Atrial Sensing and Blanking in Dual-Chamber Implantable Cardioverter-Defibrillators

Accurate atrial sensing during tachycardia is essential for reliable determination of atrial rate, which is a critical component of interval-based dual-chamber supraventricular tachycardia (SVT)–VT discrimination algorithms. Thus, atrial sensing in dual-chamber implantable cardioverter-defibrillators (ICDs) must be reliable at fast ventricular rates, a technically challenging requirement.

Determining the atrial rate during rapidly conducted atrial flutter (AF) requires accurate sensing of low-amplitude signals (Figure I in the Data Supplement). The required high atrial sensitivity increases the risk of atrial oversensing, especially of far-field R waves. Pacemakers rely on a long postventricular atrial blanking period (PVAB) to prevent oversensing of far-field R waves, but ICDs cannot: for a fixed PVAB, the blanked fraction of the cardiac cycle increases with the ventricular rate. For example, a 100-ms PVAB blanks 10% of the cycle at a bradycardia pacing cycle length of 1000 ms, but 33% during rapidly conducted AF with ventricular cycle length of 300 ms. PVABs longer than 80 ms produce clinically significant, functional atrial undersensing in rapidly conducted AF, and any PVAB may cause undersensing of alternate atrial electrograms in AF with 2:1 atrioventricular conduction. The inherent trade-off between atrial oversensing and undersensing is problematic. Both cause errors in dual-chamber SVT–VT discrimination algorithms. In contemporary ICDs, ventricular electrogram morphology algorithms mitigate this problem but do not eliminate it.

Atrial Oversensing of Far-Field R Waves

Determinants of Far-Field R Waves

General Considerations

In the absence of atrial lead dislodgement, the amplitude of far-field R wave depends on 4 variables. The first is the amplitude of the ventricular electrogram in the myocardium. Thus, there is a correlation between far-field R–wave oversensing and left ventricular hypertrophy. The second is interelectrode spacing. Closely spaced electrodes (1.1 mm) minimize far-field R waves in comparison with conventional 10-mm spacing, but they also reduce the amplitude of atrial electrograms during short-term follow-up and may not record adequate atrial electrograms in diseased atria. The third and fourth factors are the proximity of ventricular myocardium to the sensing bipole and the bipole’s spatial orientation relative to the ventricular depolarization wavefront. These are determined by the anatomic position of the atrial lead (Figure 1). To minimize far-field R waves by at implant, it is useful to know the positions commonly associated with problematic far-field R waves.

Anatomic Location of Atrial Leads

Three anatomic locations are particularly susceptible to far-field R–wave oversensing.

Right Atrial Appendage

The distal appendage overlies the anterior free wall of the right ventricular outflow tract and anterior tricuspid annulus. Because this ventricular myocardium is activated late during normally conducted rhythm, the far-field R wave often cannot be rejected without excessive prolongation of the PVAB.

Tricuspid Annulus

Leads placed along the tricuspid annulus either posteriorly near the coronary sinus ostium or anteriorly in the para-Hisian region lie close to the ventricular septum.

High Septal Right Atrium

Leads placed at the junction of the superior vena cava and septal right atrium (adjacent to the noncoronary cusp of the aortic valve) are in close proximity to the left ventricular outflow tract. In contrast to these locations, leads placed in the lateral right atrium or Bachman bundle region minimize far-field R–wave oversensing.

Evaluating Clinical Significance of Far-Field R Waves

In most patients, measurement of far-field R–wave amplitude in the supine position is adequate to evaluate far-field R–wave...
oversensing in other positions.\textsuperscript{13} Three features of the far-field signal should be considered, whether it is oversensed: relative amplitude, timing, and variability.

**Relative Amplitude in Relation to the Sensed Atrial Electrogram**
Clinically significant oversensing during tachycardia is rare when the ratio of the amplitude of atrial electrogram to that of the ventricular electrogram is $\geq 4:1$.\textsuperscript{14} Oversensing becomes problematic when the ratio is $<2:1$ and usually cannot be managed reliably with reprogramming when the ratio approaches 1:1.

**Timing in Relation to the Atrial Electrogram**
In 1:1 tachycardias, far-field R waves are more problematic when the interval between the atrial electrogram and far-field R wave is long because of atrioventricular or intraventricular conduction delays.\textsuperscript{15,16} Such delayed far-field R waves either exceed the automatically adjusting atrial sensitivity threshold (which decreases with time) or extend beyond the PVAB.

**Variability**
Intermittent oversensing of far-field R waves may occur because their absolute amplitudes vary or the automatically adjusted atrial sensing threshold varies because of changes in the amplitude of the atrial electrogram or the atrioventricular interval. Intermittent oversensing is problematic for 2 reasons. First, it may be missed at implant. Second, intermittent oversensing during 1:1 SVT cannot be rejected by algorithms that identify far-field R waves.\textsuperscript{16}

**Solutions to Far-Field R–Wave Oversensing**
In patients with atrial electrograms of adequate amplitude and an amplitude ratio of atrial to far-field R wave $>2:1$, the simplest approach is to reduce the minimum atrial sensitivity (increase the programmed value) to 0.45 to 0.6 mV. Further decreases in sensitivity risk clinically significant undersensing during AF. If reprogramming sensitivity does not reject far-field R waves, PVAB may be adjusted. Each manufacturer provides programmable options for atrial blanking intended to provide sufficient blanking to manage far-field R waves without compromising the detection of AF significantly (Figure 1). Far-field R waves may also be rejected by algorithms that identify 2:1 AF or specifically recognize far-field R waves based on the combination of a 2:1-atrioventricular pattern combined with additional A-A and A-V interval criteria\textsuperscript{16} (Figure II in the Data Supplement). Rarely, lead repositioning is required.

**Single-Lead Atrial Sensing ICD**
In patients who do not require atrial pacing, a single-lead ICD with floating atrial electrodes may permit dual-chamber SVT–VT discrimination and detection of AF without the
complexity and risks of an atrial lead. The sensing performance of an initial system was hampered by low-amplitude atrial electrograms.\textsuperscript{14} However, when the lead is coupled with an ICD that incorporates a preamplifier for the atrial sensing channel (Figure 2),\textsuperscript{17} sensing in sinus rhythm is generally reliable during 6-month follow-up.\textsuperscript{18–20} However, data on sensing during rapidly conducted AF are scarce, and the only comparative study reported more atrial sensing problems with this method than a conventional atrial electrode (36\% versus 11\%; $P=0.002$).

**Consequences of Atrial Oversensing or Undersensing for SVT–VT Discrimination**

Atrial sensing problems result in inaccurate device-detected A-A, A-V, and V-A intervals and thus interfere with accurate rhythm classification based on dual-chamber intervals.

Intermittent oversensing of far-field R waves may cause incorrect classification of regular 1:1 SVT as VT because of device-detected atrioventricular dissociation with a regular ventricular rate (Figure I in the Data Supplement).\textsuperscript{4,14} Consistent oversensing of far-field R waves is less of a problem. It may delay detection of VT\textsuperscript{14} if the true atrial rhythm is so slow that the only sensed atrial electrograms are far-field, resulting in classification of the rhythm as 1:1. It could also delay detection if there is consistent VA conduction so that the ICD measures 2:1 atrioventricular association.

Rarely, the relative timing of the sensed far-field R wave and sensed ventricular electrogram varies;\textsuperscript{21} so, the far-field signal may be sensed before or after the ventricular electrogram on different complexes. Such variations may cause misclassification of 1:1 SVT as VT by algorithms that identify 2:1 atrioventricular association or those that analyze the number and relative timing of atrial events between ventricular events.

True or functional atrial undersensing during SVT or AF may result in measuring the atrial rate as slower than the ventricular rate, causing misclassification of the rhythm as VT or ventricular fibrillation (VF; Figure I in the Data Supplement). Programming to prevent atrial oversensing of far-field R waves is the most important cause of atrial undersensing. This may take the form of either reduced atrial sensitivity, resulting in true undersensing of low-amplitude electrograms in AF despite adequate sensing in sinus rhythm (Figure I in the Data Supplement), or functional atrial undersensing because of PVAB, or both (Figure 1). Functional atrial blanking was problematic for some early dual-chamber algorithms\textsuperscript{3} and remains a modest problem.\textsuperscript{5,6} Although the ventricular electrogram morphology discriminator may override misclassification of SVT because of far-field R–wave oversensing, it does not override misclassification because of atrial undersensing because it is not applied if the ICD detects more ventricular than atrial electrograms.

**Figure 2.** Single chamber implantable cardioverter-defibrillator (ICD) lead with floating atrial electrode. The ICD generator has a preamplifier with a gain of $\approx 4$ to compensate for the intrinsically smaller electrograms (EGMs) because of variable tissue contact. Arrows on chest radiographic denote floating electrodes (arrows) for atrial sensing in posterior–anterior (A) and lateral views (B). C, EGM shows accurate sensing of atrial fibrillation. D, A brief period of atrial undersensing (horizontal double-headed arrow) does not lead to rhythm misclassification. A indicates atrial; FF, far-field; and RV, right ventricular.
Troubleshooting Sensing for Subcutaneous ICDs

Sensing and Detection in Subcutaneous Versus Transvenous ICDs

Sensing Subcutaneous Versus Endocardial Electrograms
In comparison with closely spaced endocardial sensing electrograms, widely spaced far-field subcutaneous electrograms have lower amplitude (0.3–4.0 mV), longer duration, lower frequency content, and greater postural variation. The dominant frequency of VF is similar in the surface ECG (≈4 Hz) and endocardial electrograms (≈5 Hz). However, the frequency content above 10 to 20 Hz is higher in endocardial electrograms.

Sensing for Pacing Versus Sensing for Rhythm Classification
Transvenous ICDs must sense the cardiac rhythm on a beat-to-beat basis because they provide bradycardia pacing and cardiac resynchronization therapy. Because subcutaneous ICDs (S-ICDs) do not provide bradycardia pacing, they are not required to classify each individual electrogram. Thus, the design constraints for sensing and rhythm detection in S-ICDs have similarities to those for automatic external defibrillators, which may identify VF by signal characteristics, such as frequency content and fraction of isoelectric baseline content over a several second epoch. Similarly, S-ICDs may integrate traditionally distinct features of sensing and detection rather than sense and classify each electrogram. Present publications on the first commercial S-ICD (S-ICD™; Boston Scientific) do not review S-ICD’s approach to this integration (Figure 3). We therefore provide details with the understanding that future S-ICDs may use different sensing and detection strategies.

S-ICD Sensing Bipoles, Signal Processing, and Sensing Algorithm
S-ICD uses 1 of 3 far-field sensing bipoles (vectors) chosen among 2 sensing electrodes and the S-ICD’s can (Figure 4). To minimize the undersensing of VF, S-ICD operates with a lower minimum sensing threshold (0.08 mV or 80 μV) than transvenous ICDs (0.3–0.5 mV) and a lower high pass filter (3 versus 14–20 Hz).

In contrast to transvenous ICDs, S-ICD does not rectify signals; so, the sinus rhythm template is sensitive to postural changes in electrogram polarity. In addition, S-ICD classifies signals as noise if they exceed the range of the sensing amplifier and does not detect VF unless the entire peak–peak baseline-rhythm signal is in the amplifier’s range. Thus, large sinus R waves prevent the detection of VF. Like transvenous ICDs, S-ICD uses the stored sinus-rhythm template to discriminate VT from SVT. In addition, it uses the template to prevent oversensing. The template is not updated automatically and thus does not adjust for temporal changes in the electrogram.

The sensing algorithm comprises 3 phases: (1) sensed event (detection) phase, (2) certification phase, and (3) decision phase. The sensed event phase filters the input signal and generates sensed events for further analysis. The certification phase certifies that the sensed events are cardiac rather than oversensed signals. The decision phase detects VT/VF and discriminates it from SVT.

Figure 3. Signal processing architecture for sensing and detection. A, Conventional implantable cardioverter-defibrillator (ICD) architecture. Events on the near-field (NF) sensing electrogram (EGM) are sensed when their amplitude exceeds the sensing threshold; a tachyrhythmia is detected when the rate and duration criteria are met. The far-field (FF) shock EGM is used only for analysis of ventricular EGM morphology to discriminate ventricular tachycardia (VT) from supraventricular tachycardia (SVT). B, Enhanced ICD architecture. Algorithms designed to identify T-wave oversensing or oversensing of signals generated by lead failure are applied after rate and duration criteria for VT/ventricular fibrillation (VF) are fulfilled. In addition, both conventional and enhanced Medtronic ICDs apply a dual-chamber algorithm that identifies consistent far-field R waves. C, S-ICD architecture. Only the far-field subcutaneous EGM is sensed. Sensed events are not used for calculation of ventricular rate until they are certified by algorithms designed to reject electromagnetic interference (EMI), myopotentials, T-wave oversensing, and R-wave double counting.
Sensed Event (Detection) Phase

Like transvenous ICDs, S-ICD uses a sensing blanking period to prevent R-wave double counting and autoadjusting sensitivity to reduce T-wave oversensing. Typically, the duration of the global subcutaneous sensing electrogram is greater than that of the local right ventricular bipolar sensing electrogram in transvenous ICDs. Thus, a blanking period long enough to prevent R-wave double counting in baseline rhythm may cause undersensing in VF. To achieve reliable sensing in both baseline rhythm and VF, the nonprogrammable blanking period is shorter in the shock (VF) zone than in the conditional shock (VT) zone (160 versus 200 ms). The longer blanking period in the conditional shock zone delays the start of the decay for autoadjusting sensitivity, similar to the programmable feature in St. Jude Medical ICDs. Thus, unlike transvenous ICDs, addition or removal of a VT detection zone alters the sensing profile on a beat-to-beat basis.

Sensed Event Certification Phase

The certification phase analyzes sensed events and classifies them as certified QRS complexes or as suspected oversensing events. First, events corresponding to signals with excessively high frequency and slew rate are classified as noncardiac (noise) and discarded. Their suspected sources include myopotentials, electromagnetic interference, and lead failure. The remaining sensed events are passed through 3 additional certification steps to recognize and correct for R-wave double counting and T-wave oversensing based on (1) electrogram amplitude and morphology, (2) short intervals, and (3) patterns of alternating intervals typical of physiological oversensing. Each oversensed event is corrected by summing the 2 intervals created by the event into 1 longer certified interval. S-ICD calculates the ventricular interval associated with a certified event as the average of the last 4 certified intervals rather than the interval between the last 2 sensed events. Thus, at the onset of VT/VF, certified sensed events are not classified in the shock or conditional shock zone until the 4-beat average enters the zone. This method reduces the sensitivity of the calculated interval to a few undersensed electrograms or a few rapid beats.

Rhythm Decision Phase

The rhythm is analyzed after a certified ventricular rate is calculated. The S-ICD shock zone detects VF using only (corrected) rate and duration. The conditional shock zone also uses SVT–VT discrimination based on static electrogram morphology (comparison with sinus template), QRS duration, and dynamic electrogram morphology. The last criterion classifies detected tachyarrhythmias as shockable if their beat-to-beat morphology varies sufficiently to indicate that the rhythm is polymorphic. Each criterion requires accurate sensing.

S-ICD Sensing Performance

Sensing and Detection in VT/VF

In the US pivotal study, 897 of 899 (99.8%) of induced VT/VF episodes were detected. In 1 patient, cyclic variations in the amplitude of VF electrograms caused true undersensing. In the other, S-ICD did not certify true VF electrograms. Instead, it classified them as noise and did not detect VF. Data for spontaneous VT/VF are limited. In the US pivotal study, all 119 episodes of VT or VF in 21 patients were detected (including 81 episodes in 2 patients with VT storm). Similarly, in the EFFORTLESS registry of patients outside the United States, all 91 episodes of VT or VF in 33 patients were detected (including 40 episodes in 4 patients with VT storm). Figure 5 illustrates typical sensing during spontaneous VF. Figure 6 illustrates postshock undersensing.

Oversensing

Oversensing accounts for a much higher fraction of inappropriate shocks in S-ICD than in transvenous ICDs (30/51 [59%] in the US pivotal study and 62/73 [85%] in the EFFORTLESS registry). Shocks because of oversensing...
were reported at an annualized rate of 9% in the US pivotal study and 6% in the EFFORTLESS registry. Physiological intracardiac signals accounted for ≈90% of identified episodes and electromagnetic interference for ≈10%. The most common cause was T-wave oversensing.

**Optimizing S-ICD Sensing and Troubleshooting Oversensing**

S-ICD does not display the amplitude of the sensed R wave and has no programmable sensing parameters. The workflow emphasizes the prevention of oversensing by screening, optimizing sensing vectors, and programming a conditional shock zone.

**Screening of S-ICD Candidates Using the ECG**

Before implantation, S-ICD candidates undergo an ECG screening process (Figure III in the Data Supplement) based on similarities between the cutaneous ECG and subcutaneous electrogram signals. The screening process rejects patients who have QRST complexes in which the QRS amplitude is too large, the QRS duration is too long, or the ratio of QRS amplitude to T-wave amplitude is insufficient. Screening is performed in both supine and standing positions because the unrectified R/T ratio is sensitive to posture. Presently, >90% of patients pass this screening. Additional screening during exercise testing may be considered to ensure that exercise-induced repolarization changes do not cause T-wave oversensing.

**Selection of Sensing Vectors and Therapy Zones**

The sensing vector is selected via an automatic process at implant, subject to manual override via the programmer. A proprietary vector-selection algorithm calculates a weighted combination of the QRS:T wave ratio and R-wave amplitude for each vector and selects the best combination of sense vector and gain, which is used for all sensing and arrhythmia analysis. The effect of posture on sensing is assessed before hospital discharge.

Programming a conditional shock zone reduces T-wave oversensing and R-wave double counting because it alters sensing on a beat-to-beat basis. Thus, 2-zone programming is preferred for zones slower than 220 beats per minute.

**Electrogram Analysis and Troubleshooting**

**Analysis of S-ICD Electrograms**

Analysis of S-ICD electrograms can be challenging for ≥2 reasons. First, S-ICD displays neither its classification of each certified electrogram nor the reasons for noise and intracardiac oversensing markers. Second, diagnostic certainty is improved by analysis of multiple ECG leads or electrograms, but S-ICD provides only a single far-field electrogram. In transvenous ICDs, we have seen that comparison of near-field sensing and far-field shock electrograms are critical when a single electrogram cannot be interpreted with certainty. In analysis of SVT versus VT, physician experts were less likely to interpret stored electrograms classified as VT/VF by dual-chamber ICDs as appropriate when the atrial electrogram was displayed than when it was withheld. Similar interpretive difficulty applies to a single subcutaneous electrogram, especially when signal amplitude is low (Figure IV in the Data Supplement).

**Troubleshooting Oversensing**

Perioperatively, incomplete insertion of the IS-1 lead pin affects the proximal sensing electrode, as it does in transvenous leads. In S-ICD, this causes oversensing on both the primary and alternate vectors but not on the secondary vector between can and distal electrode (Figure 4). In contrast, air trapped at...
the superior end of the lead incision affects only the distal sensing electrode, resulting in oversensing on the alternate and secondary vectors but sparing the primary vector between can and proximal electrode. The former usually requires reoperation, whereas the latter resolves spontaneously.

If T-wave oversensing occurs, metabolic causes of large-surface ECG T waves should be excluded, such as hyperkalemia and hyperglycemia. Rare postimplant lead or generator (Figure V in the Data Supplement) migration can also cause T-wave oversensing. Reprogramming to a different sensing vector with larger R waves or a larger R/T ratio during exercise testing may eliminate the problem (Figure VI in the Data Supplement). If changing the sensing vector does not prevent T-wave oversensing, an exercise-recorded sinus rhythm template may correct consistent T-wave oversensing. Invasive procedures were required to correct T-wave oversensing in 5 of 22 patients (23%) in the US pivotal study. In 1 case report, intraventricular conduction changes altered QRST complexes sufficiently that no vector provided reliable sensing; the S-ICD was replaced by a transvenous ICD.

**Disclosures**

Dr Swerdlow received research grants from and has licensed intellectual property to Medtronic, is a consultant and received honoraria from Medtronic and St. Jude Medical, and received honoraria from Boston Scientific. Dr Friedman has licensed intellectual property to Aegis Medical, NeoChord, Preventice, and Sorin; he received research support from St. Jude Medical and honoraria from...
Medtronic and LeadeX. Dr Asirvatham is a consultant to Abiomed, Attirecure, Biosense Webster, Biotronik, Boston Scientific, Medtronic, Spectranetics, St. Jude Medical, Sanofi-Aventis, Wolters Kluwer, and Elsevier. Dr Ellenbogen received research grants and fellowship support from Medtronic and Boston Scientific; he is a consultant and received honoraria and research grants from Medtronic, Boston Scientific, and St. Jude Medical.

References


30. Powell BD, Asirvatham SJ, Perschbacher DL, Jones PW, Cha YM, Cesario DA, Cao M, Gilliam FR 3rd, Saxon LA, Noise, artifact, and


**Key Word**: implantable cardioverter-defibrillator
Troubleshooting Implantable Cardioverter-Defibrillator Sensing Problems II
Charles D. Swerdlow, Samuel J. Asirvatham, Kenneth A. Ellenbogen and Paul A. Friedman

_Circ Arrhythm Electrophysiol._ 2015;8:212-220
doi: 10.1161/CIRCEP.114.002514

_Circulation: Arrhythmia and Electrophysiology_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2015 American Heart Association, Inc. All rights reserved.
Print ISSN: 1941-3149. Online ISSN: 1941-3084

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circep.ahajournals.org/content/8/1/212

Data Supplement (unedited) at:
http://circep.ahajournals.org/content/suppl/2015/09/28/CIRCEP.114.002514.DC1

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in _Circulation: Arrhythmia and Electrophysiology_ can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to _Circulation: Arrhythmia and Electrophysiology_ is online at:
http://circep.ahajournals.org//subscriptions/
Atrial undersensing. A. Atrial undersensing due to a small atrial electrogram during AF with rapid ventricular rate results in misclassification of AF as VT and inappropriate ATP. B. Functional undersensing of atrial EGMs in sinus tachycardia with prolonged AV conduction due post-ventricular atrial blanking (PVAB) of 90 ms. On marker channel, upward vertical marks denote atrial sensed events and downward marks denote ventricular sensed events. Just above numbers denoting ventricular intervals in ms, the upper short and thick horizontal bars denote PVAB (arrow), and the subsequent thinner and longer bars denote post-ventricular atrial refractory period (PVARP). Due to prolonged AV conduction, atrial EGMs time during the PVAB, resulting in functional undersensing (absence of upward vertical marks). VT with ventricular rate > atrial rate (denoted by “VT>”) is detected inappropriately (“Trigger”) despite a good ventricular EGM morphology match (80 – 100%) because the dual-chamber SVT-VT discrimination algorithm does not evaluate morphology when the ventricular rate exceeds the atrial rate. This results in inappropriate ATP (“STIM”), which dissociates atrial and ventricular EGMs, permitting sensing of atrial EGMs (upward vertical marks) during ATP.
Supplement Figure 2

Algorithm for identifying far-field R wave oversensing by pattern analysis. A. Atrial, RV sensing (RV Tip-Ring) and dual-chamber marker channel are show. ICDs with short (30 ms) post-ventricular atrial blanking period (PVAB) reject FFRWs by the consistent timing pattern of atrial and ventricular intervals (Medtronic). Atrial events are classified as FFRWs if each of 5 criteria are met: (1) there are exactly two atrial events for each V-V interval; (2) the timing of one P wave is consistent with a FFRW (R-P interval <160 ms); (3) there is a stable interval between the FFRW and the ventricular electrogram (VEGM); (4) there is a short-long pattern of P-P intervals (to distinguish FFRW oversensing from atrial flutter); and (5) the pattern occurs frequently (4 of 12 intervals). This episode of sinus tachycardia with consistent FFRW oversensing is classified correctly (ST). These markers apply only to the first two ventricular EGMs because the third EGM equals the VT detection interval of 360 ms, resetting the VT counter to zero. Rhythm-classification markers are displayed only after the duration criterion for VT has been fulfilled. The interval plot at left shows the typical “railroad track”
alternation of atrial intervals. The right panel shows the corresponding EGMs. From top to bottom are atrial, ventricular, and marker channels. A, atrial EFM; FFR, far-field R wave; AR, atrial refractory event; TS, ventricular event in VT zone. B. Intermittent oversensing of far-field R waves results in misclassification of sinus tachycardia as VT. This rhythm was classified as sinus tachycardia for the first 28 s after the ventricular cycle length crossed the Fast VT (TF) detection interval due to consistent oversensing of far-field R waves. After the fourth ventricular complex, far-field R waves time intermittently in the PVAB so that oversensing is intermittent. Paradoxically, correct blanking of far-field R waves interferes with consistent oversensing pattern, and results in classification of regular ventricular rhythm with variable AV ratio and relationship as Fast VT (FVT), resulting in inappropriate ATP (FVT Therapy 1 Burst). During transition to detection of VT, rhythm is classified transiently as atrial fibrillation (AF) due to variable number of atrial EGMs in each of last 12 ventricular intervals. In modern ICDs, SVT-VT discrimination algorithms that give priority to ventricular EGM morphology prevent this type of misclassification.
Electrocardiographic screening for the S-ICD. **A.** The patient screening tool is used to assess QRS:T-wave amplitude ratios from a printed surface ECG. **Left panel:** Using a standard 3-lead ECG, the limb leads are placed at the cutaneous locations corresponding to implanted S-ICD electrodes and generator. When printed, the resulting Lead I, II, and III signals represent the Alternate, Secondary and Primary sense vectors, respectively. **Right panels:** Clear plastic screening templates of varying sizes are placed over ECG tracings to determine whether the QRST profile fits within the shaded region, predicting that the subcutaneous EGM will be sensed correctly. The screening tool rejects complexes in which the QRS amplitude is too large, the QRS
duration is too long, or the ratio of QRS amplitude to T-wave amplitude is insufficient. The ECG baseline must be stable to ensure accurate measurements. The patient is a candidate for S-ICD if (1) all complexes in a 10-second segment of at least one sense vector pass the screening process in at least two postures and (2) significant QRS morphology changes (primarily polarity) do not occur across postures. Panels B-E show examples. 

B. For the template positioned at the second complex (arrow), the QRS peak reaches the horizontal dashed line but does not extend beyond the template boundary, indicating the template size is correct. The remainder of the QRS complex and the T wave fit within the template, so the complex passes screening. 

C. The template size is correct for the second complex (arrow), but the T-wave extends beyond the shaded regain, so the complex fails screening because of the risk of T-wave oversensing. 

D. The R-wave amplitude of the third complex exceeds the largest template (arrow) at the minimum gain of 5 mm/mV, so the complex fails screening because the R wave may exceed S-ICD’s amplifier range. 

E. Pseudo screening failure: Pseudo screening failure. The signal extending beyond the template on modified Lead I (arrow) is a P-wave in a with prolonged AV conduction, not a T wave. Asterisks in Leads II and III denote P waves.
**Ventricular oversensing of subcutaneous atrial EGMs (S-ICD).** Low-amplitude, stored subcutaneous EGM from shocked episode is difficult to interpret. Tracing is most consistent with the patient’s known atrial flutter with variable AV conduction. Oversensing likely occurred because atrial and ventricular EGMs have comparable amplitude and frequency content. Abbreviations as in Figure 5. (Courtesy of Pierre Bordachar, MD.)
**Supplement Figure 5**

T-wave oversensing and inappropriate shock due to S-ICD generator migration. The top panels show T-wave oversensing and shock (lightening bolt) using the primary sensing vector. Bottom Panels show left lateral chest X-rays immediately post-implant at left and after shock at right. Since the pulse generator is a sensing electrode for the primary and secondary sensing vectors, its migration may change the recorded EGM. In this case, reprogramming to an alternate vector eliminated T-wave oversensing in various postures and with exercise, without the need for reoperation. Repeat testing to ensure reliable defibrillation should be considered in cases of generator migration.
S-ICD T-wave oversensing during exercise. A. Stored episode shows T-wave oversensing (Secondary vector) during exercise with QRS amplitude reduction and axis change relative to baseline template, reducing QRS:T-wave ratio. Oversensing results in charge begin (C) but no shock because rate decreases below therapy zone.

B. Baseline, peak, and recovery ECGs during exercise testing. The Secondary-vector EGM reproduces the morphology change recorded in the stored episode. Programming the Primary sense vector prevented subsequent inappropriate shocks. Abbreviations as in Figure 5.