Troubleshooting Implanted Cardioverter Defibrillator Sensing Problems I

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Background
Multicenter studies1–3 demonstrate that unnecessary implanted cardioverter defibrillator (ICD) shocks can be reduced by evidence-based programming of detection rate and duration, antitachycardia pacing, and algorithms that discriminate supraventricular tachycardia (SVT) from ventricular tachycardia (VT). Reducing unnecessary shocks from oversensing has attracted less attention. Excluding patients with recalled leads, ventricular oversensing accounts for <10% of shocks for rhythms other than VT or ventricular fibrillation (VF).4,5 However, oversensing often causes multiple shocks. In a study, oversensing accounted for 23% of shocked episodes with ≥4 shocks.6 Further, recalled leads remain implanted in >100,000 patients; and, without an alert for oversensing, 50% of lead fractures present with ≥5 shocks.7,8 Thus, oversensing commonly produces severe symptoms, which may cause post-traumatic stress disorder.9 Furthermore, recognition of transient, asymptomatic oversensing may prevent major complications.7,8,10

Other sensing problems also provide challenges for ICDs. These include undersensing of VF, atrial undersensing, and oversensing in relation to SVT–VT discrimination, and unique issues related to sensing subcutaneous electrograms.

In ICDs, sensing is usually defined as it is in pacemakers, the process for determining the timing of individual cardiac depolarizations. Correspondingly, detection is the process by which an ICD algorithm classifies a sequence of sensed signals to determine the cardiac rhythm. Thus, sensing typically precedes detection. However, algorithms that identify oversensing may be applied after detection, and subcutaneous ICDs may integrate traditionally distinct features of sensing and detection. This review focuses on ICD sensing problems.

Electrograms, Marker Channels, and Episode Diagnostics

Electrogram Sources
Analysis of sensing begins with ICD electrograms and corresponding annotated event markers (commonly referred to by the trademarked term Marker Channel, Medtronic Inc). ICDs store 2 to 4 channels of electrograms and telemeter them to the programmer. The 2 primary ICD electrograms are the shock or high-voltage electrogram displayed on the shock channel and the ventricular sensing electrogram displayed on the sensing channel (Figure 1). The marker channel (Figure 1) indicates the timing of sensing electrograms that reach the amplitude threshold for a sensed event.

The sensing electrogram records a local (near-field) ventricular signal between the tip electrode and the adjacent ring or right ventricular (RV) coil. Electrograms recorded between the tip and the RV coil are referred to as integrated bipolar electrograms because the RV coil integrates both pace-sense and defibrillation functions. Those recorded between the tip and a small proximal ring electrode are referred to as dedicated (or true) bipolar electrograms because the ring electrode is dedicated to pacing and sensing, not used for defibrillation. Leads designed for integrated bipolar sensing do not require a ring electrode and are thus simpler than those designed for dedicated bipolar sensing.

The shock electrogram records a more global (far-field) signal between widely separated, high-voltage electrodes, most commonly RV coil and generator housing (can). In analyzing ventricular sensing, the shock electrogram is used as a check on the sensing electrogram: signals sensed on the sensing channel that do not correspond to signals on the shock channel indicate oversensing. Conversely, true cardiac electrograms on the shock channel that is not associated with events on the marker channel indicate undersensing, except for rare marker telemetry errors. Dual-coil leads permit recording additional far-field signals, including the shock electrogram between RV and superior vena cava (SVC) coils and the leadless ECG between the can and SVC coil.11

In some ICDs, additional electrograms may both facilitate analysis of sensing issues and introduce new sensing issues. The left ventricular electrogram in cardiac resynchronization ICDs (CRT-Ds) provides another check on ventricular sensing. Electrograms recorded from bipolar atrial leads introduce novel sensing problems that affect the accuracy of SVT–VT discrimination. In single-chamber ICDs, atrial electrograms may be recorded using either the leadless ECG or the
electrograms from floating bipolar atrial electrodes on defibrillation leads.\textsuperscript{12,13} The former requires a dual-coil lead and the latter a specialized lead.

**Evaluating Sensing From ICD Electrograms**

Filter settings may influence electrogram appearance (Figure 2). Wideband signals with minimal filtering reproduce QRS complexes accurately and retain the distinctive, rounded appearance of T waves. Highly filtered narrowband signals display the signal that is compared with the sensing threshold in the sensing process, but they alter signal amplitude and polarity, markedly reducing the amplitude of signals with prominent low-frequency components, such as T waves and some components of VF (Figure I in the Data Supplement). Programmable filter settings (St. Jude Medical and Biotronik) permit assessing the effect of filtering on R- and T-wave amplitude.

Sampling is the process of converting an analog signal into a digital sequence. It must be performed at ≥2x the source’s signal frequency to reproduce the source’s information content completely. ICD telemetry reproduces cardiac signals completely because it samples at 128 to 256 Hz per channel, but it may distort nonphysiological signals periodically (Figure II in the Data Supplement)\textsuperscript{14} and it may not completely reproduce myopotentials that have frequency content >100 Hz.

**Stored Versus Real-Time Electrograms**

Stored electrograms and their corresponding interval and episode data are the primary sources for diagnosing device-detected tachycardias. Real-time electrograms are useful in troubleshooting reproducible oversensing: lead or connector problems in the pocket may be identified by pocket manipulation, pectoral or diaphragmatic myopotentials can be provoked by pectoral muscle contraction and straining or deep breathing, respectively (Figure III in the Data Supplement). Differential electrograms recorded simultaneously between 1 common electrode and 2 different electrodes are useful when lead or connector-related oversensing is suspected (Figure 3).

**Role of Additional Diagnostics, Alerts, and Remote Monitoring**

Trend plots of P- and R-wave amplitude, impedance measurements and trends, and algorithms that identify oversensing facilitate electrogram interpretation as discussed below. Alerts for suspected oversensing may notify the patient using audible tones or pulse generator vibration, may be transmitted via internet-based remote-monitoring networks, or both. Remote monitoring has transformed follow-up of sensing problems, permitting rapid determination of cause of an alert and implementation of a response plan, especially for devices with wireless telemetry.\textsuperscript{16,17}

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**Figure 1.** Implantable cardioverter defibrillator (ICD) leads and electrograms (EGMs). Left, A single-chamber ICD system including left-pectoral active can and right ventricular (RV) dual-coil, dedicated bipolar lead. Right, Telemetered EGMs: leadless ECG recorded between superior vena cava coil and can, shock EGM recorded between RV coil and can, sensing EGM recorded between tip and ring electrodes, and annotated markers. Marker channel denote timing of R waves sensed from the sensing EGM by arrows and ICD’s classification of each ventricular event by letter symbols. The morphology of shock EGMs stored during detected tachycardias is useful for discriminating ventricular tachycardia from supraventricular tachycardia. Leadless ECG provides a signal with identifiable atrial EGM from a single-chamber ICD, providing a dual-coil lead is used. VS indicates ventricular sensed event in sinus zone.
Systematic Approach to Analysis of Sensing Issues

Our approach begins with five questions: (1) Is the sensing channel displayed? If not, event markers provide the only record of sensed events. (2) Does the sensing channel record dedicated bipolar or integrated bipolar electrograms? As discussed below, the likelihood of specific sensing errors depends on the length of the proximal electrode. The sensing electrogram is always integrated bipolar if the lead is an integrated bipolar lead. Currently, 1 manufacturer (Medtronic) permits programming integrated bipolar sensing with a dedicated bipolar lead. (3) Are the electrograms displayed after narrowband or wideband filtering? Narrowband filtering approximates the input to the sensing circuitry but distorts electrogram morphology significantly. (4) Are all true atrial and ventricular electrograms sensed as indicated by corresponding markers? If not, undersensing is present. (5) Do all sensing markers correspond to electrograms that represent true atrial or ventricular depolarizations? If not, oversensing is present.

Troubleshooting Ventricular Oversensing

Presentation, Classification, and Recognition

Clinical Presentation

In ICD patients, ventricular oversensing of rapid signals presents as oversensing alerts or inappropriate detection of VT/VF, often resulting in inappropriate shocks. In pacemaker-dependent patients it also presents as failure to deliver bradycardia pacing.

Classification

Oversensing can be classified by electrogram morphology, temporal pattern (cyclic versus noncyclic), source type (physiological versus nonphysiological), and source location (intracardiac versus extracardiac; Figure 4). Specific sources may generate oversensed signals with characteristic morphological features that differ from true cardiac electrograms in frequency content and amplitude.

It is useful to classify the temporal pattern of oversensed signals as varying consistently with the ventricular cycle (cyclic) or independent of the ventricular cycle (noncyclic). Cyclic oversensing indicates an intracardiac signal, usually physiological, R-wave double-counting or P/T-wave oversensing. These usually produce a characteristic pattern of 1 oversensed event and corresponding marker for each true ventricular cycle. Noncyclic oversensing is diagnosed when superposed, extraneous signals are dissociated from true ventricular electrograms, analogous to the relationship between ECG artifacts and the cardiac rhythm. The diagnosis is most certain.
when independent, true ventricular electrograms are identified. However, in patients without an intrinsic ventricular rhythm, oversensing inhibits bradycardia pacing, hence the absence of true ventricular electrograms or pacing markers complicates the diagnosis. In these patients, oversensing may be confirmed if the oversensed signal is not recorded on the shock channel, even if the analysis of the sensing channel alone does not permit definitive differentiation of VF from oversensing.

Figure 3. Differential recordings isolate source of nonphysiological signals. A, Surface ECG, sensing electrograms (EGM; right ventricular [RV] tip-ring), and shock EGM (can-RV coil) are displayed. T-wave synchronous, simultaneous, nonphysiological, high-frequency signals are recorded on both EGMs in beats 2 to 7; subsequent beats show T-wave morphology without nonphysiological signals. Occurrence of simultaneous, cyclic nonphysiological signals on both channels indicates that the signals on the shock channel originate in the RV coil because the implantable cardioverter defibrillator housing cannot generate signals synchronous with the cardiac cycle. B, Extended bipolar EGM between RV and left ventricular (LV) tip electrodes (RV tip-LV tip) replaces shock EGM. On sensing channel, nonphysiological signals are denoted by asterisks when oversensed and crosses when not sensed. The absence of nonphysiological spikes on RV tip-LV tip EGM indicates that these signals enter the sensing circuit from the ring cable, not the central helix to the tip. These signals were recorded from an inside-out insulation breach of a Durata lead that resulted in contact between the cable to the ring electrode and the RV shock coil. It is likely that contact between the cable to the ring electrode and the cable to the RV shock coil could produce an indistinguishable EGM. SIC (sensing integrity count) denotes 130 ms interval on marker channel that increments the Sensing Integrity Count. Reprinted from Swerdlow et al15 with permission of the publisher. Copyright © 2013, Elsevier. AR indicates atrial refractory event; AS, atrial sensed event; BV, biventricular pacing; and VS, ventricular sensed event in sinus zone.

Figure 4. Ventricular oversensing in implantable cardioverter defibrillators (ICDs): classification and common causes. *Oversensing atrial electrograms in atrial fibrillation (eg, ventricular lead dislodged to atrium) also causes noncyclic oversensing. EMI indicates electromagnetic interference.
Oversensing Physiological Intracardiac Signals

Consistent oversensing usually produces characteristic electrogram patterns, but atypical patterns occur, including those caused by intermittent oversensing.

P-Wave Oversensing: Clinical Aspects and Troubleshooting

P waves may be oversensed if the proximal ventricular sensing electrode is close to the tricuspid valve. During a stable, 1:1 rhythm, the device-detected R-R pattern consists of alternating sensed P-R and R-P intervals. However, P-R and R-P intervals may be approximately equal if first degree atrioventricular (AV) block occurs during sinus tachycardia. Recording an atrial electrogram facilitates recognition of P-wave oversensing. Ventricular oversensing of atrial electrograms in AF may result in multiple oversensed physiological signals for each true cardiac cycle, producing an interval plot with short, irregular intervals, characteristic of nonphysiological oversensing.

P-wave oversensing is rare in adults because the ventricular sensing bipole is usually far from the atrium. Thus, early after implant, P-wave oversensing usually indicates RV lead dislodgement to a position closer the atriun. However, P-wave oversensing may occur in children with small right ventricles and in adults with integrated bipolar sensing. It must be distinguished from atypical, end-diastolic cyclic oversensing in fractures of the cable to the ring electrode (see below).

P-wave oversensing may result in inappropriate detection of VT if the atrial rhythm is a tachycardia and in inappropriate detection of VF if the atrial rhythm is AF (Figure 5). The first approach to clinically significant P-wave oversensing is to reduce the programmed ventricular sensitivity. If this is unsuccessful or sensing of VF is not reliable at the reduced sensitivity, the ventricular lead should be revised. As a temporary measure, P-wave oversensing in sinus rhythm may be mitigated by forced atrial pacing, by introducing or increasing ventricular blanking period. In CRT-Ds, loss of RV capture may present as R-wave double counting (Figure 7). The ICD counts both the paced ventricular event and the waveform conducted from left ventricular capture to the RV sensing bipole, if the conduction delay exceeds the ventricular blanking period.

R-Wave Double Counting: Clinical Aspects and Troubleshooting

R-wave double counting occurs if the duration of the sensed electrogram exceeds the short ventricular blanking period in ICDs. Consistent double counting results in an alternation of ventricular cycle lengths: The expected sensed event early in the R wave is followed by a second, event as soon as the ventricular blanking period ends, which always corresponds to an interval in the VF zone. The duration of the device-detected interval that begins with the second event approximates the difference between the spontaneous ventricular cycle length and ICD’s blanking period. This produces a characteristic railroad track pattern on a plot of stored of ventricular intervals. Of course, any cause of alternating cycle lengths also produces this pattern (Figure 6).

R-wave double counting often results from local ventricular conduction delay. In conducted rhythm, it is most common when ICDs with short ventricular blanking periods ≤120 ms (Sorin, Biotronik, Medtronic) are connected to integrated bipolar leads. If the blanking period is programmable, it may be increased when using these generators with integrated bipolar sensing. R-wave double counting may be precipitated by reversible conduction block caused by hyperkalemia or sodium channel blocking antiarrhythmic drugs. Conduction delays during premature ventricular complexes or VT/VF may facilitate R-wave double counting (Figure 7). Most such double counting does not require intervention because it is infrequent (premature ventricular complexes), occurs only intermittently during VT, or occurs during VF. Rarely, slow monomorphic VT may be treated with shocks or self-terminating VT may receive unnecessary therapy. The primary troubleshooting intervention is to increase the ventricular blanking period. In CRT-Ds, loss of RV capture may present as R-wave double counting (Figure 7). The ICD counts both the paced ventricular event and the waveform conducted from left ventricular capture to the RV sensing bipolar, if the conduction delay exceeds the ventricular blanking period.

T-Wave Oversensing: Clinical Aspects

T-wave oversensing presents as alternating morphologies of device-detected sensing electrograms: Higher frequency R waves alternate with the lower frequency T waves. Device-detected R-R intervals may not alternate if the R-T and T-R intervals are approximately equal. This occurs either if the QT interval is short or the sinus rate is fast. When present, R-R alternation is often subtle. Thus, the hallmark of T-wave oversensing is alternation of electrogram signal frequency content, not device-measured cycle length (Figure 6; Figure V in the Data Supplement), which is easier to appreciate on wideband electrograms than narrowband electrograms. A simultaneous shock electrogram confirms that alternate low-frequency electrograms represent T waves. Bigeminal premature ventricular complexes during sinus tachycardia may produce a similar pattern on the filtered sensing electrogram, but each R wave has a corresponding T wave on the shock electrogram. Alternation of electrogram amplitude without alternation in morphology is rare and suggests true tachycardia.

T-wave oversensing was a major problem for early ICDs: oversensing that could not be treated by reprogramming accounted for 13% of lead revisions in a multicenter study conducted from 1993 to 2004. Its impact has been reduced by better understanding of conditions that promote it, changes in sensing processes, and programmable algorithms, but it remains problematic for some manufacturers and has emerged as the leading cause of oversensing for the subcutaneous ICD. The cause is rooted in the requirement that ICDs sense VF reliably. VF is characterized by R-R intervals shorter than the typical QT interval in sinus rhythm as well electrograms with variable and sometimes low amplitudes and slew rates. To reduce T-wave oversensing associated with a fixed-low sensing threshold while retaining sensitivity for VF, ICDs adjust sensitivity dynamically to become progressively more sensitive after each sensed or paced event (Figure IV in the Data Supplement). The details of this automatic control of
sensitivity differ among manufacturers, and these differences affect the trade-off between preventing T-wave oversensing and minimizing VF undersensing.20

Oversensing of spontaneous T waves may be dichotomized by the amplitude of the corresponding R waves (Figure V in the Data Supplement) because the therapeutic approaches often differ20. With large R waves, T-wave oversensing usually can be resolved by reducing programmed sensitivity; with small R waves, resolution usually requires an alternative approach (see below). T-wave oversensing with large R waves is caused by an absolute increase in T-wave amplitude. Clinical correlates include pediatric patients,22,23 hypertrophic cardiomyopathy,24 long QT syndrome,25,26 short QT syndrome,27,28 hyperkalemia,29 and, rarely, other drug and metabolic abnormalities.30,31 In contrast, in the setting of small R waves, oversensed T waves usually have normal amplitude, such as in Brugada Syndrome32,33 or advanced myocardial disease. The root cause relates to a fundamental limitation of automatically adjusted sensitivity, which links the initial value of sensitivity to the amplitude of the preceding R wave (Figure IV in the Data Supplement). Exercise-induced T-wave oversensing may be caused by increase in absolute T-wave amplitude, decrease in R-wave amplitude, or both.23,34

When we proposed dichotomizing T-wave oversensing by R-wave amplitude, we did not appreciate that large variations in R-wave amplitude are common in dedicated bipolar leads.
In a systematic study of patients with R waves <3 mV during T-wave oversensing, 64% had R waves ≥3 mV at implant. All had unpredictable, abrupt, and often transient decreases in amplitude of the filtered and rectified R wave, rather than a predictable, gradual, and progressive decline. The first inappropriate detection of VF/VT occurred at disparate times after implant. Most cases have no identifiable clinical correlate, although 1 case report attributed temporal variation to an inflammatory process (sarcoidosis). In addition, temporal variations in T-wave amplitude might reflect changes in ventricular repolarization, posture, or metabolic effects; however, their effect on T-wave oversensing has not been reported.
Troubleshooting T-Wave Oversensing: Prevention and Remediation

Programming Sensing Parameters

Minimum Sensing Threshold

Often, the filtered and rectified amplitude of oversensed T waves barely exceeds the sensing threshold. For ICDs with highly sensitive nominal minimum sensitivity (e.g., ≤0.4 mV), the simplest approach is reprogramming to a less sensitive setting. For example, it is reasonable to program 0.6 mV if there are large R waves during T-wave oversensing and sensing of VF was tested at implant and reliable using a threshold of 1.0 mV.

Dynamic Sensitivity

The specifics of automatic adjustment of sensitivity differ in terms of adaptive starting voltage (percent of R wave or fixed), temporal onset relative to the end of the blanking period, and shape of threshold decay (step function versus continuous). There are differences among manufacturers, between different models from a single manufacturer, and often differences in response of a single device as a function of the amplitude of the preceding R wave. These specifics probably influence the likelihood of T-wave oversensing and the inverse likelihood of VF undersensing. For example, setting the initial sensitivity to a high value (e.g., 75% of the R wave) reduces T-wave oversensing either nominally5,19 or after T-wave oversensing has occurred.20,37 St. Jude Medical provides a programmable delay in the start time for dynamic adjustment of sensitivity.

Filtering and Rectification

Three manufacturers minimize T-wave oversensing by setting the high-pass filter in the range of 20 Hz (versus 10–15 Hz) either nominally (St. Jude Medical and Boston Scientific) or as a programmable option (Biotronik).37 In addition, Biotronik offers programmable rectification options that may reduce T-wave oversensing.38

Parameter Combinations and Risk of Undersensing in VF

There is no sweet spot of perfect sensing parameters that prevents T-wave oversensing, yet ensures reliable sensing in VF. One approach to minimizing T-wave oversensing is to combine features such as a higher high-pass filter and high initial starting point for dynamic sensitivity. Its effectiveness is supported by reports that T-wave oversensing can be corrected by inserting a new generator that combines these features.39,40 but this is usually an unnecessarily expensive solution.

Figure 7. R-wave double counting. A. Continuous recording of sensing electrogram (EGM) from cardiac resynchronization implantable cardioverter defibrillator (ICD [CRT-D]). There is failure of right ventricular (RV) capture after the first and third pacing pulses (BV) in the upper panel and all pulses in the lower channel. When RV capture is lost, the left ventricular pacing pulse captures and conducts slowly to the RV sensing bipolar. The propagated impulse reaches the sensing bipolar 200 ms later and activates local myocardium, which was not activated by the subthreshold pacing pulse. This 200 ms interval is classified in the ventricular fibrillation (VF) zone (FS). B. Nonsustained ventricular tachycardia (VT). During VT, local conduction delay between RV tip and coil of an integrated bipolar lead results in R-wave double counting. Usually this does not cause a clinical problem. However, because the ICD counts twice the true number of fast ventricular intervals, nonsustained VT that lasts for only half the programmed number of intervals may be misclassified as VF. Ab indicates atrial blanking period; AP, atrial pacing; AR, atrial refractory period; and FS, interval in ventricular fibrillation zone.
these combinations usually are safe, rare cases of serious undersensing in VF have been reported.\textsuperscript{38,41,42} There is no consensus as to if or when sensing during induced VF should be tested if these features are programmed, but it is prudent to do if the R wave is small.

### Algorithmic Rejection of T Waves

Medtronic ICDs include an algorithm that identifies oversensed T waves by their lower frequency content and alternation with true R waves (Figure XII in the Data Supplement; Figure 8).\textsuperscript{35} In bench testing of stored electrograms from 22 patients, the algorithm withheld therapy in 80/83 T-wave oversensing episodes (96.6% adjusted efficacy) and did not prevent or delay detection of VF (166 episodes in 92 patients).\textsuperscript{35} Clinically, it did not prolong detection of induced VF in any of 196 episodes.\textsuperscript{43} However, it has failed to prevent some inappropriate therapies in pediatric patients during sinus tachycardia because it does not analyze R-R intervals within 20 ms of the ventricular blanking period. Also, because it is only applied when either the RT or the TR interval is in the programmed VT or VF zone, it does not correct T-wave oversensing in bradycardia pacing or when both intervals are in the sinus zone.

### Changing From Dedicated Bipolar to Integrated Bipolar Sensing

When a dedicated bipolar lead is connected, Medtronic ICDs permit sensing from either the dedicated bipolar or the integrated bipolar electrogram. Anecdotal reports indicate that integrated bipolar sensing may prevent T-wave oversensing, especially when dedicated bipolar R waves are small or more variable compared with the integrated bipolar R waves (Figure 8).

### Algorithms Designed for Other Purposes

The first subcutaneous ICD uses apparent alternation of ventricular electrogram morphologies to identify physiological oversensing, especially T-wave oversensing. In transvenous ICDs, SVT–VT morphology discrimination algorithms classify device-detected tachycardias as SVT if alternate electrograms match the sinus rhythm template. These algorithms do not reject T-wave oversensing, but they withhold inappropriate therapy providing that the SVT limit applies to the short cycle lengths associated with T-wave oversensing, and T-wave oversensing does not occur simultaneously with non-sustained VT.\textsuperscript{20} In addition, algorithms that withhold shocks

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<td>Differentiation of sense EGM enlarges R-wave to T-wave amplitude ratio</td>
<td>Integrated bipolar electrograms often have a larger R-T wave ratio</td>
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**Figure 8.** Features to minimize T-wave oversensing. Each column depicts a different strategy minimize T-wave oversensing, with the concept (top), tracing with T-wave oversensing before applying the strategy (middle), and tracing after applying the strategy (bottom). In the left column, the before tracing depicts a dedicated bipolar electrogram (EGM) with T-wave oversensing, and its corresponding filtered and rectified EGM. The after tracing shows the EGM’s first derivative with respect to time has been taken. These processes enlarges the R/T ratio, enabling algorithmic R-T pattern recognition. This algorithm is applied during initial detection and redetection, but not during pacing. The middle column depicts the effect of altering the sensing vector from dedicated bipolar (before) to integrated bipolar (after). The larger bipolar amplifies the R/T ratio; see text for details. In the right column, increasing the high-pass filter reduces the amplitude of the T wave more than the amplitude of the R wave (Figure I in the Data Supplement). RV indicates right ventricular; VF, ventricular fibrillation; and VT, ventricular tachycardia.
for oversensing related to pace-sense lead failure may prevent T-wave oversensing (see below).

New Sensing Lead
If R-wave amplitude is low and prevention of T-wave oversensing requires reprogramming that compromises sensing of VF, a new pace/sense lead with or without defibrillation electrodes should be inserted unless the lead was implanted recently and can be repositioned.

Prevention Versus Remediation
Because unpredictable variations in R-wave amplitude are an important cause of T-wave oversensing, measuring R waves at routine follow-up cannot reliably identify patients at risk. Thus, features that minimize T-wave oversensing should be enabled proactively at implant and operate continuously, providing they do not cause undersensing in VF (eg, algorithmic rejection). In contrast, features that may increase undersensing in VF (eg, reduced sensitivity, increased blanking) usually are only implemented reactively, after T-wave oversensing has occurred.

Postpacing T-Wave Oversensing
T-wave oversensing is a lesser problem after paced than sensed beats for 2 reasons. First, although ICDs have short ventricular blanking periods in spontaneous rhythm, they have longer postpacing blanking periods, comparable with those in pacemakers, reducing the likelihood of T-wave oversensing. Second, postpacing T-wave oversensing resets the pacing timing cycle, which prevents inappropriate detection of VT/VF in pacemaker-dependent patients. In these patients, it is not a clinical problem unless it causes bradycardia pacing or antitachycardia pacing at the wrong rate. If AV conduction is intact (eg, CRT-D patients), consistent postpacing T-wave oversensing causes a repeating sequence of 3 intervals in which the first 2 are in the VT or VF zones: pacing stimulus to oversensed T, oversensed T to spontaneous R, and spontaneous R to pacing stimulus. Inappropriate therapy is unusual, but it may occur with a probabilistic counting scheme and either a short number of intervals to detection VT (eg, 8/12 with fast first and last intervals) or a few spontaneous premature beats. The usual solution is to increase the postpacing blanking period. When possible, changing the pacing vector may also solve the problem. In CRT-Ds, programming V-V pacing delay or left ventricular–only pacing may resolve T-wave oversensing that inhibits biventricular pacing.

Effect of Sensing Bipole (Integrated Versus Dedicated) on Physiological Oversensing
In adults, P-wave oversensing occurs mostly with integrated bipoles, when the proximal end of the RV coil is close to the tricuspid valve. R-wave double counting is also more common with integrated bipoles because they record activation from a greater volume of myocardium than dedicated bipoles, and the total activation time is thus more likely to exceed the ventricular blanking period. An early report indicated that T-wave oversensing was more common with integrated than dedicated bipole, but the authors primarily analyzed postpacing T-wave oversensing. Currently, oversensing of spontaneous T waves is more common with dedicated bipoles, possibly because of greater variability of R-wave amplitude. It is rare in patients with integrated bipole.

Oversensing Physiological Extracardiac Signals: Myopotentials
ICDs may oversense myopotentials of diaphragmatic, pectoral, or (rarely) intercostal origin. Skeletal myopotentials have dominant frequencies in the range of 75 Hz, but they have substantial frequency content as high as 100 to 200 Hz and as low as 20 Hz. ICD low-pass filters in the range of 40 to 80 Hz attenuate high-frequency components, but sufficient high-frequency signal passes these filters to give myopotential electrograms a distinctive appearance.

Diaphragmatic Myopotentials
These low-amplitude, high-frequency signals are more prominent on the sensing electrogram than the shock electrogram because the sensing bipole is closer to the source. Their amplitude varies with respiration, but not the cardiac cycle (Figure VI in the Data Supplement). Oversensing is most common with integrated bipolar sensing at the RV apex and rare with dedicated bipolar sensing or leads in the RV outflow tract. It occurs when sensitivity is maximal, after long diastolic intervals or ventricular paced events, and often ends with a sensed R wave, which reduces sensitivity abruptly. Thus, it commonly occurs in pacemaker-dependent patients, in whom inhibition of pacing maintains high ventricular sensitivity, resulting in persistent oversensing and inappropriate detection of VF. It may present as syncope because of inhibition of pacing followed by an inappropriate shock. With chronically implanted leads, oversensing may first occur after the dominant rhythm changes from ventricular sensed to ventricular paced, such as upgrade to CRT-D or AV junction ablation. Oversensing may be reproduced by monitoring real-time electrograms during deep breathing or straining in different positions, after programming VF detection off.

Oversensing may be corrected by reducing ventricular sensitivity if VF sensing is reliable. In pacemaker-dependent patients, pacing at a faster rate may prevent oversensing by not allowing sensitivity to reach its minimum value, but this is rarely a desirable long-term solution. To minimize the risk of oversensing proactively in pacemaker-dependent patients, it may be prudent to program to a sensitivity of 0.45 to 0.60 mV if this sensitivity is not nominal, especially if integrated bipolar sensing is used. The nonprogrammable Boston Scientific noise rejection algorithm operates continuously and may reduce oversensing. Occasionally, correction requires inserting a new sensing or defibrillation lead away from the diaphragm.

Pectoral Myopotentials
These high-frequency, variable amplitude signals are prominent on electrograms that include the ICD can, including shock electrograms and leadless ECG. They may be reproduced by pectoral muscle exercise. However, because ICDs do not use these signals as primary sensing channels, pectoral myopotentials do not cause oversensing if the lead is intact.
they may cause misclassification of exercise-induced sinus tachycardia as VT because algorithms that discriminate VT from SVT based on ventricular electrogram morphology use the RV coil-can vector as the default signal (see below). Pectoral myopotentials might also interfere with algorithms that evaluate lead integrity by comparing near-field and far-field signals.

The diagnosis may be confirmed by monitoring the real-time sensing electrogram during pectoral muscle exercise. Oversensing of pectoral myopotentials on dedicated bipolar electrograms typically indicates an in-pocket insulation breach55—(Figure 9). Such breaches may also cause oversensing on integrated bipolar electrograms. Rarely, however, pectoral myopotentials may be oversensed in pacemaker-dependent patients with intact integrated bipolar leads.56 In addition, reversal of high-voltage connections on DF-1 dual-coil, integrated bipolar leads may present as myopotential oversensing because of change of the sensing vector to a far-field signal that includes the SVC coil and can as electrodes.57,58

**Oversensing Nonphysiological Signals: Electromagnetic Interference**

**Recognition**

Radiated or conducted electromagnetic interference (EMI) has multiple potential effects on ICDs,59 including oversensing. As recorded by ICD electrograms, the frequency, amplitude, and temporal characteristics of EMI depends on the source signal. For example, alternating current from line sources (60 Hz in the United States, 50 Hz in most countries) shows a characteristic uniform, high-frequency pattern—(Figure II in the Data Supplement).

External EMI inputs signal on all ICD channels. Thus, it typically presents as rapid, noncyclic signals on multiple channels; and the diagnosis can often be confirmed by a history of exposure at the time of the stored episode. However, EMI may not be recorded on every channel because of differences in electrode surface area, interelectrode distance, antenna spatial orientation, amplifier sensitivity, and bandpass filters. External EMI usually has lower amplitude on channels recorded from small, closely spaced electrodes than on those recorded from widely spaced electrodes or those that include a large defibrillation electrode. Thus, EMI usually has lower amplitude on atrial or dedicated bipolar ventricular sensing channels than on integrated bipolar sensing channels, shock channels, or other electrograms that include the can (Figure 10). Despite constant amplitude of the EMI source, oversensing may vary because of automatic adjustment of sensitivity and postural variation in orientation of the sensing bipolar relative to the electric or magnetic field.

Distinguishing atypical EMI may be challenging. Some types may be difficult to distinguish from myopotentials or lead failure based on morphology and frequency content alone—(Figure 10). However, most myopotentials can be reproduced by physical maneuvers, diaphragmatic myopotentials are not recorded on shock channels, and pectoral myopotentials are not recorded on closely spaced sensing channels with intact leads. Internal sources of EMI may be recorded only on sensing electrodes in proximity to the source, such as ventricular assist devices (VADs, Figure 10), bipolar electrosurgery, and poorly grounded guide wires with an uncoated tip.60

**Medical Sources**

EMI is usually divided into medical and nonmedical sources. We refer the reader to a comprehensive review59 and consider only selected effects of medical sources because household sources rarely interfere with ICD sensing.

Monopolar electrosurgery injects 100 to 5000 kHz current from the cautery tip to a dispersive pad, resulting in oversensing when the current path intersects the ICD sensing bipolar. The relative amplitude of the interfering signal on the sensing and shock channels depends on which electrodes are in the current path. Electrosurgical signals are limited to the duration of the application. Recent guidelines61,62 address prevention of oversensing. For procedures above the umbilicus, these include either perioperative magnet application or programming the ICD to a surgery mode that provides bradycardia pacing while disabling VT/VF detection. The dispersive pad should be placed on a leg for procedures performed on the hips or lower extremities. Infrequently used bipolar electrosurgery transmits current between closely spaced pen electrodes and does not cause oversensing unless applied in proximity to the heart.

VADs are associated with multiple causes of oversensing. R-wave amplitude often decreases after VAD implant, possibly because of left ventricular core removal for cannula insertion and remodeling.63,64 Thus, the ICD operates at a more sensitive setting, increasing the risk of oversensing all extracardiac signals. Because the power line or motor is often in close proximity to the sensing bipolar near the RV apex, VAD EMI often has greater amplitude on the sensing channel65–67 than the shock channel. The amplitude of the source signal is related to the impeller’s rotational speed.67 EMI has also been reported when VADs have been plugged into wall outlets. Management of VAD-related continuous EMI includes decreasing ventricular sensitivity, decreasing rotational speed if flows remain adequate, or inserting a new bipolar sensing lead remote from the VAD, typically in the RV outflow tract.68 In addition, specific VAD models interfere with telemetry communication of some older ICDs.68 This may be corrected by shielding the programmer, telemetry wand, and its cable.69

MRI scanners generate fixed magnetic fields, and varying (gradient) magnetic fields, and radiofrequency fields. Scanning of ICD patients has been reviewed.64,70–72 With respect to sensing, detection of VT/VF is deactivated routinely in MR scanners, so oversensing is not a problem, except for the remote possibility of power-on reset. Both the gradient field and radiofrequency fields induce current in ICD-lead conductors, rarely causing thermal tissue injury. This could reduce R-wave amplitude, resulting in oversensing related to the more sensitive operation of dynamic sensitivity or undersensing.

**Noise Rejection Algorithms**

High-frequency noncyclic signals that replace the isoelectric baseline77 may be referred to as noise. ICDs (except Medtronic) include noise rejection algorithms to reduce oversensing of rapid signals.74 These algorithms distinguish noncardiac oversensing from VF using 1 or both of 2
Figure 9. Pectoral myopotentials. **A**, Normal right ventricular (RV) sensing (RV tip-ring) and shock (can-RV coil) electrograms (EGMs) during exercise-induced sinus tachycardia. Pectoral myopotentials are visible on the shock channel but not the sensing channel. **B**, High-amplitude pectoral myopotentials on RV sensing EGM caused by lead-can abrasion (photo of explanted Riata lead). **C**, Real-time recording during pectoral muscle exercise shows simultaneous pectoral myopotentials on sensing and shock EGMs of Riata lead, which was capped and abandoned at lead replacement. A lead-can abrasion was visible at surgery. **D**, **Left**, Stored EGM recorded during sinus tachycardia because of exercise on rowing machine in a patient with a dual-chamber implantable cardioverter defibrillator (ICD). Atrial EGM, shock EGM, and dual-chamber marker channels are shown. The shock EGM records constant amplitude myopotentials, a normal finding. Normal ventricular sensing is inferred from the correspondence of the shock EGMs with the ventricular markers in the ventricular tachycardia (VT) zone (TS). The atrial EGM shows intermittent, high-amplitude pectoral myopotentials, which should not be recorded from an intact closely spaced, intracardiac bipole. Atrial oversensing resulted in inappropriate detection of VT based on a rapid, irregular atrial rate (presumed AF) with a regular dissociated ventricular rhythm. This older ICD does not use ventricular EGM morphology to discriminate VT from supraventricular tachycardia. **Right**, Real-time recording during pectoral muscle exercise. High-frequency pectoral myopotentials on atrial channel confirm atrial lead insulation breach because of coil-can abrasion. Ab indicates atrial blanking period; and AR, atrial refractory period.
characteristics of VF. First, in VF at least a few intervals are not extremely short (>150–200 ms). Second, in VF, sensed electrograms occur after a physiological ventricular refractory period, thus noise is defined as uniformly rapid, sensed events that begin immediately after the ventricular blanking period. During the noise signal, sensitivity is reduced and therapy is withheld. We are not aware of published performance data.

Oversensing in the Diagnosis of ICD Lead Failure

Of all the causes of oversensing, early diagnosis may be most important in lead failure, which commonly presents with repetitive inappropriate shocks and less commonly causes loss of bradycardia pacing or failure to deliver therapeutic shocks. Pace-sense malfunctions, either conductor fractures or insulation breaches, account for the majority of clinically diagnosed lead failures and present most commonly with consequences of oversensing: patient alerts; inappropriate detection of VF, either asymptomatic nonsustained VF or sustained VF resulting in inappropriate shocks; and inhibition of pacing.

Figure 10. Electromagnetic interference (EMI). A, External interfering signals from electrosurgery. Left, High-amplitude EMI is readily identified on integrated bipolar ventricular sensing channel but cannot be identified on closely spaced atrial bipole, simulating lead-related oversensing. Right, Recorded 30 seconds later, prominent EMI on both channels. B, Internal interfering signals from left ventricular assist device (LVAD; HeartWare, HeartWare, Inc). In contrast to commonly occurring external EMI, intracardiac sources of EMI may have greater amplitude on adjacent electrograms (EGMs). The source of the 60-Hz alternating current signal from this LVAD is close to the dedicated bipolar sensing bipole in the right ventricular (RV) apex, resulting in a readily identified nonphysiological signal and intermittent oversensing. In contrast, the signal cannot be identified on the remote, closely spaced atrial bipole and is barely distinguishable on the widely spaced superior vena cava coil-can EGM (leadless ECG). Ab indicates atrial blanking period; and FD, fibrillation detected.

Oversensing Nonphysiological Signals From Lead Problems

Oversensed Signals in Pace-Sense Conductor Fractures and Connection Problems

The mechanism(s) by which conductor fractures cause nonphysiological signals are not understood completely. These signals often are referred to as make-break potentials because indistinguishable signals can be generated by connecting and disconnecting cables from the sensing circuit and because it is surmised that a similar process applies during intermittent contact between fractured sections of the helix or broken filaments of a cable. However, make-break potentials do not explain how pacing can induce similar, fracture-related signals.

The typical signal has 6 characteristics, of which the first 3 are almost always present (Figure 11): (1) signals are intermittent and have a high dominant frequency. (2) They display ≥1 types of variability including amplitude, morphology, or frequency. (3) In dedicated bipolar leads, they are not recorded on the shock channel. (4) Usually, at least some signals are not cyclic. (5) Often, some intervals are nonphysiological,
shorter than typical physiological intervals. (6) Signal amplitude may exceed the range of the sensing amplifier and thus appear truncated. Importantly, connection problems between DF-1 leads and headers may also cause this electrogram pattern (Figure 11, see below). Pacing, especially high-output pacing, may precipitate these signals (Figure VII in the Data Supplement) and exacerbate oversensing.

Less commonly, conductor fractures (and insulation breaches, see below) present with cyclic oversensing. This occurs with fractures of the conductor to the ring electrode, when cyclic lead flexing produces cyclic oversensed signals (Figure 12). It may simulate P-wave oversensing (Figure VII in the Data Supplement) or T-wave oversensing (Figure 12), but it can take multiple forms (Figure 12). In our experience, simultaneous occurrence of cyclic and noncyclic oversensing in the same event usually indicates a lead problem.

Oversensed Signals in Insulation Breaches
Unlike conductor fractures, insulation breaches themselves do not generate abnormal signals. Instead, oversensing occurs because signals enter the intact conductor at the insulation breach. Thus, electrogram patterns vary, reflecting the physiological or nonphysiological source signal.

Data are limited on characteristics of oversensed electrograms. Intermittent, high-amplitude pectoral myopotentials on the sensing channel suggest in-pocket, outside-in abrasion (Figure 9). Inside-out insulation breaches may cause mechanical interactions between the 2 shock components, the 2 pace-sense components (ring cable and central helix), or 1 pace-sense and 1 shock component. The latter 2 may present as oversensing. Inside-out breaches of Riata leads often have characteristic spikes on the sensing channel or both sensing and shock channels that may represent such mechanical interactions (Figures 12 and 13). Simultaneous nonphysiological signals on the shock and sensing electrograms have been reported in inside-out abrasion of the ring electrode cable against the RV shock coil (Figure 3) when cyclic, they may be confused with T-wave oversensing.

Figure 11. Nonphysiological signals of pace-sense conductor fracture and lead-header connection problem. A, Signal characteristics. See text for details. B, Left, Fidelis (Medtronic, Inc) lead fracture. Right, Connection problem because of incomplete insertion of IS-1 lead pin into header (arrow on insert spot radiograph). Signal characteristics do not distinguish fractures from connection problems. Each panel shows sensing channel (right ventricular [RV] tip-ring), shock channel (can-RV coil) and marker channel. Reprinted from Swerdlow et al with permission of the publisher. Copyright © 2011, Elsevier. AR indicates atrial refractory period; and TS, interval in VT zone.

Peri-Implant Air in the Header
Air trapped in the header by insertion of the lead pin escapes into surrounding electrolytic body fluid as bubbles if the set-screw seal plug is damaged or the seal is loose. Bubbles escape when they produce a threshold pressure on the seal plug, generating a nonphysiological signal. The interval between signals depends on the time required to develop this threshold pressure after a bubble escapes. In contrast to highly variable, high-frequency signals related to lead or connector problems, these signals characteristically are monotonously uniform and intermediate in frequency. The interval between signals may decrease
over time as pressure is relieved. It may even decrease within a single episode (Figure IX in the Data Supplement), but slower, nearly constant frequency signals may also occur.\textsuperscript{85} Postoperatively, it usually resolves within 24 hours.\textsuperscript{86} The diagnosis is based on the characteristic electrogram with a normal pacing impedance. In patients with AV conduction, it presents as inappropriate detection of VT/VF or an oversensing alert\textsuperscript{87} and can be resolved by disabling detection temporarily. In pacemaker-dependent patients, pacing should be programmed temporarily to a nonsensing mode (VOO or DOO).
Lead–Lead Interactions
Mechanical interaction between 2 endocardial leads or a lead and a retained fragment is a rare cause of oversensing that is usually suggested by the proximity of 2 leads on imaging. The few reports show substantial variation in signal morphology, mostly transient, intermediate-frequency signals. If this problem is identified during implant testing, the new lead can be moved. If it is detected during follow-up, the frequency and duration of the oversensing should guide management. Infrequent, single oversensed events usually can be tolerated, but frequent or rapid and prolonged events require surgical intervention (Figure IX in the Data Supplement).

Role of Electrograms in Suspected Failure of High-Voltage Components
Shock impedance is the primary diagnostic for high-voltage components of ICD leads. Electrograms play a lesser role than in pace-sense failures because spurious signals isolated to shock electrograms neither cause oversensing nor trigger alerts. However, abnormal signals on shock electrograms may confirm abnormal impedance, and occasionally they are the first indicator of lead failure. Inside-out insulation breaches resulting in contact between a pace-sense conductor and shock coil may trigger alerts because of oversensing on the pace-sense conductor. If the shock electrogram is recorded, it may show simultaneous nonphysiological signals (Figures 3 and 13) for this reason, the RV coil–SVC coil electrogram should be monitored on Riata leads at risk for this failure mode. Real-time electrograms may identify an insulation breach to a shock coil when stored electrograms do not (Figure 3). However, intact, widely spaced shock electrodes may record extracardiac signals, thus nonphysiological signals must be interpreted with caution.

For integrated bipolar leads, the RV coil is the proximal sensing electrode, so either insulation breaches or conductor fractures present as oversensing (Figure 14). As noted previously, reversing DF-1 high-voltage connections on integrated bipolar leads may present with pectoral myopotentials on both pace-sense and shock channels (Figure 14).

Figure 13. Electrogram (EGM) spikes and impedance trends in insulation breaches. Nonphysiological, simultaneous spikes on both sensing (right ventricular [RV] tip-ring) and shock (can-RV coil) EGMs in inside-out insulation breaches of St. Jude Medical leads (A and B, Riata; C, Durata; and D, Riata ST Optim). D, Displays pacing and shock impedance trends for the same lead, showing transient, small, simultaneous decreases in both trends. Adapted from Ellenbogen et al with permission of the publisher. Copyright © 2013, Elsevier. Authorization for this adaptation has been obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.
Lead Integrity Diagnostics That Incorporate Oversensing

Sensing Integrity Count

Short R-R intervals near the ventricular blanking period do not represent successive cardiac depolarizations except occasionally during VF. Medtronic ICDs count extremely short-sensed intervals within 20 ms of the blanking period (nominally ≤130 ms) as an indicator of nonphysiological oversensing (Sensing Integrity Count). A rapidly increasing Sensing Integrity Count (>10/d for 3 consecutive days) is a sensitive indicator of pace-sense lead fracture. However, in

Figure 14. Sensing issues in integrated bipolar leads (Endotak, Boston Scientific). A. Discrete nonphysiological signals on both sensing channel and shock channel. Signals are highly variable within each channel, but simultaneous signals on different channels are similar in frequency, amplitude, and duration. This suggests the common right ventricular (RV) coil as their source. The lead was capped and abandoned. B. Confirmed fracture of cable to RV coil shows simultaneous, high-frequency, nonphysiological signals on both narrowband filtered integrated bipolar channel and wideband filtered shock channels, more continuous than in A. Differences in appearance of these signals on the 2 channels may relate to filtering. C. Diagram of reversed DF-1 high-voltage connections. Electrically, the connection to the SVC coil is connected in parallel with the can. Reversing the high-voltage connectors results in a sensing vector that incorporates the can, permitting oversensing of pectoral myopotentials as occurs in unipolar pacemakers. D. Stored electrograms recorded from a shock that occurred during pectoral muscle exercise in a patient with reversed DF-1 high-voltage connections showing pectoral myopotentials on both sensing and shock channel, indistinguishable from electrogram of in-pocket insulation breach. AS indicates atrial sensed event; PVC, premature ventricular complex; RVP, right ventricular pacing; RVS, right ventricular sensed event; and VF, ventricular fibrillation.
isolation it has low specificity, ≈20%.7 Surprisingly, the most common causes of isolated, extremely short intervals resulting in a high Sensing Integrity Count are nonphysiological combinations of physiological signals such as R-wave double counting, P-wave oversensing, or T-wave oversensing followed by a premature ventricular beat.73

Other manufacturers provide histograms of R-R intervals. Nonphysiological events may increment the count in the highest rate bin. Although this finding is nonspecific, many counts in the fastest bin with no counts in adjacent bins suggest nonphysiological oversensing.

**Lead Integrity Alert**

This first-lead alert algorithm to incorporate oversensing was based on evidence that monitoring both rapid oversensing and impedance trends provided earlier warning of lead failure than a fixed impedance threshold.7 It includes 1 criterion related to abrupt changes in pace-sense impedance and 2 related to transient, rapid oversensing (Figure X in the Data Supplement).8 If any 2 criteria are fulfilled, it triggers an audible alert tone immediately and every 4 hours thereafter, initiates an immediate remote-monitoring notification in ICDs with wireless telemetry, Lead Integrity Alert (LIA) reprograms the number of intervals to detect VF to 30/40 if this setting is not already programmed. The false-positive rate is low and lower for dedicated bipolar than integrated bipolar leads, primarily because of more triggering by EMI in integrated bipolar leads (<1/400 versus 1/80 patient-years).7,8,73 Clinical data confirm that LIA improves early detection of Fidelis lead fractures compared with monitoring impedance alone.7,8,94 In a prospective study, LIA reduced inappropriate shocks compared with conventional impedance monitoring (LIA: 38% versus control: 70%; P<0.001).9 When LIA is used with wireless remote monitoring, <15% of patients with Fidelis fractures receive inappropriate shocks.80,81 LIA also identifies fractures in various lead models.10,90 Once LIA is triggered, it stores electrograms corresponding to short intervals that satisfy the Sensing Integrity Count. This feature has proved particularly useful for storing electrograms of transient oversensing caused by Riata and Durata insulation breaches.10

**Algorithms That Compare Sensing and Shock Electrograms**

Two algorithms (Medtronic Lead Noise Algorithm and St. Jude Medical SecureSense) operate on the principle that ventricular electrograms should be present simultaneously on the sensing and shock channels. Each algorithm identifies oversensing as more signals on the sensing channel that are not identified on the shock channel, and each withholds therapy if oversensing is diagnosed. Both algorithms may trigger false-positive alerts for conditions other than lead failure. Some false-positives are desirable, triggered by significantly sufficient oversensing events that, if unrecognized, might result in inappropriate shocks. For both algorithms, the most serious potential risk is that undersensing VF on the shock channel could result in false-negative diagnosis of oversensing and failure to deliver life-saving therapy. With integrated bipolar sensing, neither algorithm is triggered reliably by oversensing related to the RV coil conductor because this coil is common to both the sensing and shock channels. The algorithms operate and perform differently.

**Lead Noise Algorithm (Medtronic Inc)**

The Lead Noise Algorithm samples a 192-ms window on the shock channel centered on each sensed event. It classifies a sensed event as oversensed if both of 2 criteria are met: the shock channel is approximately isoelectric in the sampling window (<1 mV peak-to-peak amplitude, using a 2.5- to 100-Hz bandpass filter) and shock-channel sampling windows around other sensed events correspond to signals consistent with true ventricular electrograms (>6× the average of the 2 smallest electrograms in the window (Figure XI in the Data Supplement). Oversensing is identified in a 12-event sliding window if both ≥2 events are oversensed and ≥2 events are true ventricular electrogram. If oversensing occurs in ≥3 of 12 consecutive windows,81 the algorithm classifies the event as noise, overrules VT/VF detection, and triggers both an auditory and remote-monitoring alert. Note that this algorithm does not sense the shock channel. Rather it analyzes a shock-channel temporal window centered on a sense-channel event.

In preclinical testing, the Lead Noise Algorithm did not prevent or significantly delay therapy for VF, except for rare cases of agonal VF with low-amplitude shock-channel electrograms.81 In clinical testing, the maximum delay for detecting 196 episodes of induced VF was 2 seconds.41 One false-positive but clinically appropriate shock-withholding episode has been reported related to dislodgment of the ventricular lead to the atrium in a patient with AF.96

**SecureSense RV Lead Noise Discrimination Algorithm (St. Jude Medical)**

SecureSense (Figure XII in the Data Supplement) uses 2 independent sensing amplifiers, 1 on the sensing channel and 1 on a far-field discrimination channel (nominally RV coil). See Figure XIIA in the Data Supplement for diagram and corresponding legend for details. When the algorithm is activated, events on the sensing channel with intervals shorter than the slowest VT/VF detection interval are classified as oversensing if they do not correlate with fast intervals on the discrimination channel (within 50 ms of the slowest VT/VF detection interval). When rate and duration criteria for detection of VT/VF are met, the algorithm withholds therapy if too many events are classified as oversensing. SecureSense also functions as a diagnostic that triggers lead alerts when a sufficient number of intervals is classified as oversensing (non-sustained oversensing).

False-positive alerts can be triggered by (1) non-lead-related oversensing on the sensing channel (Figure 5), (2) undersensing on the discrimination channel,97 or (3) classification of a true ventricular interval in the VT zone on the sensing channel and slow on the discrimination channel. The third is a new class of sensing problems related to the algorithm’s novel comparison of events sensed independently on 2 ventricular channels, because of temporal offset in the time of sensing (point of sensing) between the 2 channels. The root cause relates to differences between the channels both in operation of autoadjusting sensitivity and in electrogram amplitude and frequency content. The algorithm’s highly sensitive trigger (2/3 sensing-channel
intervals in VT/VF zone) facilitates false-positive alerts during normal device operation, including nonintuitive alerts because of pacing blanking periods,79 cross-talk (Figure 5), and other noncorrelated short intervals on the sensing channel related to bradycardia pacing and intermittent intervals in the VT zone that represent true cardiac depolarization. Some false-positives may be prevented by changing the discrimination channel to the alternate RV tip-can; but in this configuration, SecureSense cannot reliably identify oversensing related to the conductor to the tip electrode, which is common to both channels.

## Impedance and Imaging in Evaluating Lead-Related Sensing Problems

### Impedance Measurements and Impedance Trends

ICDs perform periodic measurement of direct current electric resistance, commonly referred to as impedance. Impedance changes are insensitive metrics of early lead problems because the conductors contribute only a small fraction of nominal impedance measurements. Thus, although conductor fractures often cause high impedance, impedance changes usually occur after oversensing (Figure VII in the Data Supplement). For example, high impedance preceded oversensing in only 28% of confirmed Fidelis fractures;4 oversensing with normal impedance was the presentation of 70% of Medtronic non-Fidelis conductor fractures,79 62% of Boston Scientific Endotak failures,10 and 74% of St. Jude Medical Riata and Durata failures.10 Similarly, most silicone abrasions of multilumen leads present with pacing impedances within the nominal range.76 In a remote-monitoring study, 0 of 31 Riata or Durata failures presented impedance decreases ≥50% or <200 Ω.10 In a multicenter study, only 15% of clinically diagnosed Riata failures presented with out-of-range impedance, which was not specified as high or low.76 The Table summarizes other causes of rapid oversensing with normal impedance that may be considered in the differential diagnosis of lead failure.

Thus, out-of-range impedance does not provide reliable warning for inappropriate shocks, and the typical initial presentation of pace-sense lead failures is characteristic oversensing with normal impedance. However, oversensing accompanied by characteristic impedance abnormalities is highly specific for a lead or lead-connection problem. Thus, it is important to understand these characteristics, as well as the characteristics of impedance changes that do not represent lead problems.

### Impedance Increases

#### Conductor Fracture

An abrupt 50% to 75% relative change in impedance is more specific for an ICD system problem (conductor fracture or connection problem) than the absolute impedance value (Figure 15) and slightly more sensitive.79 As discussed below, impedance trends and imaging are important to distinguish fractures from connection problems, which cannot be differentiated from fractures by electrogram characteristics (Figure 11).79

#### Connection Problems

Connection problems because of incomplete pace-sense pin insertion into the header constitute ≤10% of suspected fractures for leads with older DF-1 connectors.79 However, the time course of abnormalities in impedance trends often distinguishes fractures from incomplete pin insertion.8,79 Furthermore, oversensing with normal impedance is common in fractures but extremely rare in connection problems.79 An algorithm incorporating impedance trends and oversensing correctly classified 100% of fractures and 87% of connection problems that were misdiagnosed as fractures clinically.79 Differential real-time recordings may be helpful in differentiating connection problems from fractures. In DF-1 connectors, incomplete lead pin insertion with a tight set screw results in nonphysiological signals limited to the proximal electrode.79 Thus, nonphysiological signals from the tip electrode indicate fracture if a loose set screw is excluded. Incomplete insertion of a DF-1 lead pin usually can be diagnosed radio graphically, but this may require spot films or intraoperative radiography (Figure 11). With newer DF-4 leads, it is virtually impossible to achieve an acceptable pacing threshold and in-range impedance with incomplete pin insertion. Thus, an abrupt impedance rise should probably be considered a fracture.

### Impedance Rises at the Electrode–Myocardial Interface

A gradual impedance increase to an out-of-range value usually occurs at the electrode–myocardial interface (Figure 15),79 in some cases caused by calcium deposition in the form of hydroxyapatite. Absence of oversensing is important in establishing the diagnosis because no intervention is required as long as sensing and pacing threshold remain acceptable.

### Impedance Decreases

Occasionally, silicone insulation breaches present with low pacing impedance, but to date, no study provides criteria that identify insulation breaches by impedance changes. Nevertheless, a visually apparent trend of decreasing impedance should motivate a systematic review of real-time sensing and shock electrograms for nonphysiological signals that indicate an insulation breach. Impedance decreases have also been reported in RV perforations. These usually occur acutely or subacutely but may be delayed.99,100

### Imaging

When lead failure is suspected as the cause of oversensing, the chest radiograph should be inspected for lead conductor discontinuity, kinks or sharp bends (especially at lateral axillary venous insertions) or twisting suggesting twiddler’s syndrome.55 However, the chest radiograph is unrevealing in most cases of lead failure.101 It is important primarily for excluding alternative causes of oversensing such as lead dislodgment, abandoned leads that may suggest lead–lead interaction, or incomplete insertion of DF-1 pins into the header (Figure 11).79 Cineloisangraphy in multiple views is useful for detecting lead–lead interactions. It is also the primary method for identifying Riata leads in which the cables protrude outside the outer insulation,102 especially in the right atrium near the tricuspid valve. However, there is controversy on a correlation between externalized cables and oversensing.103–106

### Troubleshooting Undersensing of VF

Undersensing of VF is classified as true if electrograms have amplitudes below the dynamic sensing threshold or
True Undersensing
Common causes include changes at the electrode–myocardial interface because of myocardial disease; lead, connector, or generator malfunction; and lead dislodgement. Low-amplitude electrograms in sinus rhythm usually result in lower amplitude electrograms in VF (Figure XIII in the Data Supplement). Although the correlation between baseline rhythm R wave and electrogram amplitude during VF is weak, small studies have shown that sensing of VF is adequate with a nominal sensitivity of 0.3 mV if the baseline peak–peak R wave is ≥5 to 7 mV, and 1 study of dedicated bipolar leads found that VF was sensed with device-measured, base-peak R waves as small as 3 mV. In practice, we consider induction testing to assess VF sensing if the R wave is under 3 mV and an adequate R wave cannot be achieved by reprogramming the sensing vector. Undersensing may result from combinations of programming (sensitivity, dynamic sensing parameters and filter settings), low-amplitude electrograms, metabolic effects (including hyperkalemia), antiarrhythmic drugs that cause conduction block (Figure XIV A in the Data Supplement), and rapidly changing electrogram amplitudes (Figure XIVB in the Data Supplement). Lead revision is needed if reliable sensing during VF cannot be achieved.

Functional Undersensing
Functional undersensing of VT/VF may occur because of device–device or intradevice interactions.

Oversensing of Stimuli From Other Implantable Electronic Devices
Functional undersensing because of interactions between ICDs and pacemakers are rare because separate pacemakers are not routinely used. Other devices inject current into the body (eg, devices that modulate cardiac contractility, transcutaneous electric nerve stimulators, deep brain stimulators,
Early or late after implant delay or prevent detection of VT/VF during high-rate atrial pacing in older ICDs, enough of the cardiac cycle may be blanked to minimize functional undersensing. In addition, algorithms that detect VT/VF during atrial pacing (Brady Tachy Response, Boston Scientific) extends the AV delay to increase the ventricular sensing window in response to patterns of atrial pacing followed by ventricular sensing during the AV delay.

### Sensing the Shock Electrogram for SVT–VT Discrimination

The large, widely spaced shock electrogram is not used for rate counting because integrated or dedicated bipole electrograms are less susceptible to R-wave double-counting and extracardiac signals. However, ICDs analyze shock electrograms for 2 purposes: as previously described, ICDs correlate the timing of shock and pace-sense electrograms to confirm pace-sense lead integrity. ICDs also analyze shock electrograms for SVT–VT discrimination.

The ventricular electrogram morphology discriminator classifies tachycardias as SVT if the morphology (shape) of the electrogram is similar to the morphology during conducted baseline rhythm. It is the most versatile single-chamber SVT–VT discriminator and the only one that does not rely on interelectrogram time intervals. Shock electrograms are preferred to sensing electrograms for differentiating VT from SVT because they integrate activation from a much greater volume of myocardium. A modeling study reported the fraction of ventricular myocardium recorded by dedicated bipolar electrograms as 3% to 7%, usually greater on shock than on dedicated bipolar leads.59–61 Clinically, an algorithm that used the sensing electrogram for morphology analysis misclassified >10% of VTs as SVTs (Figure XV in the Data Supplement). Algorithms that use the shock electrogram perform better, misclassifying <5% of VTs as SVT.62–115

To compare the shape of the analyzed tachycardia electrogram with that of the sinus rhythm template, morphology algorithms must first time align the 2 electrograms. This puts an additional requirement for precise electrogram reproducibility on sensing for morphology analysis beyond those for conventional sensing. For this reason, contemporary morphology algorithms sense electrogram peak as a more temporally reproducible fiducial point than the threshold crossing point, which occurs at a greater signal amplitude during tachycardia than baseline because of automatic adjustment of sensitivity. In addition, digital-sense amplifier quantization (jitter) in low-amplitude signals reduces the accuracy of timing measurements made at threshold.

In general, sensing electrograms have higher frequency content and thus sharper peaks than shock electrograms. For this reason, Boston Scientific and St. Jude Medical use the sensing electrogram for alignment and the shock electrogram for pattern recognition.

### Table. Rapid Oversensing With Normal Pacing Impedance: Differential Diagnosis of Lead Failure

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Sensing Electrogram Characteristics</th>
<th>Clues to Diagnosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor fracture</td>
<td>Typical nonphysiological signals*</td>
<td>Postpacing oversensing</td>
</tr>
<tr>
<td>Insulation breach: in pocket</td>
<td>Pectoral myopotentials on dedicated bipolar electrogram</td>
<td>Pectoral muscle exercise reproduces oversensing</td>
</tr>
<tr>
<td>Insulation breach: inside out</td>
<td>Spikes</td>
<td>Simultaneous spikes on multiple electrogram channels</td>
</tr>
<tr>
<td>Electromagnetic interference</td>
<td>Reflects characteristics of source</td>
<td>More common in integrated bipolar than dedicated bipolar leads. History may suggest source. In dedicated bipolar leads, amplitude usually greater on shock channel than sensing channel</td>
</tr>
<tr>
<td>Diaphragmatic myopotentials</td>
<td>Uniformly low-amplitude and relatively uniform morphology vs lead failure signals, which vary in morphology, amplitude, or both</td>
<td>Usually occur in paced rhythm or bradycardia with integrated bipolar leads at RV apex, may be reproduced by deep breath or valsalva</td>
</tr>
<tr>
<td>Ventricular fibrillation</td>
<td>Variable</td>
<td>Present on both shock and sensing channels</td>
</tr>
<tr>
<td>Lead–lead mechanical interactions</td>
<td>Spiky electrogram</td>
<td>Presence of other leads by history; cinefluoroscopy with real-time electrogram recordings confirms diagnosis</td>
</tr>
<tr>
<td>Perioperative period only</td>
<td>Uniform, medium-frequency signals</td>
<td>Postoperatively it is a diagnosis of exclusion</td>
</tr>
<tr>
<td>Air trapped in header</td>
<td></td>
<td>Radiography, pocket manipulation, repeat measurement of impedance</td>
</tr>
<tr>
<td>Connection problems</td>
<td>Indistinguishable from lead fracture</td>
<td></td>
</tr>
</tbody>
</table>

*1(1) Intermittent, high-dominant frequency; (2) not cyclic; (3) intervals in the ventricular fibrillation zone; (4) in dedicated bipolar leads, not on shock channel; (5) variability of amplitude, morphology, or frequency; and (6) may saturate sensing amplifier.79

gastric and bladder pacemakers). They may cause ICDs to misinterpret their pulses as QRS complexes and undersense VF. Such interactions are exceedingly rare and can be identified by correlation of delivered pulses with sensing markers.

### Intradevice Interactions Because of Cross-Chamber Blanking Periods

ICDs use cross-chamber blanking to prevent cross-talk, but compensate with dynamic sensing and short ventricular blanking periods to minimize functional undersensing. In older ICDs, enough of the cardiac cycle may be blanked to delay or prevent detection of VT/VF during high-rate atrial pacing or dual-chamber pacing. Prolonged delays in detection may occur if blanked events occur at an interval that is a multiple of the VT cycle length.110,111 Algorithms for rate smoothing and other features that increase atrial pacing may exacerbate this risk by introducing repetitive postpacing blanking periods (Figure XIV A in the Data Supplement). Programmer warnings may be issued when parameters that risk undersensing are selected.112 Functional undersensing can be mitigated by limiting the upper pacing rate to 125 beats per minute, using dynamic AV delay and avoiding aggressive rate smoothing. In addition, an algorithm that detects VT/VF during atrial pacing (Brady Tachy Response, Boston Scientific) extends the AV delay to increase the ventricular sensing window in response to patterns of atrial pacing followed by ventricular sensing during the AV delay.
for morphology analysis, whereas the Medtronic algorithm both aligns and analyzes the shock electrogram. This can be problematic when shock electrograms have multiple peaks with similar amplitude and frequency content.\textsuperscript{12,14}

Sensing for morphology analysis is subject to 2 additional constraints that do not apply to conventional sensing. For ICDs that digitize the electrogram signal using 256 voltage levels (ie, 8-bit quantization), adequate sampling for morphology requires that the electrogram cover a minimum of 25% to 50% of the amplifier’s range. However, accurate alignment requires that the amplifier range exceed the electrogram’s peak to ensure that the electrogram is not truncated (Figure XV A in the Data Supplement). Because electrogram amplitude (but not morphology) undergoes significant postural variation, the electrogram should fill 25% to 75% of the amplifier’s range. A lower percentage may be acceptable for some newer ICDs with 10-bit or greater quantization, which provide greater amplitude resolution.

Nominally, the analyzed electrogram is can-RV coil. If this signal has low amplitude, it may be distorted by pectoral myopotentials during exercise (Figure XVB in the Data Supplement). One manufacturer permits programming an alternative RV coil–SVC coil electrogram. This electrogram is not susceptible to pectoral myopotentials but may be distorted by atrial electrograms that occur simultaneously with the ventricular electrogram, for example, in 2:1 conduction of atrial flutter or atrial tachycardias with long AV intervals.

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**Effect of filtering on ICD EGMs.** A. Effect of high-pass filtering on dedicated-bipolar RV sensing EGM in sinus rhythm (left) and induced VF (right). From top to bottom, panels display EGMs with high pass filtering at 2.5 Hz (“unfiltered”), 10 Hz, 20 Hz. EGM amplitude decreases as the high-pass frequency increases. The relative decrease is greater during VF than sinus rhythm because EGM frequency content is higher in sinus rhythm. The sinus panels at left show that high-pass filtering attenuates low-frequency T waves more than high-frequency R waves. B. RV dedicated-bipolar sensing EGMs with dual-chamber markers during an episode of T-wave oversensing caused by low-amplitude R waves. The upper channel displays the wide-band signal, and the lower channel displays the narrow-band (“Sense Amp”) signal. High-pass filtering distorts the morphology of the T-wave, removing low-frequency components. When the narrow-band signal is viewed in isolation, it may be difficult to determine whether it represents T-wave oversensing or fixed-coupled ventricular bigeminy. T1 marker denotes intervals in slower VT zone (VT-1); X marker indicates absence of match between morphology of sinus rhythm template and “tachycardia” EGMs as assessed by comparing sensing EGMs.
Distorted appearance of a telemetered EMI signal due to sampling. To reproduce the information content of the source signal completely, sampling must be performed at twice the signal frequency or faster. This is known as the Nyquist–Shannon sampling theorem, and twice the signal frequency is referred to as the Nyquist rate. ICD telemetry samples at 128 - 256 Hz per channel, far above dominant cardiac frequencies. However, myopotentials have significant content above 100 Hz, and 128 Hz telemetry does not represent them completely. When sampling is just faster than the Nyquist rate, the output may be distorted periodically due to inadequate representation of signal peaks, even though it contains all the information content of the input signal. For 128 Hz telemetry, this occurs with 60 Hz electromagnetic interference (EMI). This stored EGM from inappropriate detection of 60 Hz EMI as VF shows right atrial (RA) EGM, shock (RV Coil-Can) EGM, and dual-chamber markers. Insert at bottom right enlarges 1-second segment of shock EGM. When the sampling frequency is only slightly above the Nyquist rate, the signal appears to have a "beat" frequency equal to the sampling rate minus two times the signal frequency. In this example, the 128 Hz telemetry sampling frequency is only 8 Hz above the Nyquist rate for a 60 Hz signal. The resulting sampled signal appears to "beat," or modulate the amplitude of the signal, at 8 Hz (125 ms intervals). In countries that use 50 Hz alternating current, the beat frequency is 28 Hz (128 Hz – 2x50 Hz, corresponding to 36 ms intervals), which is difficult to identify on the EGM.
Use of real-time EGMs to evaluate sensing issues. A. Cough during real-time telemetry. Surface electrocardiogram (ECG), shock EGM (Can-RV Coil), and marker channel are shown. During cough, high-frequency signals are recorded on the shock EGM while the ECG displays sinus rhythm, confirming that the high-frequency signals do not represent ventricular activations. The marker channel shows appropriate QRS sensing, indicating that the non-physiologic signals involve the shock coil but spare the conductors to the tip or ring used for sensing in this dedicated bipolar lead. B. Real time wireless remote telemetry displays EGMs and ventricular marker channel in a patient with Riata™ inside-out insulation breach involving the cable to ring electrode. Both spikey and lower frequency non-physiologic signals (arrows) are recorded on the sensing channel (RV Tip-Ring), but not the shock channel (Can-RV Coil) or Leadless ECG (Can-SVC). This EGM was recorded from a scheduled transmission one month before the Lead Integrity Alert was triggered. C. Oversensing of diaphragmatic myopotentials from an integrated-bipolar lead. The patient has high-grade atrioventricular block. From top to bottom: surface ECG, atrial EGM, integrated-bipolar sensing EGM, and markers. With deep inspiration, diaphragmatic myopotentials are sensed as ventricular tachycardia (VT) and ventricular fibrillation (VF) events (beginning at marker VT-1, 436). Pacing is inhibited by sensed intervals in the VT/VF zones. This patient had received a shock during deep breathing exercises. Reducing programmed sensitivity eliminated the problem. (Panels A. and C. with permission.)
Comparison of automatic adjustment of sensitivity after paced and sensed ventricular events. The figure shows the filtered and rectified sensed ventricular EGM, the corresponding sensing threshold, and ventricular event markers. Horizontal bars denote post-pacing blanking periods. The blanking periods after paced events are longer than those after sensed events (nominally 200 vs. 120 ms in Medtronic ICDs). In this example, the initial value of sensitivity is less after pacing than sensing (4.5 vs. 10 x the minimum programmed sensitivity of 0.3 mV). The goal of a lower initial post-pacing threshold is to prevent pacing into VF. It compensates in part for the longer post-pacing blanking period. V pace, ventricular pacing; V sense, ventricular sensing.
T-wave oversensing. Wide-band recordings of dedicated-bipolar RV EGMs during sinus tachycardia with dual-chamber markers. Each EGM shows the characteristic pattern of alternating high-frequency and low-frequency sensed events with two ventricular events for each atrial event. One mV calibration marker at left indicates R-wave amplitude. A. Normal (~10 mV base to peak) R wave with high-amplitude T wave causes intermittent T-wave oversensing. Absence of a consistent pattern of T-wave oversensing prevents the T-wave oversensing algorithm (Medtronic Inc.) from classifying the rhythm correctly. “VF Therapy 1 Defib” at lower right denotes inappropriate detection of VF. B. Low-amplitude (1.5 – 4.0 mV, base to peak) R wave with typical T wave results in consistent T-wave oversensing. The T-wave algorithm identifies the pattern and withholds VF therapy (TW marker).
Oversensing of diaphragmatic myopotentials with integrated-bipolar leads at the RV apex. Each panel shows oversensing (black bars) of uniform morphology, high-frequency, low amplitude signals in patients with baseline ventricular paced rhythms. In panels A and B, post- biventricular (BV) paced sensitivity is high (Supplement Figure 4). A. Potentials at onset of respirophasic diaphragmatic muscle activity initiate oversensing. The underlying rhythm is AF with complete heart block. B. The underlying rhythm is sinus bradycardia with normal AV conduction. Oversensing terminates when a conducted ventricular EGM resets sensitivity to the less sensitive, post-sensed value while myopotentials continue. In both panels A and B, the onset of oversensing inhibits pacing and perpetuates highly-sensitive, post-sensed sensitivity relative to the amplitude of the sensed myopotentials. C. Interaction of oversensing with failure of atrial capture and algorithm to maintain AV conduction (Managed Ventricular Pacing™ (MVP), Medtronic Inc.). The underlying rhythm is profound sinus bradycardia with cycle length ~ 2300 ms and first-degree AV block (intracardiac PR
Native P waves (arrows) have low amplitude. Large signals on atrial channel correspond to non-capturing atrial pacing pulses (AP on marker channel) at a paced rate of 80 bpm (750 ms). In MVP, the VA escape interval is 80 ms less than the programmed lower rate limit (750 ms), corresponding to a VA escape interval of 750 – 80 = 670 ms. Diaphragmatic myopotentials are oversensed during long diastoles as autoadjusting sensitivity reaches its minimum value. MVP interprets the first oversensed event after atrial pacing as AV conduction, inhibiting V pacing and keeping ventricular sensitivity high. This results in repetitive oversensing until a spontaneous P wave initiates a conducted R wave that resets the sensing threshold. Myopotential amplitude decreases after each R wave, corresponding to mechanical systole. A possible explanation is that ventricular filling (diastole) causing the RV lead to move to a position more favorable to sensing the far-field potentials.
**Atypical presentation of early conductor fracture.** **A.** Stored EGM shows cyclical presystolic oversensing identified by elevated Sensing Integrity Count™ (Medtronic, Inc.). **B.** Subsequent real time recordings with simultaneous surface ECG show that presystolic signals precede the P wave, excluding P-wave oversensing. Differential recordings in panels **A.** and **B.** isolate cyclical, non-physiologic, presystolic signals to ring-electrode cable of this Fidelis™ lead (Medtronic, Inc.). **C.** Ventricular pacing triggers non-physiologic signals characteristic of conductor fracture, despite absence of such spontaneous signals. Pacing had been performed weekly since cyclical oversensing was first identified on January 27 and did not trigger typical, noncyclical signals until almost two months later. **D.** Shortly thereafter, impedance trend begins to show abrupt and erratic increases. Occurrence of oversensing prior to impedance increase is typical of conductor fracture. With permission. ²
Air bubbles escaping from header. Stored EGM from shock delivered during clinical asystole, hours post-implant. If minor damage to the header seal plug prevents complete closure after the torque wrench is removed, body fluid may enter the header via the defect, forming a secondary sensing input pathway. Air bubbles escape through the damaged seal plug as they develop sufficient pressure to disrupt the seal transiently. This displaces fluid, resulting in characteristic repetitive, uniform, non-physiologic signals. In this tracing, the interval between signals increases progressively, probably indicating that it takes longer to develop the pressure required to open the seal plug as air is released. Modified with permission.
Lead-lead interaction. Mechanical interaction between RV defibrillation lead and coronary venous defibrillation lead. Real-time EGMs were recorded during cine fluoroscopy, which confirmed that transient, repetitive, non-physiologic signals corresponded to contact between leads. Note that while signals within each episode appear erratic, they are similar among episodes: Each begins with R-wave synchronous signals on a postextrasystolic QRS, possibly due to greater acceleration of leads due to post-extrasystolic potentiation of contractility; each has a similar intermediate frequency, and each lasts approximately 1.5 cardiac cycles, possibly related to damping of mechanical oscillation.
**Lead Integrity Alert™ (LIA, Medtronic Inc.).** See text for details. The relative, abrupt impedance-increase criterion is met if any impedance is ≥ 75% or < 50% of an updated baseline value. The two oversensing criteria comprise the Sensing Integrity Count™ (≥ 10 for 3 consecutive days) and evidence of transient, rapid, repetitive oversensing based “nonsustained tachycardia (NST) ≥ 5 device-detected intervals with mean cycle length < 220 ms. NID = number of intervals to detect VF; SIC = Sensing Integrity Count. With permission.2
Supplement Figure 11. Lead Noise Algorithm™ (LNA, Medtronic Inc.). In pace-sense conductor fracture, the shock EGM has long isoelectric segments, which are not present in VF. Each panel shows sensing EGM (RV Tip-Ring), shock EGM (Can-RV Coil), and marker channel. A. EGM illustrates algorithm operation during bench testing of a stored EGM from a conductor fracture that was detected as VF (FD marker) by an older ICD and shocked. The sensing EGM shows characteristic non-physiologic signals resulting in oversensing. The shock EGM shows sinus R waves with an isoelectric baseline. The boxes highlight the difference in shock EGM amplitude corresponding to oversensing (0.2 mV) vs. a true R wave (9.6 mV). LNA identifies oversensing by a consistent pattern that includes both low and high amplitude shock EGMs corresponding to ventricular sensed events. See text for details. B. Algorithm operation during bench testing of a stored EGM from spontaneous VF. Most sensed events correlate with high amplitude signals on shock EGM (arrows). C. Clinical example of LNA performance during oversensing caused by fracture in Riata™ lead (St. Jude Medical). “N” on marker channel indicates that episode is classified as oversensing (“noise”). D. Clinical example. A. LNA classifies episode as oversensing at “N.” “NT” marker 50 seconds later indicates that criteria for oversensing are no longer fulfilled and that the “noise” classification has terminated.
SecureSense™ RV Lead Noise Discrimination Algorithm (St. Jude Medical).

A. Simulation illustrates algorithm operation. SecureSense uses a counter to compare sensed events on the RV dedicated-bipolar, sensing channel (“Near-Field (Sensing)”) with events sensed independently on a Far-Field (“Discrimination”) channel (nominally RV coil-CAN). When 2 of 3 sensing-channel intervals in a moving window are shorter than the slowest VT/VF detection interval, the Discrimination-channel sense amplifier is enabled; the algorithm is activated; and each sensed event on the Discrimination channel is indicated by the VS² marker displayed directly on the channel’s EGM. An interval on the Discrimination channel is classified as fast if it is within 50 ms of the slowest VT/VF detection interval (30 ms in the original implementation). The algorithm’s counter increments by 1 for every VT/VF interval on the sensing channel and resets to 0 after 2 consecutive fast intervals on the Discrimination channel. When detection criteria for VT/VF are met, the algorithm withholds therapy if the count is ≥ 10. In this example, the programmed number of intervals for detection of VF is 12. Additionally, when the count reaches 10 (5 in the original implementation), SecureSense stores an
EGM as “Non-sustained Oversensing” (“Non-sustained Lead Noise” in the original implementation, (Figure 5), whether or not VT/VF has been detected. After a shock, SecureSense is disabled until the device-defined episode ends. B. Clinical example of Riata™ (St. Jude Medical) lead failure. Panel shows atrial EGM, filtered RV sensing EGM (“V Sense Amp”), shock EGM (Can-RV Coil, “Discrimination”) and marker channel that annotates events sensed on RV sensing channel (“F” denotes intervals in VF zone). Visually, oversensed, spikey non-physiologic signals on sensing channel correspond with lower-amplitude non-physiologic signals on Discrimination channel some of which are not sensed. The disparate appearances of non-physiologic signals on the two channels may be caused by differences in filtering. When the number of intervals to detect VF (12) is reached the algorithm classifies the episode as oversensing and withholds capacitor charging (RV Lead Noise, asterisk). VPP indicates loss of capture with output 0.25 V above threshold followed by higher-voltage, back up pulse.
Undersensing of VF due to low amplitude R wave in sinus rhythm. Atrial and dedicated-bipolar EGMs are shown with dual-chamber markers. Black bars denote periods of ventricular undersensing. A. At (1) calibration markers (1 mV) show that the R wave amplitude in sinus rhythm is 1.8 mV. B. At (2) T-wave shock induces VF. C. Just after (3) undersensing results in ventricular bradycardia pacing (asterisks) at cycle length of 1200 ms (50 bpm); post-pacing blanking period and signal distortion prolongs undersensing. (4) Detection of VF when rate and duration criteria are fulfilled (18/24 intervals < 320 ms, VF marker and "VF Rx1 text"). D. At (5) unsuccessful 10 J shock (lightening bolt) followed by post-shock undersensing. Panels E, F: At (6) and (7) persistent undersensing prevents redetection of VF (12/16 intervals < 320 ms). (8) External rescue shock.
Undersensing of VF/polymorphic VT despite adequate R wave in sinus rhythm. A. Atrial, integrated-bipolar sensing, and shock EGMs are shown with dual-chamber markers. Interval storage begins with the 11 ventricular intervals prior to the third event sensed in the VT or VF zone (VF 168ms, oval). The shock EGM shows unequivocal VF/polymorphic VT. In contrast, the amplitude of the integrated-bipolar EGMs vary faster than sensing is adjusted, in this ICD the sensing threshold begins at 75% of the amplitude of the previous R wave, so undersensing occurs when lower-amplitude signals follow high-amplitude signals (†). Additionally, functional undersensing occurs after those atrial paced events (AP) that are followed by ventricular paced (VP) events (boxes). Detection of VF at right is denoted by "Epsd" marker (asterisk). B. Amiodarone-induced conduction block into myocardium at lead tip. Real-time EGM during induced polymorphic VT displays surface ECG, dual-chamber markers, and dedicated-bipolar EGM. The ECG shows polymorphic VT was cycle length of approximately 280 ms. The EGM shows much longer intervals between sharp near-field EGMs interspersed with far-field EGMs of lower amplitude and frequency that are not sensed, indicating entrance block. One month after discontinuation of amiodarone, repeat testing showed typical, reliable sensing in VF. The sinus rhythm R-wave had and amplitude of 8 mV.
Shock-EGM sensing issues that affect SVT-VT discrimination by EGM morphology. A. Truncation error. In the top panel, the baseline morphology (red) and the tachycardia morphology (blue) have a morphology match score that exceed the 70% threshold to classify the tachycardia complex as supraventricular. In the bottom panel, the peak of the tachycardia EGM is truncated (arrow) because its amplitude exceeds the amplifier’s dynamic range. This lowers the match score for two reasons. First, the shape of the stored representation of the tachycardia EGM is altered. Second, the algorithm aligns the EGMs based on their peaks. Thus the algorithm compares morphology off misaligned EGMs. This results in a match score below the 70% threshold. B. Panel shows integrated-bipolar (Tip-Coil) EGM, shock (Coil-Can) EGM, and morphology match scores in a patient with sinus tachycardia induced by upper body exercise. Pectoral myopotentials distort the shock EGM, causing misclassification as “no match.” C. Misclassification due to minor variations in the initial part of sensing EGM in an older ICD that aligned EGMs based on the onset of the sensing EGM. Note that the first and
third EGMs do not match the template (“X” at top, match score 6% and 0%, respectively with threshold 60%), but the second complex matches (check mark, 75% score). The non-matching EGMs have a small deflection at their onset (arrows, magnified in boxes) that shift the onset time of the EGM, resulting in misalignment. D. Misclassification of VT as SVT by the same algorithm that analyzes morphology of the sensing EGM, which is less sensitive to morphology changes than the shock EGM. See text for details. E. Time frame for resolution of post-shock distortion of real-time shock EGM (black) vs. template (gray). With permission. This may cause misclassification of post-shock sinus tachycardia or shock induced AF as VT if a new device-defined episode begins before EGM morphology recovers.
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