Automated Vulnerability Testing Identifies Patients with Inadequate Defibrillation Safety Margin

**Running title:** Birgersdotter-Green et al.; Automated Vulnerability Testing

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Abstract:

Background - Implantable cardioverter-defibrillator (ICD) system efficacy is tested at implant by induction of ventricular fibrillation (VF). Defibrillation safety margin can be assessed without VF induction using upper limit of vulnerability methods, but these methods have required manual determination of T wave timing.

Methods and Results - To test the feasibility of an inductionless system of implant testing, a multicenter prospective study was conducted of an automated vulnerability safety margin (AVSM) system which measured T-wave timing using an intracardiac electrogram during a ventricular pacing train. The system delivered up to 4 T-wave shocks of 18J. Lack of VF induction by all 4 shocks was considered evidence of defibrillation adequacy. Patients subsequently underwent conventional defibrillation testing to meet a standard implant criterion. The 95% lower confidence interval for defibrillation success at 25J for non-induced patients was found using Bayesian statistics. Sixty patients were enrolled at 6 centers. Vulnerability testing and defibrillation success results were obtained from 54 patients. Vulnerability testing induced VF in 10 (19%) patients, of whom 2 required system revision. All patients not induced by vulnerability testing were successfully defibrillated twice at 25J or less. The Bayesian credible interval was 97-100% for population success rate of defibrillation at 25J for AVSM non-induced patients.

Conclusions - An automated system identified all patients who failed conventional safety margin testing, while inducing only 19% of patients. While limited by sample size, this study suggests the feasibility of automated implant testing that substantially reduces the need for VF induction in patients receiving ICDs.

Key words: defibrillation; implantable cardioverter-defibrillator; upper limit of vulnerability
Introduction

Defibrillation testing is performed at ICD implantation to ensure adequate defibrillation efficacy and sensing of ventricular fibrillation (VF).\textsuperscript{1,2} This is commonly done by defibrillation safety margin (DSM) testing, which determines if 2 successive induced episodes of VF can be defibrillated with shocks at least 10J below the maximum device output. Major complications or death associated with defibrillation testing are rare but have been reported.\textsuperscript{3,4}

A potential alternative to intentionally inducing VF and defibrillating it is to assess defibrillation efficacy by measuring the Upper Limit of Vulnerability (ULV) at ICD implantation.\textsuperscript{5-15} The ULV is the energy threshold at which shocks can no longer induce VF. The ULV has been shown to be a reproducible estimator of the shock strength associated with 90\% probability of successful defibrillation\textsuperscript{15}, and the energy of a non-inducing shock can therefore be a reliable test of ICD system efficacy. In many patients, ICD implant testing can be performed without induction of VF using methods based on the ULV.\textsuperscript{5,6,11,14}

Clinical assessment of the ULV is performed by delivering shocks coupled to overdrive ventricular pacing trains, usually at 500 ms. The pacing trains are necessary to establish a controlled electrophysiologic substrate. Shocks induce VF only if they are delivered while the heart is actively repolarizing, during the "vulnerable period", as shown in Figure 1. Shocks nearest in energy to the ULV will only induce VF near the peak of the vulnerable period. Assessment of the ULV involves identifying an electrocardiographic marker with a timing near the peak of the vulnerable period and delivering a series of shocks with coupling intervals that span timings near that marker. Generally, the marker
used has been the peak of the latest-peaking T wave on the surface 12-lead electrocardiogram. Because identification of the timing of this marker requires equipment, procedures and expertise not normally required for an ICD implant, clinical use of ULV-based methods has been limited.

A practical alternative to the surface T wave is the activation-recovery interval (ARI) on the intracardiac far-field electrogram. The ARI, which is the peak of the derivative of the intracardiac T wave, is an internal marker of repolarization. The interval from the R-wave to the ARI is often called the recovery time, and is denoted $T_R$. While $T_R$ does not precisely correspond to the peak of the surface T wave, studies have shown that it can be processed automatically by an ICD and used as a reliable marker for the timing of the peak of the vulnerable zone.\textsuperscript{16,17}

A new method for ICD testing has been developed in which vulnerable period timing is automatically determined by calculating $T_R$ from the far field ICD electrogram. $T_R$ is used as the timing marker for the vulnerable period, and a sequence of T-wave shocks are delivered at a pre-determined energy. Since the ULV defines the boundary between inducing and non-inducing shock energy, non-induction of VF by this sequence of shocks demonstrates that the ULV is lower than the tested shock energy. Several studies suggest that the system will then reliably defibrillate the patient at maximum output\textsuperscript{6,11}. If VF is induced, the patient is defibrillated. Because the T-wave shock energies used are above the ULV for most patients, “vulnerability safety margin testing” serves as a screening test that eliminates VF induction in these patients. Those patients for whom the screen fails (VF is induced) undergo conventional DSM testing, beginning with defibrillation of the induced episode. Many induced patients will have adequate defibrillation safety margin. The
Automated Vulnerability Safety Margin (AVSM) study prospectively assessed the performance of this method by comparing the outcome of AVSM testing to conventional defibrillation safety margin testing. The standard of comparison was the ability to defibrillate induced episodes of VF with a safety margin of at least 10 J. The study hypothesis was that any patient not induced by 18J T-wave shocks delivered by the AVSM system would also be reproducibly defibrillated with 25J shocks. Because the purpose of the study was to compare AVSM testing to standard DSM testing, neither the ULV, nor the range of the vulnerable period, were assessed in the study.

Because VF sensing is also assessed during ICD implant testing, some investigators have suggested induction of VF to test sensing if sinus rhythm R-wave amplitudes are small (usually < 7 mV)\(^1\). A secondary objective, therefore, was to assess sinus R-wave amplitude as a screen for patients who may have poor VF sensing performance. We hypothesized that patients with VF undersensing will have small R-wave amplitudes in sinus rhythm. The study was an acute, prospective, nonrandomized, multicenter feasibility study.

**Methods**

**Patients**

Patients were candidates for this study if they were eligible to receive a Virtuoso\(\text{TM}\) ICD or Concerto\(\text{TM}\) cardiac resynchronization therapy defibrillator (CRT-D) implant (Models D154AWG, D154VWC, C154DWK, or C164AWK, Medtronic, Inc., Minneapolis, MN), had a superior vena cava defibrillation coil, had a right ventricular (RV) defibrillation lead placed in the RV apex, were greater than 18 years of age, and were willing and able to give informed consent. The study was approved by the Investigational Review Board of each institution.
Patients were excluded for any of the following: frequent ventricular sensed intervals of shorter than 500 ms occurring at rest, pacemaker dependency, right-sided ICD systems, long QT syndrome, Brugada syndrome, hypertrophic cardiomyopathy, congenital heart disease, use of intravenous inotropes, class IV heart failure, known elevated defibrillation threshold greater than 35J, use of class Ia, Ib or III antiarrhythmics with the exception of amiodarone and procainamide, enrollment in a concurrent study that might confound the results of this study, or pregnancy.

System Description

The AVSM system consists of investigational software for the Medtronic programmer that implements the automated implant test and downloadable ICD software. The recovery time, $T_R$, is calculated by the downloaded software from the ICD far-field electrogram. Determination of $T_R$ has been described in detail previously.\(^\text{16-17}\) $T_R$ is the peak of the derivative of the far-field intracardiac T-wave, and is calculated numerically after the electrogram is filtered. Because numerical differentiation amplifies high-frequency signal components, conventional numerical peak detection on a differentiated signal generally produces unstable results. A stable approximation to the peak of the derivative is the weighted mean of the derivative signal (the “center of area,” or COA), in which the intervals within the T wave are weighted by the amplitude of the numerical derivative at that interval.\(^\text{17}\) Figure 2 is a schematic demonstrating the relationship of $T_R$ determined from COA to $T_R$ determined by the signal maximum. $T_R$ has been shown to be very close to the visually-identified peak of the derivative, and to produce numerically-stable results.\(^\text{17}\)

$T_R$ timing is automatically calculated from the T waves following the final two complexes invoked by an 8-pulse, 500 ms pacing train (8V, 1.5 ms). Up to four additional
pacing trains are initiated under physician control, each followed by an 18J biphasic shock, so that the waveform of the T-wave shock matches the waveform of defibrillation shock. T-wave shocks are aborted if there is evidence of loss of capture. The T-wave shock trains are separated by a minimum of 1 minute. The coupling of the shock to the final pulse in the pacing train is automatically determined by the software based on the calculated T\textsubscript{R}. To ensure that the most vulnerable intervals are included in the shock range, the shock couplings range from 50 ms before the calculated T\textsubscript{R} to 10 ms after the calculated T\textsubscript{R}, in 20 ms intervals. The couplings chosen are based on the results of a previous pilot study, and adjusted to compensate for software delays in the ICD.\textsuperscript{17} If VF is not induced, the test takes approximately 5 minutes to run. Because AVSM operates as a screen, the T-wave shock energy of 18J was set conservatively low to be highly sensitive to patients requiring more than 25J to defibrillate, with the tradeoff that some patients with induced VF would have sufficient defibrillation safety margins.

At the discretion of the investigator, a 12-lead surface electrocardiogram was collected simultaneous with telemetered device electrograms to allow comparison between T\textsubscript{R} and surface T-wave peaks.

**Protocol**

Standard implant or change-out procedures were followed up to the point of defibrillation testing. A diagram of the procedure for vulnerability and defibrillation testing is shown in Figure 3. The first and second rescue defibrillation shocks were programmed to 22J and 25J, while defibrillation therapies 3 through 6 were programmed at the discretion of the investigator. After completing the AVSM test (4 non-inducing 18J T wave shocks or any VF induction while delivering T wave shocks during the vulnerable period), additional VF
inductions were performed so that all patients had at least 2 induced VF episodes to
determine the defibrillation safety margin. The additional VF inductions were performed
for all subjects using the investigator’s method of choice, usually a 1-2J T-wave shock or
50-Hz burst pacing. Implant criterion was at least 2 out of 3 defibrillation successes at 25J
or below (giving a 10J safety margin). If an ICD system failed the defibrillation implant
criterion, the investigator could conduct additional testing and revise the system.

Sinus rhythm R-wave amplitudes were recorded at implant. Consistent with
standard implant guidelines, we called for a minimum R-wave amplitude of 5 mV for
newly implanted ventricular leads, or 3 mV for chronic leads. Ventricular sensitivity was
set to a less-sensitive value of 1.2 mV during VF inductions.

Data Analysis
For the AVSM protocol, a VF induction was defined to be a sustained polymorphic
ventricular arrhythmia with cycle length ≤ 320 ms which was detected and had VF therapy
delivered by the ICD.

To quantify VF undersensing, we examined all induced VF episodes for clear
deflections on the ventricular tip-ring electrogram which were not sensed by the ICD. A 5
second delay in detection due to undersensing was considered to be clinically significant.

The recorded 12-lead electrocardiograms (ECGs) were measured post-hoc to find
$T_{\text{peak}}$, the peak of the latest-peaking monophasic T wave that is opposite in polarity from
the R wave. $T_{\text{peak}}$ is used for setting T wave shock timings using standard ULV methods.$^5$
Figure 4 shows an example of $T_{\text{peak}}$ and $T_R$ measurements for one patient.

Statistical Analysis
We used a 2-sided exact binomial test to calculate the 95% confidence interval for
successful defibrillation at 25J for patients in whom VF was not induced with the AVSM test. To draw conservative conclusions about population behavior, we used only results of the first VF episode. Using Bayesian statistical analysis, we also calculated the probability of defibrillation success at an energy of 25J or less given AVSM non-induction. Analogous to the 95% confidence interval used in conventional (“frequentist”) statistics, the Bayesian 95% credible interval we calculated shows the predicted range of that probability. This analysis used non-informative “Jeffreys” priors and the results of both defibrillation tests. The correlation between TR and T_peak was calculated using a Pearson correlation. SAS version 9.2 for Windows was used for the statistical analyses.

Results
Sixty patients were enrolled from 6 centers in the United States. Patient demographics were typical for patients implanted with standard or cardiac resynchronization ICDs (Table 1). The RV defibrillation leads used were Models 6945, 6947, or 6949 (Medtronic, Inc., Minneapolis, MN), or Model 7120 (St. Jude Medical, St. Paul, MN). Table 2 lists patients excluded from data analysis along with the reason for exclusion. None of the 6 exclusions were due to failure of the AVSM software. All were excluded for typical reasons in a multicenter study.

VF induction and defibrillation
The collected induction and defibrillation data from 54 patients are summarized in Table 3. The AVSM test induced sustained VF in 10 patients (19%), nonsustained VF lasting 4.2 seconds in 1 patient (2%), and no arrhythmias in 43 patients (80%).

All 44 patients (81%) in whom sustained VF was not induced by the AVSM test were defibrillated at shock energies of 25J or less. Of these, all 43 patients (80%) in whom
the test induced no VF were also defibrillated at 22J, and the one patient in whom non-sustained VF was induced required 25J. Conversely, 4 of the 10 patients (40%) in whom the AVSM test induced sustained VF had at least one defibrillation failure at 22J, and 2 (20%) had defibrillation failures at 25J or higher. In the two patients with defibrillation failures at 25J, the investigator was unwilling to reattempt 22J and 25J defibrillation prior to system modification, so it was not possible to verify that the patients would have failed two of three defibrillation attempts.

For all 44 ICD systems that passed the AVSM test, the calculated 95% confidence interval for successful defibrillation at 25J was 92-100%. The confidence interval for the 38 patients not on antiarrhythmic drugs other than digoxin was 91-100%. The corresponding 95% Bayesian credible intervals for the population success rate of defibrillation at 25J were 97-100% and 97-100%, respectively.

**TR and Tpeak Results**

Loss of capture did not occur during pacing trains, but 1 patient had a single fusion beat. TR measurements were available from stored ICD data for 54 patients. TR during the initial pacing train occurred at 381 ± 19 ms. The distribution of TR measurements is shown in Figure 5.

In all patients TR was measured late on the upstroke of the T wave. Figure 6 shows an example of the RV coil-can electrogram and the corresponding derivative signal on which the automatic TR measurement is made. Note that the center of area does not necessarily occur at the peak of the derivative signal. TR timing was not significantly different for patients in whom AVSM induced or did not induce VF (372 ± 21 ms (n = 10) vs. 382 ± 18 ms (n = 44), p = 0.15).
Of the 10 patients in whom the AVSM test induced VF, 2 patients were induced with the first T wave shock at TR -30 ms, 7 with the second T wave shock at TR -10 ms, none with the third T wave shock at TR -50 ms, and 1 with the fourth T wave shock at TR + 10 ms. The interval from TR to the inducing shock was -12 ± 11 ms. The range of pace-to-shock coupling intervals which induced VF ranged from 331 to 415 ms.

Corresponding Tpeak and TR measurements were available for 44 patients. Tpeak was collected in these patients as supplementary data, and was not used to validate the algorithm, since prior studies had shown that Tpeak and TR measurements identified slightly different sections of the vulnerable zone.16, 17 TR was 382 ± 20 ms, Tpeak was 367 ± 28 ms. The mean difference (TR - Tpeak) was 15 ± 21 ms. Figure 7 shows the correlation between TR and Tpeak (r = 0.65). Consistent with the earlier retrospective analysis, TR was generally slightly later than Tpeak.17

Relationship between sinus R-wave amplitude and VF sensing
At least 1 undersensed event occurred in 42 of the 109 analyzed VF episodes (39%), with greater numbers of undersensed events occurring exponentially less often (Figure 8). No episode had as many as 6 undersensed events (25% of events in the 24-beat detection window). Undersensed events were not confined to patients with sinus R-wave amplitudes of less than 7 mV: patients with R-wave amplitudes as large as 13 mV had undersensed events, and the two patients with sinus R-wave amplitudes less than 7 mV had adequate VF sensing. The undersensed events never led to more than a 2.5 second delay in detection. Undersensing in patients with large R waves was due to rapid changes in amplitude between consecutive deflections. These results occurred with ventricular sensitivity set to 1.2 mV; undersensed events should be less common at nominal sensitivity of 0.3 mV.
Discussion

The principal finding of this prospective, multicenter study is that an automated method based on the ULV served as an effective screen for patients who have inadequate defibrillation safety margins, often without the induction of VF. AVSM avoided VF induction in 85% of patients who passed subsequent confirmatory defibrillation testing, while identifying all patients with inadequate defibrillation safety margins.

ICD implant testing is designed to assure appropriate device function at the time of clinical arrhythmia. Complications associated with defibrillation safety margin testing are rare, but there is increasing controversy over whether the risks of testing are justifiable, especially in primary-prevention patients, many of whom may have no other episodes of VF. However, a combination of anatomic and physiologic factors still contributes to a small percentage of patients being inadequately protected at the time of implant. No reliable method has been established for identifying these patients in advance, and there are no current guidelines for when ICD testing may be avoided and little prospective clinical data to assess the clinical safety question.

ULV-based testing methods have the potential to significantly reduce VF inductions at ICD implantation testing, while providing adequate sensitivity to detect patients requiring system revision. Vulnerability testing has the advantage that it screens for inadequate ICD defibrillation safety margin, yet significantly reduces the likelihood that a particular patient will experience an episode of VF compared to conventional defibrillation testing. Those patients who avoid VF induction will still experience four 18J T-wave shocks. While the 72J of total energy delivered to the patient is somewhat greater than the approximately 54J that would be delivered during nominal DSM testing (induction energy...
plus rescue energy for two episodes of VF), it is important to note first, that the individual shocks are smaller than DSM rescue shocks, second, that they are delivered into a non-ischemic substrate, and third, that at least one single-center study has found no evidence of increased myocardial damage from T-wave shocks that assess ULV, compared to defibrillation shocks that assess defibrillation threshold.24

Those patients who `fail" the vulnerability screen (in this study, the 19% who were induced by AVSM testing) receive high-voltage ICD therapy, which begins the process of conventional defibrillation testing, and thus have effectively the same experience as if AVSM testing had not been attempted. Therefore, the sensitivity of the screen can be made high, without exposing patients who fail the screen to any incremental risk relative to conventional testing.

ULV-based testing historically has consisted of identifying the repolarization period, or vulnerable zone, by manually measuring the timing of the T wave on surface ECGs, requiring extra time, additional equipment, and operator expertise during implant testing. With ULV testing, incorrect determination of T-wave timing could result in inadvertently delivering test shocks outside the vulnerable period. The result could be false reassurance of defibrillation efficacy. Thus, while ULV testing has been shown to be effective in numerous clinical trials,5-15 the extra steps and implanters’ lack of experience with the technique have hindered the wider clinical application of ULV as a screening test. An automated ULV system would have the benefit of assuring acceptable defibrillation function without the need for VF induction in most patients and without the obstacles posed by manual application of the technique.

Proof-of concept studies were performed to develop a system that could be
implemented in the ICD or programmer, and would identify the vulnerable zone by automated analysis of the ICD’s far-field electrogram.\textsuperscript{16,17} As in those studies, the automatically-determined timing, $T_R$, was close to the timing determined from the surface ECG, $T_{\text{peak}}$. The present study establishes the clinical feasibility of using the automatically-identified vulnerable zone in an automated system of ICD implant testing, the Automated Vulnerability Safety Margin (AVSM) system. Using 18J T-wave shocks, 100\% of patients who passed AVSM testing had adequate DSMs. In contrast, 40\% of patients who failed AVSM (4 of 10) had at least one unsuccessful defibrillation.

Although the sample size was limited, Bayesian statistical analysis of the primary results predicted that between 97 and 100\% of patients not induced by AVSM would be defibrillated at 25J. This compares favorably with the results of the ASSURE study in which passing a 14J vulnerability safety margin test with shock timing determined from the surface ECG had a 98.4\% positive predictive accuracy for successful defibrillation at 21 J (10 J safety margin) in 394 patients.\textsuperscript{6}

VF induction at implant is also used to assess VF sensing. Often, VF inductions have been considered necessary in patients with sinus rhythm R-wave amplitudes below 5 to 7 mV.\textsuperscript{5,6,14} This study found that clinically significant undersensing did not occur in any patient, but found sporadic VF undersensing in patients with sinus R-wave amplitudes as large as 13.9 mV, and adequate VF sensing in all patients with amplitudes between 3 and 7 mV. A significant number of induced VF episodes (39\%) had at least one undersensed event, but only half that many (21\%) showed at least 2 undersensed events, and the pattern continued for greater numbers of undersensed events. This suggests that the likelihood of large numbers of undersensed events, and therefore a clinically significant detection delay,
is vanishingly small. It also shows an almost random pattern in the occurrence of undersensed events, rather than VF sensing being consistently poor. This not only demonstrates that sinus R-wave amplitude is a poor predictor of VF sensing, but also suggests that implant testing for the purpose of evaluating VF sensing provides limited information. Sporadic VF undersensing never resulted in a detection delay greater than 2.5 seconds, even at the reduced ventricular sensitivity value used for testing. The correlation between VF undersensing and R-wave amplitude at implant has been studied retrospectively in a much larger population with similar results. Standard practice calls for a minimum R-wave amplitude of 5 mV during initial lead placement. Our evidence suggests that no additional requirement on R-wave amplitude is necessary to ensure adequate VF detection, at least for patients with true bipolar sensing, as in this study.

Limitations

Since this was a feasibility study, sample size was necessarily limited. In particular, only two patients were found to require system revision. However, statistical analysis demonstrated the principal endpoint with greater than 97% confidence. Several classes of patients were excluded from the study. In some cases, such as class IV heart failure or medical instability, the exclusion was not specifically related to the algorithm. The exclusion of rapid intrinsic rhythms was based on the inability to create a stable rhythm by overdrive pacing, as required for ULV-based testing. The exclusion of repolarization abnormalities such as long-QT or Brugada Syndrome was because the vulnerable zone is intrinsically related to repolarization and there has been insufficient study of how these abnormalities affect vulnerable zone determination. These considerations also excluded patients on some antiarrhythmic medications. Single-coil and right-sided lead systems, as
well as many patients with congenital abnormalities, use a different shock vector, which
could also have an impact on exact vulnerable zone timing. Patients with single-coil
systems likely could use the system but might need a slightly different timing range for T-
shocks, and would have to be studied separately. The number of patients affected by these
exclusions is relatively small, and this method could therefore be used on the vast majority
of the ICD patient population.

Conclusions
This multicenter, prospective study was the first to use an automated system for ICD
implant testing without VF induction. The AVSM test correctly identified all subjects with
failed defibrillation, while inducing VF in only 19% of subjects. All subjects who passed
the AVSM test were defibrillated successfully twice at 25J or less. The AVSM algorithm
provides a simplified practical tool for assessing defibrillation safety margin without
inducing VF in most patients. It eliminates the need for any additional setup or expertise,
and substantially reduces the procedure time required by ULV or vulnerability safety
margin testing based on the surface ECG. The results from the current pilot support the
feasibility of conducting a pivotal trial to study AVSM as a practical screening tool for
patients with high defibrillation threshold at time of implantation.

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**References:**


**Table 1. Patient demographics**

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<td><strong>Age, mean ± SD</strong></td>
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<td><strong>Male/female</strong></td>
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<td><strong>New implants/change-outs</strong></td>
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<td><strong>CRT-D / ICD</strong></td>
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<td><strong>LVEF (%) mean ± SD</strong></td>
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<td><strong>LBBB</strong></td>
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<td><strong>RBBB</strong></td>
<td>5 (9%)</td>
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<td><strong>Antiarrhythmics:</strong></td>
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<td>Digoxin</td>
<td>16 (30%)</td>
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<td>Amiodarone</td>
<td>4 (7%)</td>
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<td>Diltiazem</td>
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Table 2. Patients excluded from data analysis

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<tr>
<td>A14</td>
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<td>C09</td>
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<td>C13</td>
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<td>D02</td>
<td>Left atrial thrombus</td>
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<td>C15</td>
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Table 3. AVSM induction and defibrillation results for 54 patients

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<th>Sustained VF</th>
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<td>Failure at 25J</td>
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<td>2</td>
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<td>Success at 22J</td>
<td>6</td>
<td>0</td>
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Figure Legends:

Figure 1. A schematic diagram of the vulnerable zone to ventricular fibrillation induction by a T-wave shock. The range of coupling intervals for which VF induction is possible is
the “vulnerable period.” Note that the range of energies which would induce VF is greatest for coupling intervals near the center of the vulnerable period. The coupling interval at which a shock at the ULV induces VF is sometimes called the “peak” of the vulnerable zone.

**Figure 2.** Diagram of the comparison of the Center of Area method to conventional peak detection. Since the center of area method is based on an integral, it effectively processes the entire signal. It finds timings very close to the peak but is less sensitive to signal noise and so is more stable.

**Figure 3.** Procedure used for vulnerability and defibrillation testing. AVSM testing was done first, with between one and four coupled 18J T-wave shocks. A patient induced into VF by one of these shocks was categorized AVSM-fail (inadequate safety margin). A patient not induced by any of the four shocks was categorized AVSM-pass. The induced episode in an AVSM-fail patient was treated with high-voltage ICD therapy, as during conventional defibrillation testing. At least one more episode of VF was then induced to confirm repeatable defibrillation. If the patient was not induced by AVSM, VF was subsequently induced and treated at least twice using conventional methods to confirm repeatable defibrillation. Patients in whom VF was successfully treated at least twice at 25J or less were categorized DSM-pass (adequate safety margin), otherwise they were categorized DSM-fail.
Figure 4. Example of $T_R$ (351 ms) and $T_{\text{peak}}$ (368 ms) measurements for patient C16. The top tracing is the far-field ICD electrogram. The bottom two tracings are from the surface ECG. In the top tracing, the point of maximum electrogram T-wave slope (the ARI) is approximated by the ICD using the center of area method ($T_R$). In the lower tracings, the latest surface T-wave peak (in this case, on V6) is shown ($T_{\text{peak}}$). In general, $T_R$ and $T_{\text{peak}}$ are at very similar couplings, but do not identify exactly the same interval.

Figure 5. Distribution of $T_R$ measurements for 54 patients.

Figure 6. Far-field electrogram (top) and its derivative (bottom) during the T-wave analysis window, with $T_R$ marked with a vertical line. The electrogram segment is shown only during the analysis window (297-461 ms after the pace). High-frequency noise creates two “false peaks” on the signal. The center of area method identifies a stable coupling interval near the maximum.

Figure 7. Correlation between $T_R$ and $T_{\text{peak}}$ for 44 patients.

Figure 8. Percentage of VF episodes with undersensed depolarizations. The bars show the percentage of episodes with exactly n undersensed depolarizations. No episodes had more than 5 undersensed events. The line shows the cumulative percentage of episodes with n or fewer depolarizations. This number decreases exponentially, with roughly half as many patients having one additional event. This suggests that undersensed events are statistically independent, rather than part of a repeatable pattern of inadequate sensing.
Pacing Train for T wave measurement

18J T-shock Traine 1 - 3
Induce
Non-induce

18J T-shock Train 4
Induce
Non-induce

Defib at 22, 25J
(Fail) Induce VF
(Succeed) Defib at 22, 25J
(Fail)

Defib at 22, 25J
(Succeed) Induce VF
(Succeed)

AVSM Fall DSM Fall
AVSM Fall DSM Pass
AVSM Pass DSM Fall
AVSM Pass DSM Pass
Automated Vulnerability Testing Identifies Patients with Inadequate Defibrillation Safety Margin

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