originates during sinus tachycardia or SVT. However, if VT starts abruptly with an initial rate below the programmed VT detection rate, the beginning of the stored electrogram does not record the onset of the arrhythmia.

Rather, it classifies the VT as SVT when it accelerates gradually across the programmed, sinus-VT rate boundary. In Medtronic ICDs, stored (flashback) intervals preceding the stored electrogram may permit correct diagnosis of an abrupt-onset arrhythmia with an initial rate slower than the VT detection rate (Fig. 8). In the absence of flashback intervals, the few seconds of stored electrograms prior to initial detection are insufficient to make a categorical determination of a "gradual-onset" arrhythmia.

Analysis of Dual-Chamber Electrograms

Analysis of atrial and ventricular rates and atrio-ventricular (AV) relationships are the foundations of dual-chamber rhythm analysis. If the ventricular rate exceeds the atrial rate, the diagnosis is VT. If the atrial rate exceeds the ventricular rate, rapidly conducted atrial fibrillation or flutter must be distinguished from VT during atrial arrhythmia.

Tachycardias with 1:1 AV Relationship

In tachycardias with 1:1 AV association, transient AV block permits the diagnosis of SVT; transient VA block permits the diagnosis of VT. The vast majority of tachycardias with 1:1 AV relationship are SVT, primarily sinus tachycardia. VT with 1:1 VA conduction accounts for less than 10% of VTs detected by ICDs in most studies.^{12,13} The principal differentiating features between SVT and VT with 1:1 AV relationship include morphology of the ventricular electrogram, chamber of onset, and response to ventricular antitachycardia pacing (Fig. 9). Atrial tachycardia usually begins with a short PP interval followed by a short RR interval,

Figure 7. The interval number prior to detection is plotted on the abscissa, and the corresponding interval is plotted on the ordinate. The lower left panel shows 2000 RR intervals prior to detection. A tachycardia is present throughout. Shortly after the 400th interval, the rhythm accelerates gradually in a manner typical of sinus tachycardia and decreases below the programmed VF detection interval of 340 ms. The lower right panel shows this gradual acceleration on an expanded scale during the last 100 intervals prior to detection. Cycle-length measurements are truncated to the nearest 10 ms. (B) Stored electrogram during therapy of the tachycardia detected in Panel A. The first VF shock (VF Rx 1) results in widening of the electrogram without change in the cycle length of 330 ms. This is probably due to shock-induced right bundle branch block which was documented in this patient at electrophysiologic testing. The tracing is discontinuous at the end of the first line and continuous thereafter. Shocks 2, 3, and 4 resulted in no change in rate or electrogram morphology. On the second line, the fifth VF shock (VF Rx 5) induces VT with cycle length 280 ms, despite appropriate synchronization to the nadir of the R wave. The sixth VF shock (VF Rx 6) accelerates the VT to cycle length 210 ms. This rhythm terminates spontaneously 21 seconds later, and sinus tachycardia with a wide electrogram resumes (asterisk). No additional shocks were delivered during these 21 seconds because the maximum number of therapies per zone is six in this ICD. The patient reported that during exertion he experienced multiple shocks followed by syncope. The programmed shock strength was 24 J for the first shock and 34 J for subsequent shocks. Reprinted with permission from Swerdlow.⁵⁹

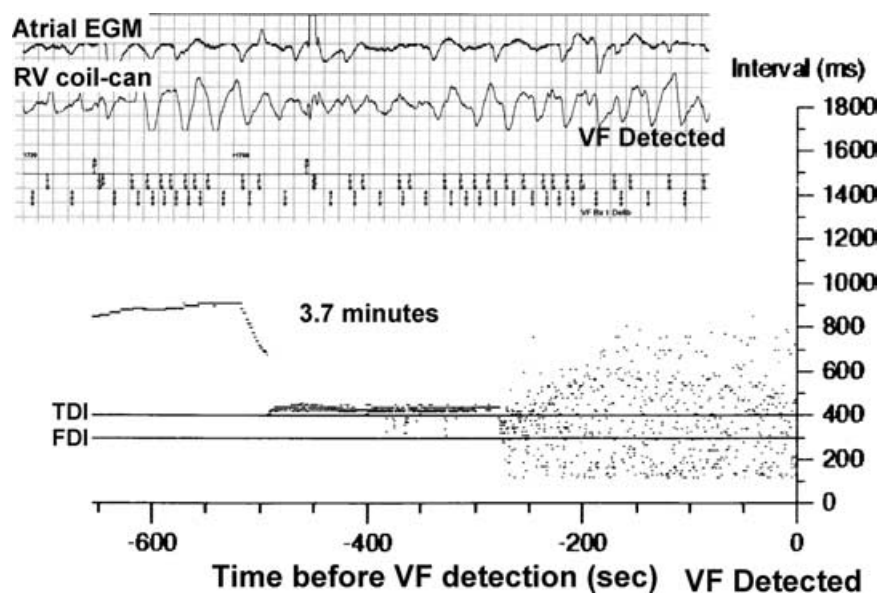


Figure 8. Underdetection of VT and undersensing of VF. The lower panel is a “flashback interval” plot of RR-intervals cycle lengths prior to detection of VF, which occurs at the right side of each panel. The interval number prior to detection is plotted on the abscissa, and the corresponding interval is plotted on the ordinate. Horizontal lines indicate the VT detection interval (TDI) of 400 ms and VF detection interval (FDI) of 320 ms. Shortly after the 500th interval preceding detection, regular tachycardia begins abruptly. The constant cycle length indicates reliable sensing. This VT is not detected despite reliable sensing because the cycle length is > the programmed TDI. VT persists for 3.7 min until approximately interval 280 prior to detection, when sensed intervals become highly variable. This indicates degeneration of the rhythm to VF with undersensing that delays detection. During VT and VF, atrial flashback intervals (not shown) indicated lower rate limit bradycardia pacing at 40 beats/min (1500 ms). The upper panel shows stored atrial and far-field ventricular electrograms immediately prior to detection with atrial and ventricular Marker Channels. Specific undersensed electrograms cannot be identified because the rate sensing electrogram was not recorded. However, long-sensed RR intervals ending with VS markers indicate undersensing and correspond to long interval in upper panel. “VF Therapy 1 Defib” at lower right (arrow) denotes detection of VF.

whereas VT usually begins with a short RR interval. A few beats of AV dissociation may occur until 1:1 ventriculoatrial conduction stabilizes. In sinus tachycardia, the atrial rhythm accelerates gradually with an approximately stable PR interval.

Tachycardias with Atrial Rate > Ventricular Rate

Once far-field R waves are differentiated from atrial electrograms, conducted atrial fibrillation or atrial flutter (Fig. 10) must be distinguished from VT during atrial arrhythmia (Fig. 11). Most VT during paroxysmal atrial fibrillation is fast enough to be classified in the VF zone.¹⁴ The single-chamber criteria of abnormal ventricular morphology and regular ventricular rate are most helpful for diagnosing VT during atrial fibrillation. Conducted atrial flutter may be diagnosed in the presence of abnormal ventricular morphology if consistent 2:1 AV association or Mobitz 1 AV block is present. VT

during atrial flutter is diagnosed based on abnormal morphology and AV dissociation.

VT versus SVT: Diagnostic Data Ancillary to Stored Electrograms

Clinical circumstances, the response to therapy, and information from the patient’s arrhythmia history may provide supportive data when analysis of electrograms is inconclusive.

Clinical Data

Inappropriate therapy for SVT does not occur in patients with complete heart block. A history of rapidly conducted atrial fibrillation suggests inappropriate therapy for atrial fibrillation. Multiple, ineffective shocks during vigorous exercise suggests inappropriate therapy for sinus tachycardia if the integrity of electrodes is verified. But shocks

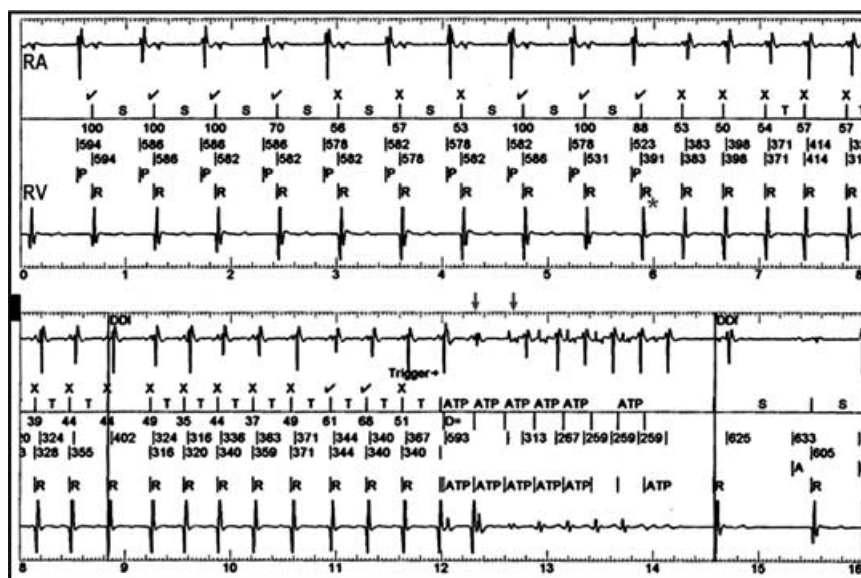


Figure 9. Appropriate therapy for VT with 1:1 VA conduction. Bipolar atrial electrogram (RA), dual-chamber Marker Channel, and rate-sensing (RV) electrogram are shown. Asterisk denotes onset of VT during sinus tachycardia, identified by abrupt acceleration of ventricular rate and change in electrogram morphology without change in atrial rate. Morphology discriminator requires 5 of 8 match scores $\geq 60\%$ to withhold therapy. During sinus tachycardia, scores exceed 60%. (Five are 100%) During VT, most scores are less than 60%. Check marks above Marker Channel indicate that morphology algorithm classifies beats as supraventricular. “X” marks indicate beats classified as VT morphology. The VT cycle length is moderately irregular. Changes in VV interval precede those in AA interval. Ventricular antitachycardia pacing (ATP) at right of lower panel results in transient VA block without acceleration of the atrial rate followed by 1:1 VA conduction. The near simultaneous atrial and ventricular activation during tachycardia is more typical of typical (antegrade-slow, retrograde-fast) AV nodal reentrant tachycardia than VT, but the shortening of the AV interval at the onset of tachycardia is inconsistent with this diagnosis. Pacing-induced VA block without acceleration of the atrial rate is also unusual in AV nodal reentry. “Trigger” in lower panel indicates detection of VT. “D=” at onset of ATP indicates that atrial rate = ventricular rate. “S” denotes intervals interval the “Sinus” zone longer than the VT detection interval of 400 ms. “T” denotes intervals in VT zone. DDI = mode switch. Time line is in section.

without antecedent symptoms do not distinguish SVT from VT.

Response to Therapy

When atrial rate exceeds the ventricular rate, termination of a tachycardia by a single trial of ventricular antitachycardia pacing favors the diagnosis of VT. However, during atrial fibrillation, retrograde concealed conduction from ventricular antitachycardia pacing may result in postpacing pauses and/or slowing of antegrade conduction that must be distinguished from true termination of VT.

In tachycardias with 1:1 AV association, transient AV block permits the diagnosis of SVT; transient VA block permits the diagnosis of VT. The success of ventricular antitachycardia pacing is not helpful because pacing terminates >50% of

inappropriately detected 1:1 pathological SVTs.¹⁵ But the atrial response to successful or unsuccessful antitachycardia pacing may be diagnostic.

If a 1:1 tachycardia is terminated by ventricular antitachycardia pacing, the differential diagnosis includes VT and pathological SVTs, usually atrial tachycardia. Atrial tachycardias are terminated by ventricular antitachycardia pacing only if the atrial rate accelerates during pacing. However, if termination occurs early in the pacing train (after 1 or 2 ventricular paced events), acceleration of the atrial rate may be transient. VT can be diagnosed if high-grade VA block occurs at the onset of antitachycardia pacing without acceleration of the atrial rate.

The response to unsuccessful antitachycardia pacing may assist in the diagnosis of 1:1 tachycardias. If the atrial cycle length is unchanged by

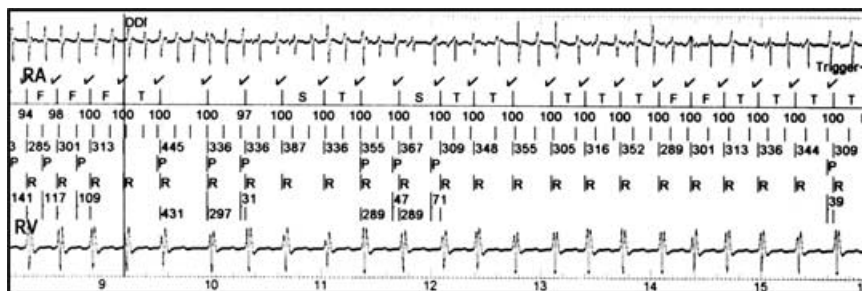


Figure 10. Inappropriate detection of rapidly conducted atrial fibrillation. Stability and morphology algorithms are combined with “ANY” in this St. Jude ICD so that VT is diagnosed if either discriminator classifies rhythm as VT. Stability algorithm incorrectly classifies rhythm because ventricular cycle lengths regularize. Morphology algorithm correctly classifies rhythm as SVT. The rhythm would have been classified correctly if the morphology discriminator alone had been programmed. “F” markers indicate ventricular intervals in VF (Fib) zone. Other abbreviations as in Figure 9.

ventricular antitachycardia pacing (tachycardia in the atrium does not depend on retrograde conduction), the diagnosis is SVT. If the atrial rate accelerates to the ventricular rate during ventricular antitachycardia pacing, the response at the termination of unsuccessful pacing may be helpful. Two atrial events followed by a ventricular event (AAV response) is diagnostic of atrial tachycardia (Fig. 12).¹⁶ Rarely, the pattern of two ventricular events followed by an atrial event (VVA response) is diagnostic of VT. But a ventricular event followed by an atrial event followed by another ventricular event (VAV response) is not diagnostic.

Because the vast majority of VTs are terminated by one or two shocks,¹⁷ failure of multiple high-output shocks to terminate a regular tachycardia suggests sinus tachycardia. The converse is not true. Termination of a regular tachycardia by a single shock is not diagnostic of VT. If multiple arrhythmias occur with similar electrogram morphology and ventricular rate, one episode may permit definitive diagnosis for all episodes. A regular tachycardia during atrial fibrillation may be identified as VT if a tachycardia with the same rate and morphology occurred during sinus rhythm.

Programming to Reduce Shocks: SVT-VT Discrimination

Quality of life in ICD patients has a strong, inverse correlation with delivery of shocks, whether appropriate or inappropriate.¹⁸ Three principal programming goals aim to reduce inappropriate shocks: (i) optimize SVT-VT discrimination, (ii) prevent oversensing, and (iii) prevent detection of nonsustained VT. A fourth goal—treat VT with antitachycardia pacing—aims to reduce unnecessary shocks, whether appropriate or inappropriate. Pharmacological treatment and/or catheter abla-

tion may reduce the frequency of both appropriate shocks (by reducing the frequency of VT/VF) and inappropriate shocks (by slowing sinus tachycardia, slowing the ventricular rate during atrial arrhythmias, or preventing atrial arrhythmias).^{19,20} They are beyond the scope of this review.

Programming the Range of Cycle Lengths to Which Discriminators Apply

SVT-VT discriminators apply in a range of cycle lengths bounded on the slower end by the VT detection interval and on the faster end by a minimum cycle length that varies among manufacturers. Usually, they will not withhold inappropriate therapy for SVT if the majority of ventricular intervals (typically 70–80%) are shorter than the SVT limit. Thus, rapidly conducted atrial fibrillation may be classified as VT even if mean cycle length is 20–40 ms longer than the SVT limit. Programming a sufficiently short minimum cycle length for SVT-VT discrimination is critical to reliable rejection of SVT. In clinical trials, ~25% of inappropriate therapy has been caused by SVT with ventricular cycle lengths sufficiently short that discriminators were not applied.^{21,22}

The performance of SVT-VT discriminators is linked to boundaries between detection zones for ventricular arrhythmias. In Guidant ICDs, this link is explicit. Starting with Vitality™ (2004), SVT-VT discriminators are programmable to the entirety of either or both VT zones. Prior to this, they were limited to the slower VT zone. In St. Jude ICDs, SVT-VT discriminators are programmable independently within the two VT zones, but cannot be programmed in the VF zone. In Medtronic ICDs, the SVT Limit™ is programmable independently of VT/VF zone boundaries. However, the performance of the SVT rejection algorithm

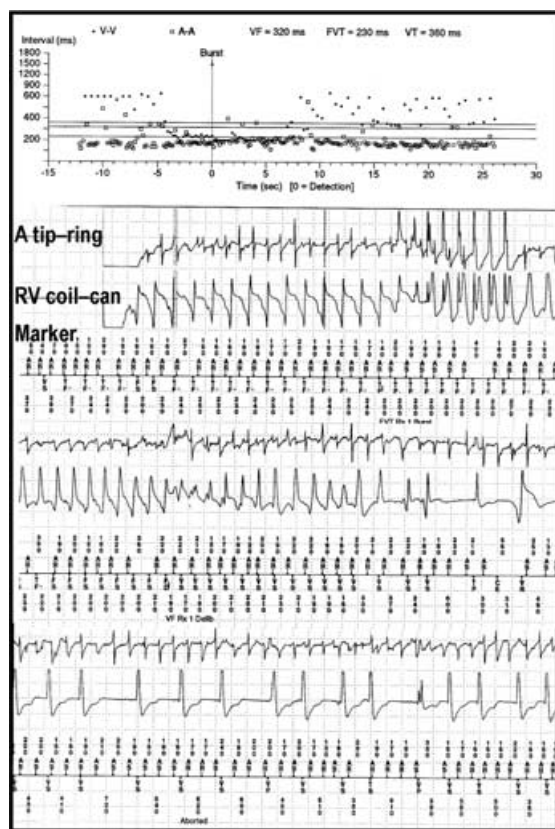


Figure 11. VT during paroxysmal atrial fibrillation. Interval plot (upper panel) and continuous stored electrogram are shown. VT at cycle length 230 ms is diagnosed by AV dissociation and rate as “Fast VT.” Change in morphology is clear on ventricular electrogram but is not used for diagnosis. Antitachycardia pacing is delivered toward the right side of the first electrogram panel. It changes the morphology of VT, which becomes polymorphic and terminates toward the right side of the middle electrogram panel (type II break). VF is detected during this delayed termination (“VF Defib Rx 1” in middle of middle panel), but shock is aborted (Aborted) in middle of bottom panel. Dual-chamber interval plot at top shows onset of VT during atrial fibrillation, persistence of VT after antitachycardia pacing, and subsequent termination. Most VT that occurs during paroxysmal atrial fibrillation is rapid and has cycle lengths classified in the VF zone using traditional programming. Antitachycardia pacing therapy for “fast” VT reduces inappropriate shocks. Ventricular intervals are classified as TS (fast VT), VS (ventricular sensed—sinus zone or during capacitor charging), FS (VF zone), TP (antitachycardia pacing), and VR (ventricular refractory) period after end of capacitor charging (CE).

changes at the programmed VF detection interval so that SVT with AV dissociation (atrial fibrillation) is not classified as SVT because it cannot be distinguished from VF. Further, Medtronic

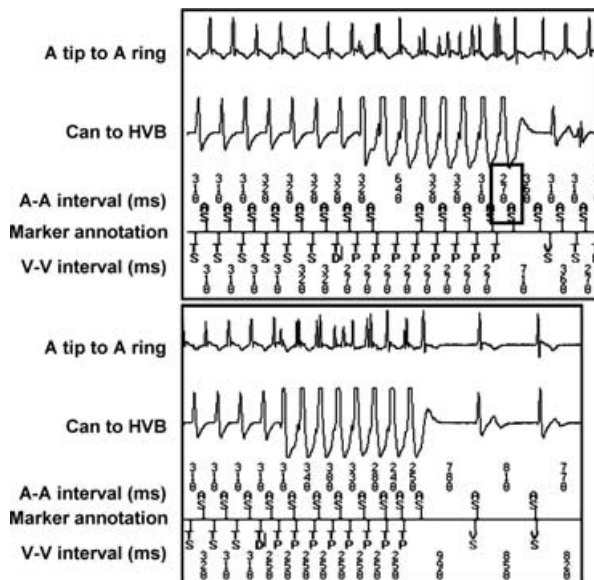


Figure 12. Effect of ventricular antitachycardia pacing on SVT with 1:1 AV relationship. Atrial electrogram (A tip to A ring), high-voltage ventricular electrogram (Can to HVB), and dual-chamber Marker Channel are shown. Upper panel: Burst ventricular antitachycardia pacing at cycle length 270 ms is applied to SVT with cycle length 310–320 ms. The atrial interval after the last paced beat is accelerated to the pacing rate, probably indicating entrainment of the atrium. The AAV response at termination of pacing is diagnostic of atrial tachycardia. Lower panel: Burst ventricular pacing at cycle length 250 ms accelerates the last two atrial intervals to the pacing cycle length and terminates tachycardia. This response does not distinguish between VT and SVT.

ICDs use consecutive-interval counting and other measures of ventricular-interval regularity to withhold inappropriate therapy for atrial fibrillation for rhythms with cycle length \geq the VF interval. Consecutive-interval counting resets the VT counter to zero if any interval exceeds the VT interval. To ensure reliable detection of VF, neither consecutive-interval counting nor regularity of the ventricular cycle length is applied to rhythms with cycle lengths shorter than the VF interval. Thus, at ventricular cycle lengths shorter than the VF interval and longer than the SVT limit (the portion of the VF zone in which discriminators are applied), sinus/atrial tachycardia or 2:1 atrial flutter is rejected, but conducted atrial fibrillation is not. In nominal programming of Medtronic ICDs, the “VF interval” forms the boundary between the VT and “Fast VT” zones. Thus, this degradation in discrimination of VT from rapidly conducted atrial fibrillation usually occurs between the VT and Fast VT zones. Conducted atrial fibrillation in the Fast VT zone may be classified correctly by

Table I.
Recommended Programming of SVT-VT Discriminators in Single-Chamber ICDs

	Medtronic	Guidant	St. Jude
Stability*	40–50 ms, NID = 16	24–40 ms, Duration 2.5 seconds	80 ms
Onset	84–88%	9%	150 ms
Morphology	3 of 8 electrograms $\geq 70\%$ match	Not programmable†	5 of 8 electrograms $\geq 60\%$ match

*Less strict values are required for patients taking type I or III antiarrhythmic drugs.

†Three of 10 electrograms with feature correlation coefficient greater than threshold.

programming “Fast VT via VT” rather than the nominal “Fast VT via VF.” The risk is delay in detection of unusual, markedly irregular fast VT with occasional cycle lengths in the sinus zone.

Single-Chamber SVT-VT Discriminators

Technical details vary among manufacturers, as do corresponding recommended programmed values, which are summarized in Table I. Interval-stability (stability) and sudden-onset (onset), the first single-chamber discriminators to be implemented, have been studied intensively.^{8,9,23} Limited data suggest that analysis of ventricular electrogram morphology^{7,24–27}—alone or in combination with stability—provides the best SVT-VT discrimination for initial detection of VT.⁷

Morphology Algorithms

All morphology algorithms share common steps (see Fig. 13). (i) Record a template electrogram of baseline rhythm. (ii) Construct and store a quantitative representation of this template. (iii) Record electrograms from an unknown tachycardia. (iv) Time align template and tachycardia electrograms tachycardia. (v) Construct a quantitative representation of each tachycardia electrogram. (vi) Compare the representation of each tachycardia electrogram with that of the template to determine their degree of morphologic similarity. (vii) Classify each tachycardia electrogram as a morphology match or nonmatch with the template. (viii) Classify the tachycardia as VT or SVT based on the fraction of electrograms that match the template. Steps 3–8 are performed in real time. Morphology algorithms differ in electrogram source(s), methods of filtering and alignment, and details of quantitative representations. But they have common failure modes:

(i) *Inaccurate template.* The template may be inaccurate because the baseline electrogram has changed (e.g., postimplant lead maturation or intermittent bundle branch block) or the template was recorded from an abnormal rhythm (e.g., id-

ioventricular or bigeminal premature ventricular complexes). Accurate SVT-VT discrimination requires periodic automatic or manual template updates. If automatic updates are not available, the morphology algorithm should not be programmed until a chronic electrogram is present. However, the template cannot be updated without intrinsic AV conduction. If software permits (Medtronic and St. Jude ICDs), the template match should be verified initially and during follow-up.

(ii) *Electrogram truncation* (clipping) occurs when the recorded electrogram signal exceeds the range of the sensing amplifier so that the maximum or minimum portions of the electrogram is clipped. This both removes electrogram features for analysis and alters the timing of the tallest peak, which can affect alignment (see below). The amplitude scale in Medtronic and St. Jude ICDs should be adjusted so that the electrogram used for morphology analysis is 25–75% of the dynamic range (Figs. 14A and 15A).

(iii) *Alignment errors* prevent match between a tachycardia electrogram and a morphologically

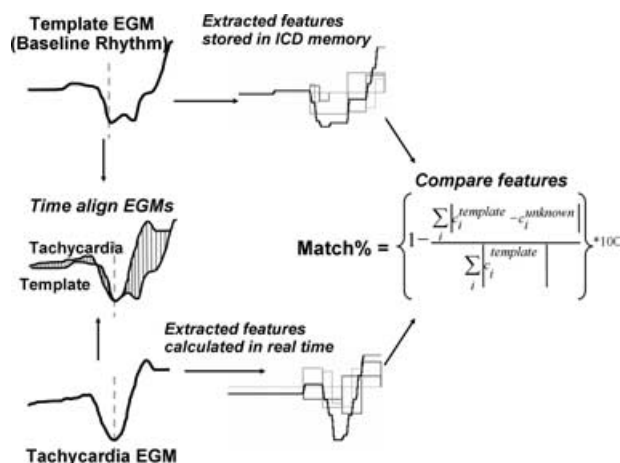


Figure 13. Steps in morphology algorithm. See text for details.

similar stored electrogram. Possible mechanisms depend on the method used for electrogram alignment. Accurate alignment in the St. Jude algorithm is sensitive to the value of sensing threshold at the onset of the ventricular electrogram, as determined by Automatic Sensitivity Control™. If a template

electrogram is acquired at the most sensitive setting of Automatic Sensitivity Control™ (either because of a slow sinus rate or after a ventricular paced beat), a low amplitude peak at the onset of the ventricular electrogram may be used for alignment. An identical tachycardia electrogram may be acquired at a sufficiently fast rate that Automatic Sensitivity Control™ does not reach its most sensitive value at the onset of the R wave. If this occurs, the low amplitude peak at the onset of the ventricular electrogram may not be used for alignment. If identical template and tachycardia electrograms are then compared, their representations in the morphology algorithm may not match. Usually, they are assigned morphology match scores of either 0% or 100% (Fig. 14B and C). In patients who have dual-chamber ICDs and intact AV conduction, the preferred solution is to acquire the template during atrial pacing at a rate closer to the tachycardia rate. In single-chamber ICDs, solutions may include altering the minimum sensitivity, threshold start, or threshold delay.

Medtronic ICDs align electrograms based on their tallest (positive or negative) peaks. If an electrogram has two peaks of nearly equal amplitude or such peaks are caused artificially by truncation of large electrograms that exceed the programmed dynamic range, minor variation in their relative amplitudes may result in an alignment error (Fig. 15A and C). An alternative source electrogram should be selected.

The Guidant morphology algorithm²⁷ aligns high-voltage electrograms based on the peak of the rate-sensing electrogram. “Slow” automatic gain control adjusts dynamic range based on the amplitude of the sensed R wave to minimize alignment

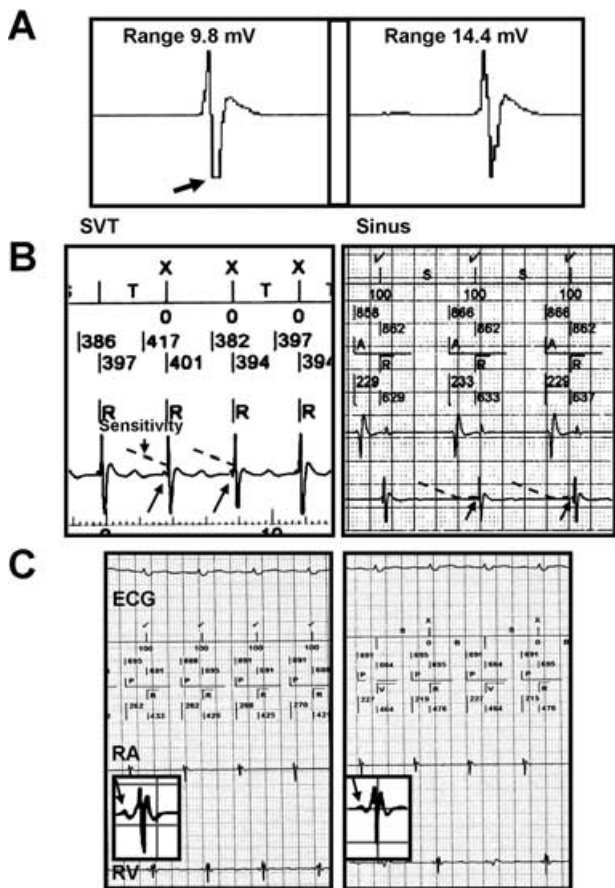


Figure 14. Inappropriate detection of SVT by St. Jude MD™ morphology algorithm. (A) Electrogram truncation: Template electrogram is truncated (arrow) with amplifier range of 9.8 mV. Truncation was corrected by increasing range to 14.4 mV. Inconsistent truncation may prevent SVT morphology from matching template. (B) Interaction of automatic sensitivity control and morphology analysis. Left panel shows stored electrogram of SVT inappropriately detected as VT. Right panel shows programmer strip of validated template in sinus rhythm. Despite identical ventricular electrograms, morphology match scores are 0% in SVT and 100% in sinus rhythm. Slanted line denotes slope of automatic sensitivity control. In sinus rhythm, automatic sensitivity control reaches minimum value before the next ventricular electrogram so that small peak at onset of electrogram (arrow) is used for alignment. In SVT, automatic sensitivity control does not reach

minimum, and small peak is not used for alignment. See text for troubleshooting solutions. (C) Programmer strip showing ECG, marker, atrial, and ventricular electrograms in sinus rhythm (left) and intermittent atrial-sensed ventricular paced rhythm at right. Insert shows identical ventricular electrogram morphology in two panels recorded seconds apart in time. Morphology match is 100% for consistently-conducted sinus beats and 0% for sinus beats following ventricular paced beats. The most likely explanation for this discrepancy is an alignment error: Automatic sensitivity control is more sensitive after paced beats than during consistently conducted sinus rhythm. Thus the small peak at the onset of the ventricular electrogram is used for alignment only after paced beats. Failure of morphology match only on postpaced beats does not degrade algorithm performance during tachycardia. Abbreviations as in Figures 9 and 10.

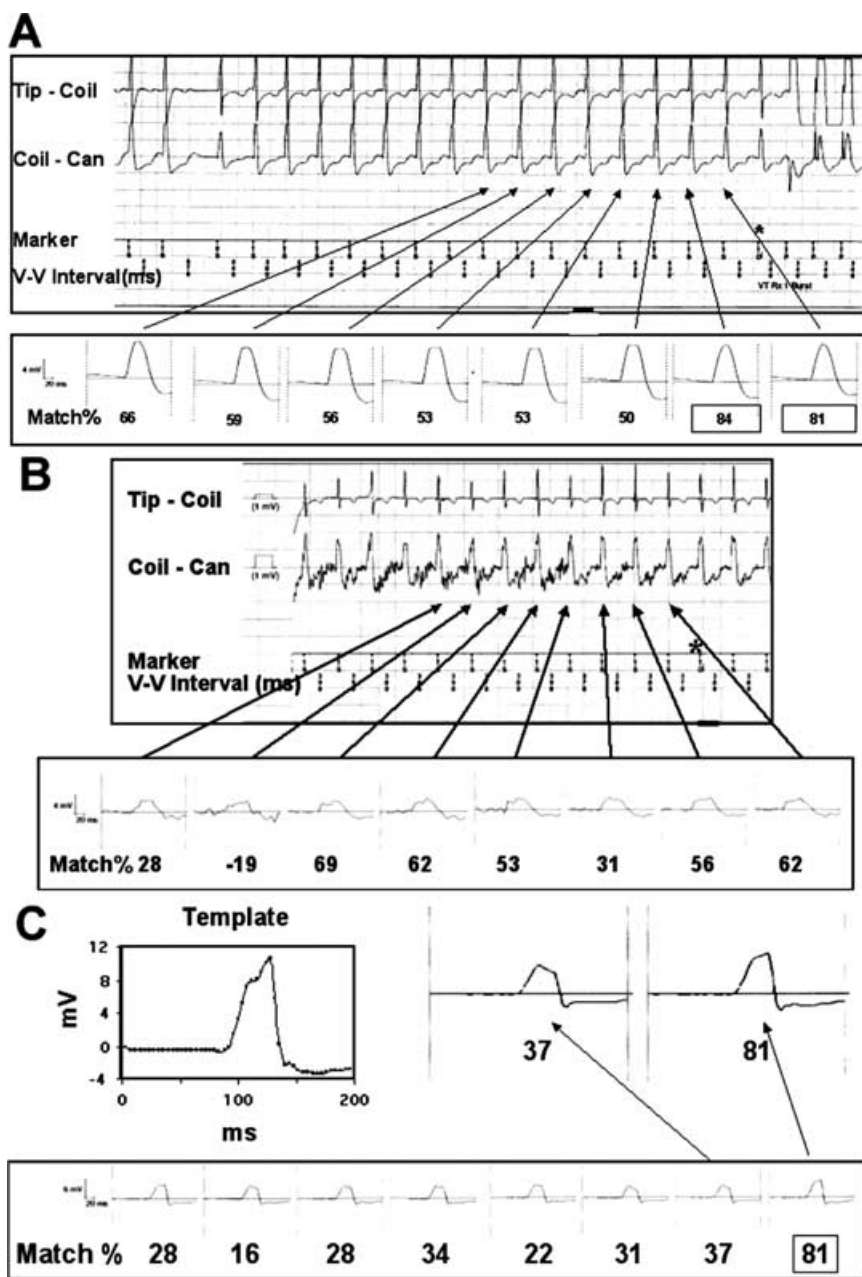


Figure 15. Inappropriate detection of SVT by Medtronic Wavelet™ morphology algorithm. Channels are as shown in Figure 3. (A) Electrogram truncation. Electrograms in rapidly conducted atrial fibrillation exceed the maximum amplitude range of 8 mV resulting in varying degrees of truncation (clipping) of the signal compared to the template. Inappropriate antitachycardia pacing occurs at right. Snapshots below show the last eight electrograms prior to detection at higher resolution. The first of these electrograms shows minimal clipping (66% match). The next five electrograms show more clipping (50–59% match). The last two electrograms are unclipped and are classified as supraventricular (84% and 81% matches). The rhythm is classified as VT because 6 of the last 8 electrograms have <70% match. This problem was corrected by expanding the electrogram scale 16 mV. (B) Myopotential interference. Exercise-induced interference from pectoral myopotentials combined with low-amplitude coil-can electrogram result in inappropriate detection of sinus tachycardia at asterisk. Inset shows sinus template. Snapshots of the coil-can

(continued)

errors caused by truncation errors. Presently, data regarding errors in this algorithm are limited.

(iv) *Oversensing of pectoral myopotential.* In Medtronic ICDs, this may prevent template matches on the coil-can electrogram if the electrogram amplitude is low (Fig. 15B). The effect of myopotentials on match percent can be tested by pectoral muscle exercise. Select an alternative source electrogram to prevent such oversensing, such as distal coil to proximal coil. Pectoral myopotentials also pose a possible source of error in Guidant ICDs, which incorporate the high-voltage electrogram in morphology analysis. Oversensing of pectoral myopotentials is not a problem for St. Jude ICDs, which use near-field electrograms for morphology analysis.

(v) *Rate-related aberrancy.* Complete bundle-branch aberrancy is rare in ICD patients. If it occurs reproducibly, the template may be recorded during rapid atrial pacing. Automatic template updating should then be deactivated to prevent subsequent, automatic acquisition of a slow baseline template without aberrancy. During rapidly conducted atrial fibrillation, subtle degrees of aberration commonly distort the terminal portion of the electrogram sufficiently that the percent match is less than the nominal threshold. In St. Jude ICDs, reducing the fraction of electrograms required to exceed the match threshold from 5 of 8 to 4 of 8 may reduce this problem without compromising detection of monomorphic VT. Reducing the match percent has a greater chance of misclassifying VT.

(vi) *SVT soon after shocks.* ICD detection algorithms reclassify the rhythm as sinus and revert to their initial detection mode within a few seconds after a shock, but postshock distortion of electrogram morphology persists for 30 seconds to

several minutes.²⁶ If postshock SVT starts after the rhythm is classified as sinus but before postshock electrogram distortion dissipates, any morphology algorithm may misclassify SVT as VT. One appropriate (or inappropriate) shock may be followed by a repetitive sequence of inappropriate shocks in which each shock perpetuates postshock electrogram changes in SVT, resulting in inappropriate detection of VT and the next inappropriate shock.

Atrial Sensing and Blanking in Dual-Chamber SVT-VT Discrimination

Dual-chamber algorithms integrate single-chamber, ventricular discriminators with analysis of the atrial rhythm. The specific features of each manufacturer's algorithm have been reviewed.^{7,21,22,28-33}

Comparison of Atrial and Ventricular Rates

This is a simple and powerful SVT-VT discriminator if atrial electrograms can be identified reliably. Because ventricular rate exceeds atrial rate in 80–90% of VTs in the VT zone of dual-chamber ICDs,^{7,21} algorithms that compare atrial and ventricular rates as their first step (Guidant RhythmID™ and St. Jude) only apply single-chamber discriminators to <10% of VTs, reducing the risk that they will misclassify VT as SVT. Dual-chamber algorithms also include measures of sTable 1:1 or N:1 AV association (Medtronic, St. Jude). Accurate sensing of atrial electrograms is essential for dual-chamber SVT–VT discrimination. Atrial lead dislodgments, oversensing of far-field R waves, or undersensing due to low-amplitude atrial electrograms or atrial blanking periods may cause inaccurate identification of atrial electrograms, resulting in either misclassification of VT as SVT or SVT as VT. Ideally, the atrial lead should have an interelectrode spacing of ≤ 10 mm

Figure 15. *electrogram result in inappropriate detection of sinus tachycardia at asterisk. Inset shows sinus template. Snapshots of the coil-can electrograms show baseline distortion by myopotentials. The tip-coil electrogram shows no interference. This problem was corrected by switching to the tip-coil electrogram for morphology analysis. (C) Alignment error. Sinus template, snapshots of last eight tip-coil electrograms prior to inappropriate detection of sinus tachycardia, and detail of last two electrograms are shown. The algorithm time aligns template and tachycardia electrograms using the tallest peak prior to calculation of percent match. This electrogram has two peaks of nearly equal amplitude. In the template, the second peak is taller than the first. In the first seven snapshots, the first peak is as tall as or taller than the second peak. The algorithm misaligns template and tachycardia electrograms, resulting in a low match percent even though the overall shape of the tachycardia electrogram is only slightly different from that of the template electrogram. Only the last tachycardia electrogram, in which the second peak is taller than the first peak, is classified as supraventricular (match = 81%). This problem was corrected by changing electrogram source to coil-can. Reprinted with permission from Swerdlow et al.²⁶*

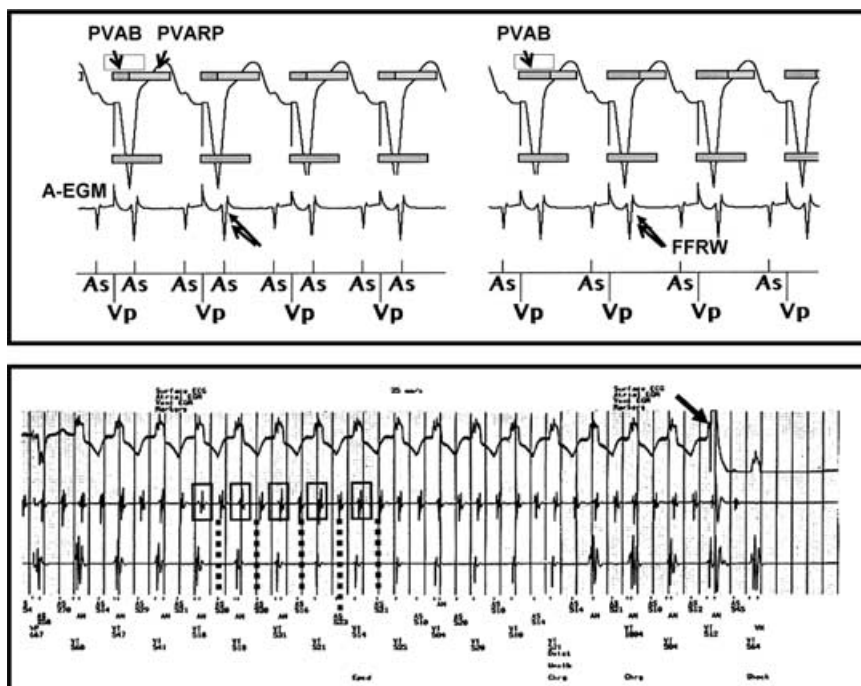


Figure 16. Effect of postventricular atrial blanking. Upper panel shows ECG, atrial electrogram, and Marker Channel during atrial sensed—ventricular paced rhythm. First segment of lower horizontal bar denotes postventricular atrial blanking period (PVAB). Second segment denotes postventricular atrial refractory period (PVARP). FFRW denotes far-field R wave on atrial channel. With a short postventricular atrial blanking period (left), far-field R waves are oversensed. Longer postventricular atrial blanking period (right) prevents oversensing of far-field R waves. Lower horizontal line bar denotes postpacing ventricular blanking period. Lower panel shows ECG, atrial, and ventricular electrograms from atrial flutter with 2:1 AV conduction. Horizontal bars on ventricular channel denote postventricular atrial blanking, which results in atrial undersensing of alternate atrial flutter electrograms (in boxes). Resultant incorrect calculation of atrial rate causes inappropriate shock (arrow) for atrial flutter because the ICD interprets the ventricular rate to be > the atrial rate.

and should be positioned at implant so that far-field R waves are minimized. To date, atrial lead and sensing problems have limited the degree to which dual-chamber algorithm improve SVT-VT discrimination over single-chamber algorithms^{34,35}

Post-Ventricular Atrial Blanking and Rejection of Far-Field R Waves

To prevent oversensing of far-field R waves, some dual-chamber ICDs have postventricular atrial blanking periods similar to those in pacemakers (Fig. 16, upper panel). Because the blanking period is fixed, the blanked fraction of the cardiac cycle increases with rapid ventricular rates. Atrial undersensing caused by postventricular atrial blanking may cause underestimation of the atrial rate during rapidly conducted atrial flutter or atrial fibrillation, resulting in inappropriate detection of VT (Fig. 16, lower panel).⁹ However,

without postventricular atrial blanking, atrial oversensing of far-field R waves may cause overestimation of the atrial rate during tachycardias with 1:1 AV relationship.²¹ This may cause either inappropriate rejection of VT as SVT if far-field R waves are consistently counted as atrial electrograms or inappropriate detection of SVT as VT if far-field R waves are inconsistently counted (Fig. 16).³³

St. Jude ICDs provide programmable atrial blanking after sensed ventricular events to individualize the trade-off between oversensing far-field R waves and undersensing atrial electrograms in atrial fibrillation. They also provide programmable atrial sensing threshold start and decay delay, corresponding to the same features in the ventricular channel. Guidant Vitality™ ICDs have a 15 ms fixed blanking period followed by period of auto-adjusting, reduced sensitivity (SmartSense™) designed to reject far-field R waves without preventing recognition of atrial fibrillation. Older Guidant

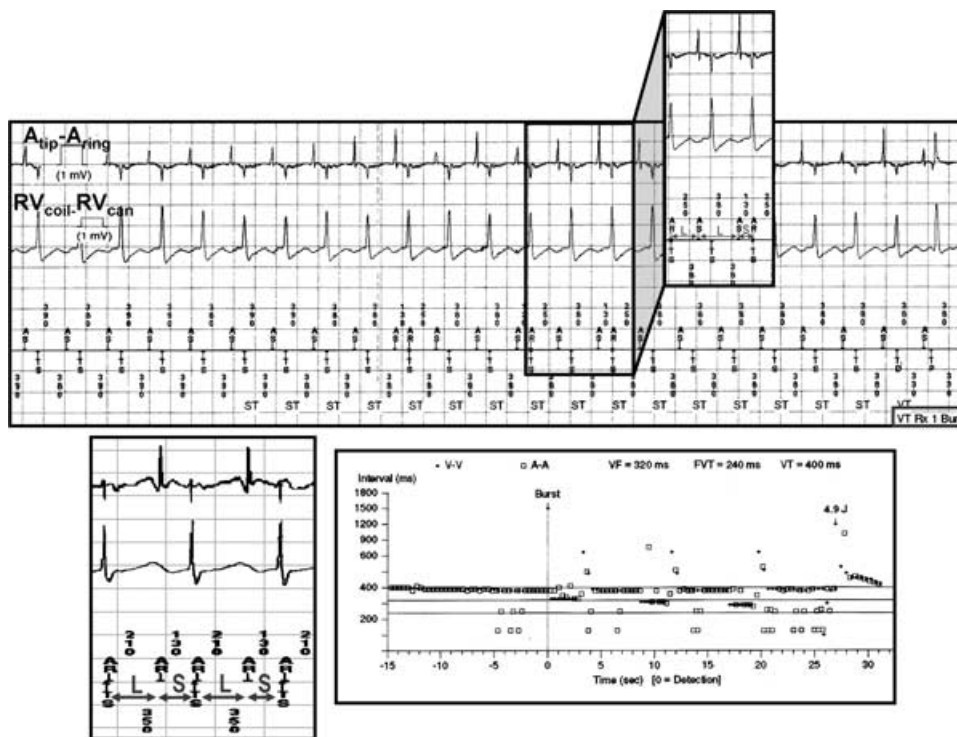


Figure 17. Inappropriate therapy of sinus tachycardia caused by oversensing of far-field R waves in a Medtronic ICD. Upper panel shows dual-chamber electrogram and Marker Channel in sinus tachycardia. Large far-field R waves on the atrial channel are oversensed intermittently (AR markers simultaneous with ventricular electrogram). ST denotes withholding of VT therapy because pattern of sinus tachycardia is confirmed. Intermittent oversensing of far-field R waves results in failure to confirm sinus tachycardia pattern, resulting in inappropriate detection of VT and antitachycardia pacing at right of panel (VT Therapy 1 Burst). Lower left panel shows alternating pattern of long (L)-short (S) atrial electrograms with 2:1 AV relationship correctly classified by far-field R wave rule as sinus tachycardia. Consistent sensing of far-field R waves results in algorithmic withholding of VT therapy. Lower right: Interval plot shows intermittent oversensing of far-field R waves in sinus tachycardia resulting in three sequences of inappropriate antitachycardia pacing and a low-energy (delivered 4.9 J) shock. During oversensing of far-field R waves, sum of two sequential, sensed AA intervals equals the RR interval. Consistent oversensing gives “railroad track appearance,” seen on the interval plot at 20–26 seconds after antitachycardia pacing.

ICDs have obligatory blanking periods after atrial sensed events, which often cause the atrial rate to be underestimated during atrial fibrillation and flutter.⁹

Medtronic ICDs provide no atrial blanking after sensed ventricular events to ensure reliable sensing of atrial electrograms during atrial fibrillation and flutter. Instead, they reject far-field R waves algorithmically by identifying a specific pattern of atrial and ventricular events that fulfill specific criteria (Fig. 17). Intermittent sensing of far-field R waves or frequent premature complexes may disrupt this pattern, resulting in misclassification of a tachycardia. Thus it is preferable to reject far-field R waves after sensed ventricular events by decreasing atrial sensitivity if this

can be done without undersensing atrial fibrillation. In our experience, atrial sensitivity can be reduced to 0.45 mV with a low risk of undersensing atrial fibrillation. Values ≥ 0.9 mV should be programmed only if the likelihood of rapidly conducted atrial fibrillation is low. Far-field R wave oversensing that occurs only after paced ventricular events (when auto-adjusting atrial sensitivity is maximum) need not be eliminated to prevent inappropriate detection of SVT as VT.

Programming Dual-Chamber SVT-VT Discriminators

Dual-chamber algorithms should be programmed “ON” in any patient with intact AV

Table II.
Recommended Programming of SVT-VT Discriminators in Dual-Chamber ICDs

Medtronic PR Logic™	Guidant		St. Jude Rate Branch™
	Atrial View™	Rhythm ID™	
AFib/AFlutter “ON”	AFib rate threshold 200 beats/min		Rate branch “ON”
Sinus Tach “ON”	Onset 9%		A=V branch: Morphology
Other 1:1 SVTs “OFF”	Inhibit if unstable 10%	“ON”	A > V branch morphology; may combine stability* with “ANY” logic
1:1 VT-ST boundary 66% ¹	V rate > A rate “ON” Sustained rate duration 3 min		

*Stability at 80 ms with AV association of 60 ms.

conduction and a functioning atrial lead. Specific considerations differ for each manufacturer. See Table II. In Medtronic and Guidant algorithms, incremental addition of discriminators increases the likelihood that SVT will be classified correctly (specificity) and decreases the likelihood that VT will be classified correctly (sensitivity). In St. Jude ICDs, discriminators may be combined using either the “ANY” or “ALL” operators. Using “ANY,” the algorithm detects VT if any discriminator classifies the tachycardia as VT, resulting in higher sensitivity and lower specificity. Conversely, using “ALL,” the algorithm detects VT only if all discriminators classify the tachycardia as VT, resulting in lower sensitivity and higher specificity. The “ALL” operator corresponds to addition of discriminators in other algorithms.

St. Jude Rate Branch™

Morphology should be programmed in both the V = A and V < A rate branches. Recommended programming adds the stability discriminator in the V < A branch using the “ANY” operator. This results in a minor increase in sensitivity for detection of VT (98–99%) and a similarly minor decrease in specificity (82–79%).⁷ Addition of the stability discriminator using the “ALL” operator reduces inappropriate detection of rapidly conducted atrial fibrillation, but at a price in sensitivity for detection of VT.⁷

Guidant Rhythm ID™

This algorithm utilizes atrial versus ventricular rate, electrogram morphology, and interval stability to discriminate VT from SVT,²⁷ the same three general features used by the St. Jude algorithm. It has no programmable features. The benefit of this algorithm’s design is that it requires no custom programming; the limitation is that its errors cannot be corrected by troubleshooting.

Guidant Atrial View™

The principal limitations of this earlier algorithm include inability to detect VT with 1:1 VA conduction and a gradual onset, inability to reject 1:1 atrial tachycardias with abrupt onset, and inappropriate detection of rapidly-conducted atrial fibrillation^{9,22,30} due to obligatory postventricular atrial blanking. The latter may be ameliorated by programming the postventricular atrial blanking period to the minimum value of 45 ms, the “AFib Rate” to the minimum value of 200 beats/min, and the “Stability” feature to the highly specific value of 10%. This programming takes advantage of the fact that VT during atrial fibrillation or flutter usually is highly regular and often more regular than conducted 2:1 atrial flutter. However, highly regular 2:1 conduction of atrial flutter will be classified as VT; and slightly irregular VT that occurs during atrial fibrillation will be classified as SVT—especially in the setting of antiarrhythmic drugs.^{11,36}

Medtronic PR Logic™

At implant, rejection rules should be programmed “ON” for Sinus Tachycardia and Atrial Fibrillation/Flutter. The 1:1 SVT rejection rule should not be programmed until the atrial lead is stable because its dislodgement to the ventricle may result in misclassification of VT as a 1:1 SVT. PR Logic™ uses the pattern and rate of AA, VV, AV, and VA intervals to discriminate VT from SVT. This dependence, combined with the absence of atrial blanking periods after sensed ventricular events, makes it susceptible to errors based on intermittent oversensing of far-field R waves. The next generation of Medtronic ICDs includes a new algorithm for rejection of sinus tachycardia that will reduce sensitivity to far-field R waves.³⁷ PR Logic discriminates VT with 1:1 VA conduction from SVT based on the ratio of PR to RR intervals. Increasing the value from the nominal setting

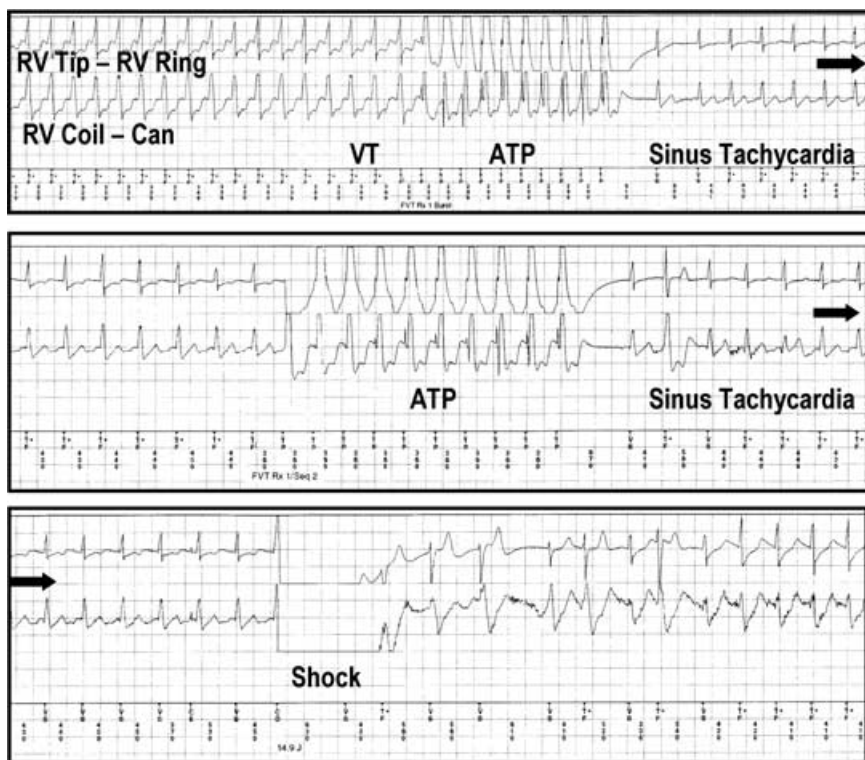


Figure 18. Inappropriate therapy of sinus tachycardia after appropriate therapy of VT in a single-chamber ICD. Ventricular sensing and high-voltage leads are shown with Marker Channel. Upper panel shows continuous stored-electrogram strips following detection of VT. The top strip shows successful antitachycardia pacing (ATP) of VT followed by sinus tachycardia in the fast VT zone (TF on Marker Channel). The second strip shows the first inappropriate sequence of antitachycardia pacing. The third shows the first of five shocks delivered after antitachycardia pacing. The interval plot in the bottom panel shows the entire episode. No U.S. ICD manufacturer provides for VT-SVT discrimination after antitachycardia pacing.

of 50–66% reduces inappropriate therapy for 1:1 SVT with long PR intervals without significantly increasing the risk of failing to detect VT with 1:1 VA conduction.³⁸

SVT-VT Discrimination in Redetection

SVT-VT discrimination in redetection serves two purposes—to prevent inappropriate therapy for SVT after appropriate therapy for VT and to provide a second chance for the algorithm to “get it right” after inappropriate therapy for SVT. ELA is the only manufacturer that provides equivalent SVT-VT discrimination in initial detection and redetection. Guidant’s Atrial View™ and Rhythm ID™ algorithms permit programming discriminators after shocks, but not after antitachycardia pacing. In Medtronic ICDs, the single-chamber stability discriminator applies to redetection if it is “ON” for initial detection, but dual-chamber discrimination does not apply. St. Jude does not apply discriminators to redetection. Thus, neither Medtronic nor St. Jude provides any single or dual-chamber discriminators to reject sinus tachycardia after therapy. See Figure 18. β -blockers may be prescribed and the programmed number of shocks for hemodynamically stable VT may be reduced to limit repetitive inappropriate shocks.

Is Ventricular Therapy for SVT Always Inappropriate?

Persistent, rapidly conducted atrial arrhythmias may cause hemodynamic compromise in patients with LV dysfunction or ischemia in patients with severe coronary artery disease. Because ventricular shocks often terminate atrial fibrillation and ventricular antitachycardia pacing often terminates 1:1 atrial tachycardia, algorithmically inappropriate ventricular therapy may fortuitously terminate clinically significant SVT. However, inappropriate ventricular therapy for SVT may have serious consequences. Antitachycardia pacing may be proarrhythmic,³⁹ and shocks for rapidly conducted atrial fibrillation is problematic: (i) Atrial fibrillation in ICD patients is often paroxysmal, rapid conduction is often transient, and symptoms are usually mild; but ventricular shocks delivered shortly after detection do not permit spontaneous termination of atrial fibrillation or slowing of the ventricular rate. Thus they may be delivered for atrial fibrillation that would have either terminated spontaneously or have had only transient, rapid conduction. (ii) Detection algorithms in ventricular ICDs cannot use the total duration of (slowly conducted) atrial fibrillation to withhold shocks. Thus inappropriate shocks for atrial fibrillation may place patients at

risk for thromboembolism if they are not anticoagulated. (iii) Early recurrence is common after transvenous cardioversion of atrial fibrillation.⁴⁰ (iv) Ventricular ICDs are not designed to ensure cardioversion of rapidly conducted atrial fibrillation without permitting inappropriate shocks for sinus tachycardia, which usually are repetitive.

Experts disagree about whether or not algorithmically inappropriate ventricular therapy of SVT may be clinically appropriate in specific clinical situations. We recommend implanting ICDs designed to deliver both atrial and ventricular therapies in ICD patients who are likely to benefit from device-based therapy of SVT.⁴¹ Unique troubleshooting aspects of ICDs that deliver atrial therapies are beyond the scope of this review.

Additional Programming to Reduce Shocks

Programming to Prevent Oversensing

Consistent *oversensing of spontaneous P waves* often requires lead revision. One amelioration strategy is to force atrial pacing using DDDR or Dynamic Overdrive™ modes. This shortens the ventricular cycle length to prevent ventricular sensitivity from reaching its minimum value and introduces cross-chamber ventricular blanking after each atrial event to prevent oversensing of P waves.

In St. Jude ICDs, *R-wave double counting* may be overcome by increasing the ventricular blanking period from the nominal value of 125–157 ms. In Medtronic and Guidant ICDs, it usually requires lead revision. Occasionally, reducing ventricular sensitivity can prevent it; but ventricular sensitivity should not be reduced unless reliable sensing of VF is confirmed at the reduced level of sensitivity.

T-wave oversensing by ICDs is an unwanted result of the requirement to sense VF electrograms reliably, which may have low amplitudes and slow rates. To minimize the likelihood of T-wave oversensing, ICDs automatically adjust sensitivity in relation to the amplitude of the preceding R wave.⁴² At the end of the blanking period after each sensed ventricular event, sensitivity is decreased to a starting value related to the amplitude of the sensed R wave (ventricular electrogram) and then decreases with time to a minimum value. The specific behavior of this adjustment depends on the manufacturer (Fig. 19). In Medtronic and St. Jude ICDs, this minimum value is the programmed sensitivity. In Guidant ICDs, the minimum value depends both on programmed sensitivity and “slow” Automatic Gain Control. This feature adjusts the dynamic range of the sensing amplifier to ensure that the peak of the sensed R wave reaches about 75% of the amplifier gain. It also increases the minimum value of amplifier range (reduces sensitiv-

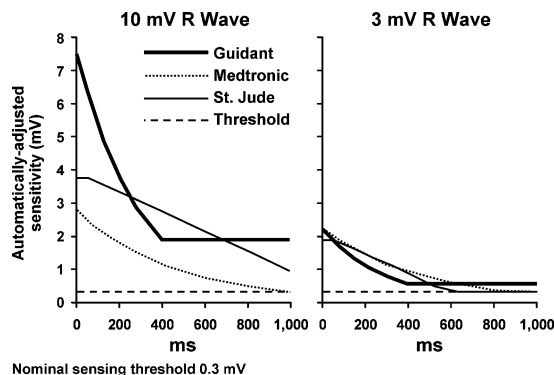


Figure 19. Comparison of automatically adjusted sensitivity after sensed ventricular events for three ICD manufacturers. Left panel shows markedly different performance after large (10 mV) R wave. Right panel shows similar performance after small (3 mV) R wave. Nominal sensing threshold ~ 0.3 mV. After sensed ventricular events, Medtronic ICDs reset the sensing threshold to 8–10 \times the time programmed sensitivity, up to a maximum of 75% of sensed the R wave. The value of auto-adjusting sensitivity then decays exponentially from the end of the (sense) blanking period with a time constant of 450 ms until it reaches the programmed (maximum) sensitivity. At the nominal sensitivity of 0.3 mV, there is little difference between the sensitivity curves after large and small spontaneous R waves. If the R wave is big, the entire auto-adjusting sensitivity curve can be altered substantially by changing the programmed value of maximum sensitivity (Fig. 22). At nominal settings, the St. Jude threshold start begins at 62.5% of the measured R-wave for values between 3 mV and 6 mV. If the R-wave amplitude is >6 mV or less than 3 mV, the threshold start is set to 62.5% of these values (3.75 mV and 1.875 mV, respectively). The sensing threshold remains constant for a decay delay period of 60 ms, and then decays linearly with a slope of 3 mV/s. Both the threshold start percent and decay delay are programmable over the range 50–75% and 0–220 ms, respectively (Fig. 21). Guidant ICDs set the starting threshold to 75% of the sensed R wave. Sensitivity (“fast” automatic gain control) then decays with a half-time of 200 ms (time constant of 289 ms) to a minimum value that depends on the dynamic range of the sensing amplifier. “Slow” automatic gain control adjusts the maximum value of this dynamic range to 150% of the value of the average R wave. The minimum value of dynamic range is 1/8 of the maximum value. This is equivalent to 3/16 (18.75%) of the amplitude of the average R wave. After a paced ventricular event, all ICDs also adjust sensitivity dynamically starting at the end of the (pace) blanking period, but the threshold starts at a more sensitive setting.

ity) as R wave amplitude increases. After ventricular pacing, all ICDs set ventricular sensitivity to a highly sensitive value to ensure that pacing does not occur during VF.

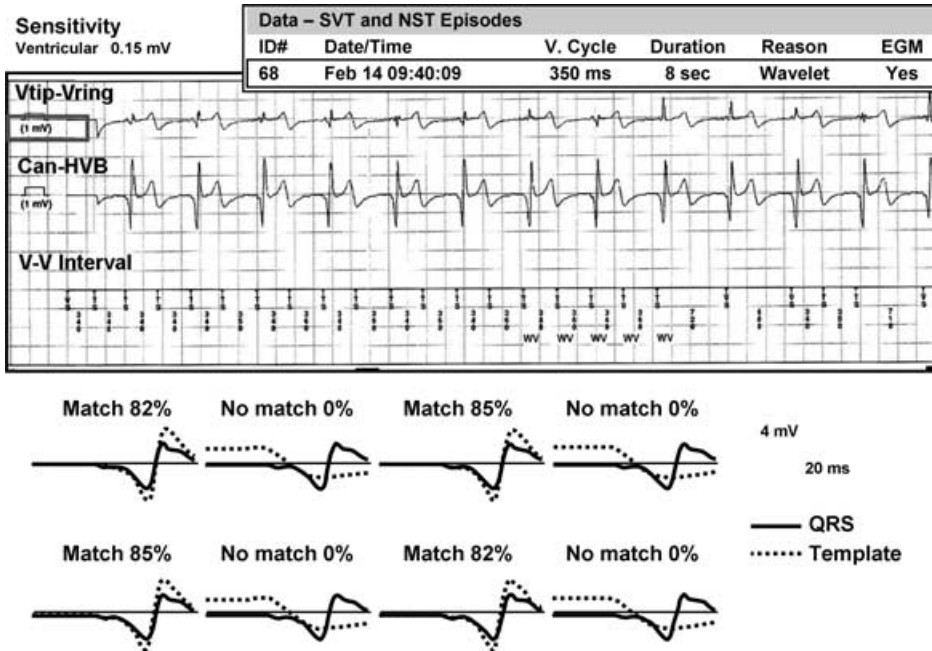


Figure 20. Inappropriate therapy for T-wave oversensing prevented by morphology algorithm. The upper panel shows true-bipolar RV sensing electrogram, high-voltage electrogram, and Marker Channel. Intermittent T-wave oversensing occurs because of the low-amplitude R wave and ventricular sensitivity setting of 0.15 mV. WV indicates that VT therapy is being withheld by the Wavelet morphology algorithm. Lower panel shows match % scores for stored electrogram. “Tachycardia” electrograms alternate morphologies between one with a high match % (82–85%) representing the R wave and one with a 0 match % representing the T wave.

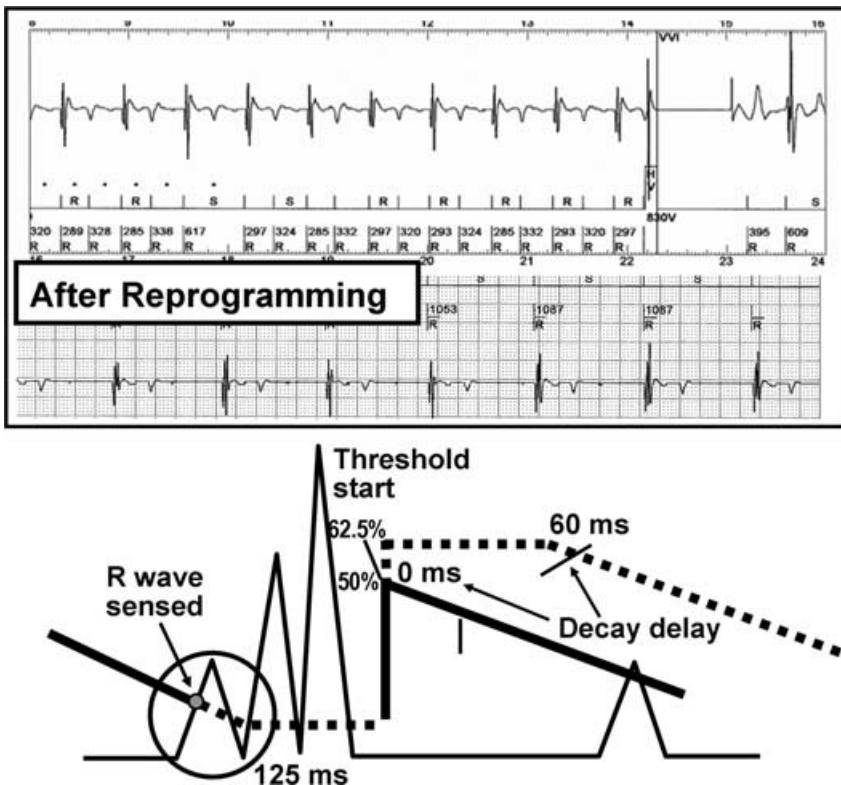


Figure 21. Specific programmable features to correct T-wave oversensing. Upper panel: Upper strip in shows stored electrogram from a St. Jude ICD showing inappropriate shock for sinus tachycardia with T-wave oversensing. Lower strip is recorded from programmer after reprogramming decay delay from 0–220 ms. Lower panel: Diagram of programmable features to avoid and correct T-wave oversensing in St. Jude ICDs. Automatic sensitivity control begins to adjust sensing at the end of the 125 ms ventricular blanking period. Both the initial sensitivity (threshold start as % of R-wave amplitude) and time delay before onset of linear decrease in sensing threshold (increase in sensitivity) are programmable parameters.

T-wave oversensing may be divided into three classes: postpacing, large R wave (>3 mV) in spontaneous rhythm, and small R wave (<3 mV) in spontaneous rhythm. Postpacing T-wave oversensing can cause inappropriate inhibition of bradycardia pacing^{43,44} or delivery of antitachycardia pacing at the wrong rate.⁴⁴ It does not cause inappropriate detection of VT/VF; but it may cause inappropriately slow bradycardia or antitachycardia pacing and increment VT or VF counters, increasing the likelihood that nonsustained VT will be detected as VT or VF. It may be corrected by increasing the postpacing ventricular blanking period.

Oversensing of spontaneous T waves often occurs in the setting of low-amplitude R waves because sensitivity and/or amplifier gain is automatically adjusted in relation to the low-amplitude preceding R wave (Fig. 20, upper panel).⁴² Further, patients with low-amplitude R waves may require lower minimum sensing thresholds to ensure reliable sensing of VF. T-wave oversensing in the setting of a low-amplitude R wave is a warning that detection of VF may be unreliable and should be assessed at noninvasive electrophysiological study. The ventricular lead should be revised if the safety margin for sensing VF is insufficient.

Specific programming features or “tricks” may be used to reduce T-wave oversensing in the setting of low-amplitude R waves, provided detection of VF is reliable: (i) St. Jude ICDs provide a programmable “threshold start” and “decay delay” designed to reduce oversensing of spontaneous T waves. These features may be helpful even if the R wave is small (Fig. 21). (ii) The apparent alternation of ventricular electrogram morphologies caused by T-wave oversensing may be exploited to prevent inappropriate detection of VT. The SVT-VT morphology discriminator may be programmed “on” to classify alternate electrograms as “sinus” and thus withhold inappropriate detection. In St. Jude ICDs, the nominal number of morphology matches for SVT must be decreased from five to four to reject T-wave oversensing. The success of this approach depends critically on correct classification of all or nearly all true ventricular electrograms. Depending on how the morphology algorithm is programmed, one or a few premature ventricular complexes may cause inappropriate detection of VT. The long-term reliability of this approach has not established; but it may be sufficient to prevent inappropriate therapy from rare episodes of T-wave oversensing (Fig. 20, lower panel). (iii) Occasionally, the RT and TR intervals differ sufficiently in the VT zone that the stability algorithm may be used to reject T-wave oversensing, but this is rare in sinus tachycardia. (iv) Rarely, T-wave oversensing can be eliminated by forcing

ventricular pacing. This alters the sequence of repolarization and may reduce T-wave amplitude; but it exposes patients to long-term adverse, desynchronizing hemodynamic effects of RV pacing.^{45,46}

Often however, lead revision or addition of a separate pace/sense lead is necessary to ensure detection of VF without T-wave oversensing. If the defibrillation lead is replaced, a true bipolar lead may be preferred because T-wave oversensing may be more frequent with integrated-bipolar leads.⁴⁷

The methods used to avoid T-wave oversensing in the presence of small R-waves are as effective or more effective in the presence of large R waves. In Medtronic ICDs, a small decrease in programmed sensitivity may prevent T-wave oversensing by the implicit effect on the starting value for threshold decay (Fig. 22). “Slow” Automatic

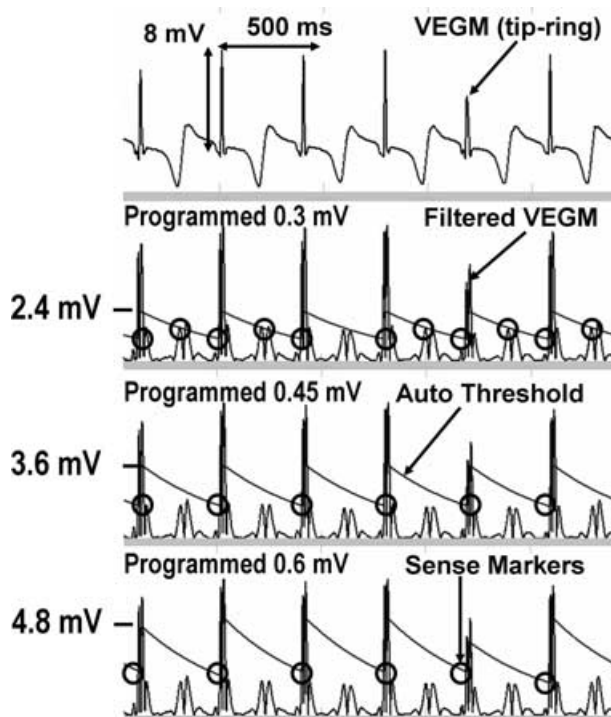


Figure 22. Correction of T-wave oversensing with large R waves by adjusting programmed sensitivity. In Medtronic ICDs, the initial value of sensitivity is 8–10× the programmed minimum sensitivity, depending on the model. Upper panel shows unfiltered true-bipolar ventricular electrogram. Second, third, and fourth panels show filtered electrogram with increasing sensitivity settings 0.3, 0.45, and 0.6 mV. The corresponding initial values of sensitivity are 2.4, 3.6, and 4.8 mV, respectively. The time constant for exponential decay of auto-adjusting sensitivity is unchanged. Intermittent T-wave oversensing at a programmed sensitivity of 0.3 mV is corrected by decreasing sensitivity to 0.45 mV.

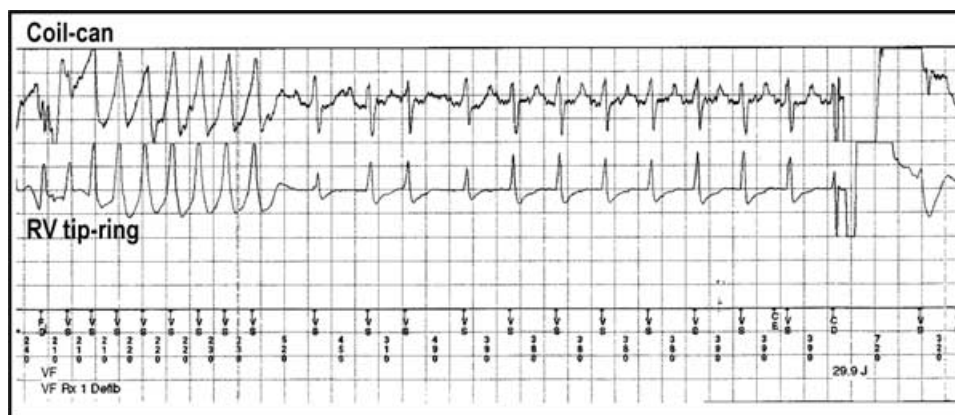


Figure 23. Postshock confirmation. Two ventricular electrograms and Marker Channel are shown from single-chamber ICD. The programmed VT and VF detection intervals are 380 and 320 ms, respectively. Detection of rapid VT as VF results in capacitor charging (VF Rx 1 Defib). After the charging cycle ends (CE), the charge is delivered (CD) as a shock if the ventricular cycle length after charging is less than the programmed VT interval + 60 ms. In St. Jude and Guidant ICDs, shocks for VF are confirmed if the ventricular cycle length is less than the VT interval.

Gain Control™ in Guidant ICDs reduces the likelihood of T-wave oversensing after large R waves. We are not aware of such an occurrence.

Oversensing of diaphragmatic myopotentials may be corrected by reducing ventricular sensitivity if VF sensing and detection are reliable at the reduced level of sensitivity.⁴⁸ Occasionally, it may be corrected by establishing an atrial paced-ventricular sensed rhythm at a sufficiently fast rate that automatic adjustment of sensitivity never reaches its minimum value. This option requires adequate AV conduction, and many patients with diaphragmatic oversensing have AV block. In some cases, diaphragmatic oversensing requires insertion of a new rate-sensing electrode.

Programming to Prevent Shocks For Nonsustained SVT or VT

An ICD may deliver inappropriate shocks for self-terminating VT or SVT if the arrhythmia terminates during the time required to charge the high-voltage capacitor. Such inappropriate shocks often serve as a sentinel event to identify repetitive episodes of aborted shocks, which reduce ICD longevity.

Shocks delivered for self-terminating arrhythmias occur for one of two reasons: The “confirmation” (“reconfirmation” in Guidant ICDs) process between capacitor charging and delivery of a first, noncommitted shock fails or the shock is committed. In all ICDs, the confirmation algorithm delivers the stored shock if a few intervals immediately following charge completion are shorter than the

programmed VT interval (St. Jude and Guidant) or 60 ms > VT interval (Medtronic). This hidden interaction effectively commits the first VF shock if the VT interval (or in some ICDs Monitor-Only interval) is programmed to a long cycle length.^{49,50} See Figure 23. All shocks subsequent to the first shock are committed. A shock is also committed if VT or VF is detected after a diverted shock and before episode termination.⁵¹

Because the confirmation process is necessarily “trigger happy,” the first line of defense against inappropriate therapy for nonsustained VT or SVT is an appropriately long detection duration. Nominal values should be increased in patients who have long episodes of nonsustained device-detected VF (e.g., long QT syndrome). In Medtronic ICDs, nominal programming of the number of intervals for initial detection of VF (18 of 24) substantially reduces inappropriate therapies without significantly delaying detection compared with 12 of 16 intervals,⁵² a commonly used setting. Comparable settings for number of intervals or duration are available in other manufacturers’ ICDs.

Inappropriate therapy for nonsustained VT or SVT may also be delivered after application or inappropriate antitachycardia pacing or shocks. Increasing the duration for redetection may prevent inappropriate redetection of delayed termination of VT (“Type II” break) or postshock nonsustained VT.

However, excessive delays in detection or redetection may result in syncope, increase in defibrillation threshold (DFT), or undersensing

caused by reduced amplitude and frequency of the sensed ventricular electrogram. Fortunately, these adverse effects are rare for VF durations <30 seconds.⁵³

Programming Antitachycardia Pacing to Reduce Shocks

Painless antitachycardia pacing terminates 80–95% of spontaneous VT with cycle length >300–320 ms with a low risk of acceleration (1–5%).⁵⁴ Recent studies have demonstrated that a single trial of antitachycardia pacing (8-pulse burst train at 88% of the VT cycle length) can terminate 75–85% of fast VT (cycle length 240–320 ms) with low rates of acceleration and syncope.^{18,55} Burst and ramp pacing sequences have similar efficacy in slower VTs. For VT CL <300, burst is more effective and less likely to result in acceleration. In general, burst cycle lengths should be 85–90% of the VT cycle length for faster VTs and 70–80% of the VT cycle length for slower VT.⁵⁴ Routine electrophysiological tailoring of antitachycardia pacing is not necessary due to the safety and effectiveness of empirical therapy.⁵⁶ Perhaps less appreciated, ventricular antitachycardia pacing reduces shocks for inappropriately detected SVT either by terminating SVT or by delaying shock therapy until SVT terminates spontaneously or slows into the “sinus” zone.¹⁵ Thus antitachycardia pacing reduces both unnecessary, appropriate shocks for fast VT and inappropriate shocks for SVT. It improves quality of life¹⁸ and should be programmed “on” empirically in most patients, even if its efficacy has not been assessed.

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Unanticipated Therapy in Monitor-Only Zones

If therapy is not programmed “on” for slow VT, the slowest rate zone may be programmed as a “monitor-only” zone with detection “on” and therapies “off.” However, in Guidant, St. Jude, and older Medtronic ICDs (prior to Marquis™), interactions between the counters in the monitor-only zone and the next zone may restrict use of SVT-VT discriminators or decrease the number of intervals required for detection in the therapy zone. The intention of the latter interaction is to ensure prompt treatment of VT if the ventricular cycle length fluctuates around the boundary between two therapy zones. Depending on the specific solution to this “competing” counters problem, events in a “monitor” only zone may increment a “combined count” counter in a faster zone and result in an inappropriate therapy even though the programmed detection criteria to deliver therapy are not met.⁵⁷ Newer Medtronic ICDs (Marquis™ forward) provide independent monitor-only zones that avoid these limitations: Because events in the “monitor” zone do not increment the “combined count” counter, tachycardias in the monitor-only zone do not accelerate therapy if a few intervals cross into the slowest therapy zone. The associated risk is that therapy can be delayed if the VT cycle length fluctuates around the boarder of the monitor-only and therapy zones.

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