Tools and strategies for the reduction of inappropriate implantable cardioverter defibrillator shocks

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Implantable cardioverter defibrillators (ICDs) represent the treatment of choice for the secondary prevention of sudden cardiac death, while robust data have also accumulated to validate their mortality benefit in the expanding pool of primary prevention patients.¹⁻⁵ Despite their undoubted evidence-based credentials, even the newer generation ICDs are plagued by the caveat of inappropriate therapies, which indeed seem to represent their Achilles’ heel. Although this major theme has been in the limelight ever since the advent of ICDs, when the use of only rate criteria was associated with a 45% occurrence of inappropriate shocks, the issue still constitutes a major challenge that we have to face.⁶

The incidence of inappropriate therapies remains high, ranging from 15 to 35%, and the related impact on patients’ quality of life is paramount.⁷⁻¹⁰ Implantable cardioverter defibrillator shocks are associated with worse mental health, impaired quality of life,¹¹ fewer new activities mainly due to an increased incidence of avoidance,¹² depression, and anxiety.¹³,¹⁴ Increased shock frequency has been reported as an independent predictor of anxiety scores¹⁴ as well as low treatment satisfaction.¹⁵ Apart from the detrimental effect on the quality of life, inappropriate therapies may also result in the induction of potentially fatal ventricular tachyarrhythmias (VTs).¹⁶⁻¹⁹ Thus, the reduction of the incidence of inappropriate ICD shocks is of primary importance. Moreover, the need to enhance device discrimination is further amplified by the tendency to broaden the eligibility criteria of ICD implantation in primary prevention subpopulations, thus inevitably increasing the relative burden of supraventricular tachycardias (SVTs) falling within the VT/VF detection zone when compared with the proportion of true VT/VF episodes.²⁰

The primary criterion for the detection of VTs by ICDs is the ventricular rate, evaluated by sensing electrical signals exceeding the programmable setting of sensitivity and falling within the selected detection zones. If a consecutive number of sensed events or a predetermined percentage of beats in a sliding detection window falls within the detection zone, then the rate criterion is satisfied. This rather crude concept makes the criterion susceptible to misinterpretation and thus false detection of tachyarrhythmias, resulting in inappropriate therapy delivery. The main causes of inappropriate shocks are the erroneous diagnosis of SVT as VT and ventricular oversensing.⁹,²⁰⁻²²

Differentiation of supraventricular from ventricular tachycardias

In order to enhance the discrimination performance of ICDs, novel discrimination algorithms have been developed with a view to improving the differential diagnosis of SVTs vs. VTs and decreasing the incidence of inappropriate therapies. A key point concerning the use of discrimination algorithms is that the increased specificity (likelihood of appropriately withholding therapies) afforded by the activation or more stringent use of these criteria is achieved in the expense of sensitivity (likelihood of detecting true
VT), and vice versa.\textsuperscript{23,24} Through this prism, the optimal programming should be individualized in relation to the rate of tachyarrhythmia as well as the likelihood of SVT occurrence in a certain tachyarrhythmia zone. The analysis of episodes in ICD recipients has demonstrated that the lower the tachycardia cycle length, the higher the relative percentage of VTs in comparison to SVTs.\textsuperscript{23} Thus, the activation of a discrimination algorithm in the VF zone would be of limited value, when one takes into consideration the small odds of rate overlap between VTs and SVTs in this detection zone, and the high likelihood that a considerable proportion of primary prevention ICD recipients will be quite unable to tolerate very rapid tachyarrhythmias because of their underlying compromised ventricular function.

**Single-chamber discrimination algorithms**

The criteria used by single-chamber ICDs focus on interval regularity, rate onset, and ventricular electrogram morphology (Table 1).

**Onset criterion**

The onset criterion is based on the premise that the acceleration of the ventricular rate can differentiate a sinus tachycardia from a VT, since the former usually displays a gradual rate increase, in contrast to the latter, which almost always accelerates rapidly.\textsuperscript{23,26–28} Although the onset criterion is extremely useful in excluding sinus tachycardia, it is also associated with a risk of VT under-detection, for example, in VT initiation during sinus tachycardia, or in VTs which do not exhibit a sudden onset.\textsuperscript{23,27,28} Furthermore, this criterion is not suitable for patients with exercise-induced VTs, since the gradual catecholamine-induced heart rate increase preceding the onset of VT would satisfy the onset criterion, resulting in inappropriate withholding of programmed therapies.

**Stability criterion**

The concept of the stability criterion is the differentiation of VTs from episodes of atrial fibrillation with ventricular rates within the detection zones, based on the presence of ventricular rate stability.\textsuperscript{23,26–29} However, the pseudo regularization of ventricular rate in the case of atrial fibrillation with a rapid ventricular response reduces the diagnostic accuracy of this algorithm.\textsuperscript{27,29} Furthermore, the application of this algorithm poses the risk of under-detection of VTs with an irregular ventricular rate, such as polymorphic VTs and irregular monomorphic VTs, as well as ischaemic VTs with dynamic changes of the re-entrant circuit. In monomorphic VTs, the stability algorithm may rarely result in delayed therapy delivery due to the initial instability of the ventricular tachycardia cycle length.\textsuperscript{23,30}

The combined use of stability and sudden-onset criteria with a time-related override has been associated with a sensitivity of 100% and a specificity of 83%.\textsuperscript{23}

<table>
<thead>
<tr>
<th>Diagnostic algorithm</th>
<th>Biotronik</th>
<th>ELA</th>
<th>Guidant</th>
<th>Medtronic</th>
<th>St Jude</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Onset</strong></td>
<td>Average of recent four VVs minus average of current four VVs &lt; programmable value (also as % value)</td>
<td>Current RR interval &gt;75% of the preceding RR interval</td>
<td>Cycle length decrease in adjacent VVs prior episode start &lt; programmable value (also as % value)</td>
<td>Average of four recent VVs divided by average of four previous VVs &gt; programmable % value</td>
<td>PreVT (sinus) average VI minus first average VI within VT zone &lt; programmable value (also % value)</td>
</tr>
<tr>
<td><strong>Stability</strong></td>
<td>Fluctuation in duration of the last four tachycardic VVs &gt; programmable value</td>
<td>Ratio of intervals within a programmable stability range &lt; programmable ratio</td>
<td>Average of RR interval differences &gt; programmable value</td>
<td>VI—any of previous three VVs &gt; programmable interval</td>
<td>Second longest-2nd shortest VI in a detection window &gt; programmed value</td>
</tr>
<tr>
<td><strong>Morphology</strong></td>
<td>Not available</td>
<td>Not available</td>
<td>Not available</td>
<td>≥3 out of 10 beats match with stored template (match percentage &gt; non-programmable value)</td>
<td>≥3 out of last 8 beats match with stored template (match percentage &gt; programmable value)</td>
</tr>
</tbody>
</table>

SVT, supraventricular tachycardia; VT, ventricular tachycardia; VI, ventricular interval.
supraventricular, then the ventricular origin of the arrhythmia is precluded and the programmed therapies are not delivered. When used as a sole discriminator, the Medtronic morphology algorithm results in a specificity (percentage of appropriately classified SVTs) of 78.2% and a sensitivity of 98.6% (percentage of appropriately classified VT/VFs). The use of the St Jude Medical discriminator alone achieved a sensitivity of 77–94.4% and a specificity of 71–95%, while its combined use with stability and onset criteria at the optimal diagnostic setting of two out of three resulted in a sensitivity of 96% and a specificity of 90.9%. Gold et al. reported that the single-chamber sensitivity of the Guidant morphology algorithm [vector time and correlation (VTC) algorithm] is 99% combined with a specificity of 97%, while in a recent retrospective analysis the single-chamber algorithm achieved a sensitivity of 100% with a specificity of 91%.

Several potential limitations should be taken into account concerning the discrimination performance of morphology algorithms. A key step in the accurate assessment of the similarity index is the proper alignment of the tachycardia electrogram and the reference template. The procedure is applied by aligning the respective positive or negative peaks. Thus, template misalignment may result in overestimation of the non-overlapping electrogram area, underestimation of the matching percentage, and thus to an increased likelihood of event misclassification as VT. Furthermore, the algorithm is prone to misclassification in the case of rate-dependent aberration, since the dissimilarity between the electrogram morphology of the aberrant supraventricular rhythm and the reference template would result in erroneous classification of the index event as VT. The algorithm also displays a poor discrimination performance in the case of VT with a similar morphology to the intrinsic rhythm, as would be the case in certain septal VTs. Caution is also required in order to prevent electrogram truncation, which occurs when the electrogram amplitude exceeds the maximum programmed range, resulting in clipping of some portions of the signal and thus preventing the optimal comparison of the index electrogram with the reference template. Other concerns that need to be addressed are ischaemia-mediated acute changes in electrogram morphology, electrogram maturation, distortion of a sinus tachycardia electrogram due to exercise-induced myopotential interference, especially with low amplitude electrograms, and post-shock electrogram distortion.

Optimal customizing of programming parameters may overcome some of the above-mentioned limitations. Electrogram truncation can be overcome by appropriate adjustment of the electrogram range. For instance, in Medtronic ICDs, it is important to select the far-field configuration (Can to RV coil) as electrogram source, since it is associated with improved detection performance and also minimizes potential posture-related changes in electrogram configuration. The St Jude Medical morphology algorithm is designed to operate with an RV bipolar electrogram source, while an interesting concept implemented in the Guidant VTC algorithm is that the comparison of the index with the reference electrogram is based on information derived from two different sources: a far-field channel of RV coil to SV coil + can and a near-field channel of RV tip to RV coil. Finally, the activation of automatic electrogram template updating overcomes time-related changes in electrogram morphology, thus averting the need for periodic manual template updating.

Dual-chamber discrimination algorithms

Dual-chamber ICD discriminators are based on information derived from the atrial electrogram pertaining to the timing and pattern of atrial events, while single-chamber ICD differentiation algorithms are also used. These data are incorporated in different flowcharts and algorithms by each manufacturer. A critical step in the hierarchical approach of dual-chamber algorithms is the comparison of the atrial and ventricular rate, since the ventricular rate exceeds the atrial rate in more than 90% of ventricular tachycardias. The dual-chamber discrimination algorithms of the most recent generation ICDs from each manufacturer are briefly presented.

Biotronik SMART detection algorithm

The initial discrimination test in the SMART algorithm is based on the comparison of the atrial and ventricular rates. If the ventricular rate is higher than the atrial rate, then VT is diagnosed. If the ventricular rate is lower than the atrial rate, the index tachyarrhythmia is differentiated based on atrial and ventricular rate stability, as well as the ratio of atrial to ventricular signals. Finally, if the atrial and ventricular rates are equal, the differentiation is performed using rate stability, and sudden onset (Figure 1, modified from reference).
Specificity and sensitivity of the SMART detection algorithm are 89 and 100%, respectively.44

ELA/Sorin PARAD+ algorithm45
The PARAD+ algorithm enables the stepwise discrimination analysis of detected tachyarrhythmias based on the flowchart presented in Figure 2 (modified from reference45). If the rate stability criterion is not satisfied, the rhythm is diagnosed as atrial fibrillation. This classification scheme is prone to false detection of polymorphic VTs as atrial fibrillation, although the nominal stability setting has been shown to be associated with high sensitivity in detecting VTs. In the PARAD+ algorithm, all stable dissociated rhythms are further differentiated to atrial fibrillation or VT on the basis of the long cycle criterion (VTLC). The concept of this criterion is that even in fast atrial fibrillation with a rapid ventricular response and pseudo-regularization, a long cycle length exceeding the average interval is present from time to time. If a programmable long cycle length is detected, then atrial fibrillation is diagnosed and therapy delivery is inhibited. Rhythms with N:1 atrioventricular association are classified as atrial flutter. In the next steps, the cycle length acceleration is evaluated for sinus tachycardia discrimination, while a final discrimination between atrial and ventricular tachycardia is performed based on the chamber exhibiting initial acceleration. A recent meta-analysis of prospective trials evaluating the PARAD/PARAD+ algorithms reported that the sensitivity of VT/VF detection was 99.3%, the respective value in slow VT detection was 94%, while the specificity of SVT recognition was 94%.46

Guidant Rhythm ID—detection enhancement algorithm47
In the Guidant Rhythm ID algorithm (Figure 3, modified from reference47), if the average ventricular rate exceeds the average atrial rate by more than 10 bpm then VT is diagnosed. Otherwise, the morphology algorithm is appraised and if it is indicative of SVT then therapy is withheld. Finally, both the criteria of rate stability and atrial rate above an atrial fibrillation threshold need to be met in order for an SVT to be diagnosed. The Rhythm ID algorithm has demonstrated 100% sensitivity for VT/VF detection, while in two studies the reported specificity of SVT discrimination was 92 and 97%.35,48

Medtronic PR Logic49
Arrhythmia detection in Medtronic dual-chamber ICDs is enhanced by the use of the PR Logic algorithm, which is optionally programmed in combination with stability onset and morphology criteria. In the PR Logic algorithm, each...
ventricular coupling interval is divided into zones (junctional, retrograde, and antegrade) (Figure 4, modified from reference49). Each atrial sensed event is categorized based on the ventricular zone in which atrial sensing occurred. The recognition of a certain atrial event pattern in two consecutive ventricular intervals enables a pattern code assignment derived from a pool of codes stored in the device. The respective assigned pattern code defines episode classification and SVT or VT rhythm identification. In order to overcome the caveat of sinus tachycardia misinterpretation as VT due to rate-dependent atrioventricular conduction delay and positioning of atrial sensing in the antegrade zone (ECG analogue sinus tachycardia with first-degree AV block classified as short RP tachycardia), the option of operator-dependent customizing of the retrograde–antegrade boundary setting is also provided. Thus, in cases of delayed AV conduction during SVT, the relative size of the antegrade zone should be increased, in contrast to cases of delayed VA conduction, where the relative size of the retrograde zone should be lengthened in order to prevent misinterpretation. The concomitant presence of PR prolongation during SVT with delayed VA conduction during VT renders the tachyarrhythmia differentiation problematic. However, this issue can be addressed by the PR Logic criteria applied in the recent Medtronic ICD models (EnTrust, Virtuoso, and Concerto). The performance of the PR Logic algorithm has been evaluated in several published full-length papers and the reported sensitivity is 100% with a specificity of 66 and 72%.41,50,51

St Jude Medical dual-chamber algorithm52
The first step in the analytical approach of the St Jude Medical algorithm is the comparison of atrial and ventricular rate (rate branch classification). If the ventricular rate is higher than the atrial, then the detected rhythm is classified as VT and therapy is delivered without having to meet further discrimination criteria. When atrial and ventricular rates are equal, then the AV interval discriminator is applied as a pre-qualifier (gate-keeper). In this way, the simultaneous occurrence of sinus tachycardia and VT with coincidentally similar rates can be detected based on the presence of AV dissociation (difference between the second longest and the second shortest AV delay in a programmed detection window). In the next step, sudden-onset and morphology discriminators are implemented. If the ventricular rate is lower than the atrial rate, then the morphology and interval stability criteria are applied with or without the use of the AV interval criterion (assessment of AV dissociation). In the latter two rate branches, the additional applied discriminators can be programmed in ‘if any’ or ‘if all’ diagnostic setting (Figure 5, modified from reference52). The sensitivity and specificity of this dual-chamber algorithm are dependent on the selected diagnostic setting and have been reported to vary from 98.7 to 100% and from 73.5 to 90.9%, respectively.52,53

Special considerations regarding discrimination algorithms
‘Whether or not’ is more important than ‘which one’ Despite the apparent differences, the algorithms introduced by different manufacturers are based on similar paradigms of tachyarrhythmia differentiation. The disparities in the reported specificity of different algorithms for appropriate detection of supraventricular arrhythmias should not be used for direct comparisons, since these differences are at least to a certain degree attributed to variances in the sample sizes of compared studies. Hintringer et al.54 elegantly demonstrated an inverse correlation between the number of patients and the specificity of dual-chamber ICD detection algorithms. With this in mind, a reliable comparison of the relative efficacy of discrimination algorithms from different manufacturers can be performed only on the basis of a prospective head-to-head randomized clinical trial. The RIGHT study will be the first to evaluate directly the differential efficacy in Guidant vs. Medtronic ICD discrimination algorithms (Rhythm ID™ vs. Enhanced PR Logic™ or Wavelet™).55 Until the literature acquires new and better data, our main interest should be focused not on ‘which one’, but on ‘whether or not’ the discrimination criteria available in every model have been appropriately utilized in each ICD recipient without complete AV block.
Single- vs. dual-chamber discrimination algorithms

The relative performance of single vs. dual-chamber ICD discriminators is the subject of a long-lasting debate.56 The implantation of an atrial lead is clearly indicated in the subgroup of ICD recipients with a concomitant indication for permanent pacing or cardiac resynchronization therapy, though without permanent atrial fibrillation.57 Furthermore, in view of the DAVID-2 results, a dual-chamber ICD can also be selected in order to provide the option of functional AAI pacing, when rate support is considered essential to increase cardiac output, or to titrate the mortality-reducing β-blocker agents in maximally tolerated doses.58 However, a major issue is whether we have a sufficient amount of evidence to recommend further, on a routine basis, the implantation of a dual-chamber ICD in all patients for the sake of enhanced discrimination performance and avoidance of inappropriate therapies.

Based on the results of recent prospective trials, as well as recently published meta-analyses, dual-chamber discriminators significantly reduce inappropriately treated episodes (per episode analysis), in comparison to single-chamber discriminators, without significantly reducing the number of patients receiving inappropriate discharges (per patient analysis).25,59–63 Furthermore, a cost-effectiveness analysis reported that the least costly strategy for device selection among ICD recipients is the a priori universal implantation of dual-chamber ICDs, since the cost of the additional atrial lead is shown to be offset by the expenses associated with the need for future upgrade, even when the latter rate is as low as 5%. However, this elegantly performed analysis is limited by the retrospective study design, the upgrade indications included, and the low generalizability due to significant variance in device cost among different countries; thus, it certainly cannot be considered adequate for policy setting.64

Taking together the reported equivalence of the compared discriminators in per-patient analysis, the superiority of dual-chamber discriminators in per-episode analysis—which is, however, prone to bias associated with the relative high contribution of a small number of patients to the total burden of inappropriate episodes53—and the rather underestimated susceptibility of dual-chamber discriminators to tachyarrhythmia misclassification due to atrial sensing errors,52,53 we believe that the decision in favour of single- or dual-chamber ICD discriminators should be individualized. When inappropriate shocks recur despite optimal programming of the available single-chamber differentiation criteria, an attempt to implant an atrial lead for enhancing the discrimination performance should be made.

Atrial sensing and dual-chamber discrimination algorithms

Reliable atrial sensing is a strict prerequisite for accurate performance of discrimination algorithms in dual-chamber ICDs. Two frequent pitfalls that may prevent accurate estimation of the atrial rate and thus impair the discrimination performance of dual-chamber algorithms are atrial event under-counting due to prolonged or fixed atrial blanking periods, and atrial event over-counting due to far-field R-wave sensing.65 Far-field R-wave sensing results in over-counting of atrial events and rhythm misclassification. The dual chamber algorithms have introduced several features in order to address these diagnostic challenges. St Jude Medical and Guidant provide the option of reducing the duration of the programmable post-ventricular atrial blanking (PVAB) period, although this entails the risk of atrial rate overestimation due to cross-chamber sensing. In Medtronic ICDs, the manufacturer-recommended PVAB operation maintains the integration of atrial sensing information during PVAB by the arrhythmia detection features in order to prevent atrial under-counting and impaired SVT–VT discrimination. The associated risk of far-field R-wave oversensing is addressed by the implementation of detection criteria based on the recognition of a consistent short–long pattern of atrial sensed events combined with non-physiological values of AV or VA intervals. In the PARAD algorithm, non-physiological PR intervals shorter than a pre-determined value are rejected as far-field sensing.

Empiric vs. tailored discriminator programming

The continuously expanding ICD features and the resulting cumbersome programming render highly attractive option of a standardized parameter setting. The EMPIRIC trial
evaluated the hypothesis whether empiric ICD programming is inferior to physician-tailored programming and demonstrated that the former was associated with a lower percentage of SVT episodes resulting in shock and similar percentages of VT/VF episodes resulting in shock. In our view, the results of this trial should not be posed as an argument in favour of the blind application of a standardized set of criteria, which would undermine the need for gaining detailed familiarity with the ICD parameters available. On the other hand, the reduced percentage of inappropriate shocks in the ‘empiric’ arm reflects the significantly higher percentage of ATP programming and PR Logic criteria activation, further establishing the value of discrimination algorithms as well as the primary importance of consistent ATP programming. Nonetheless, a critical appraisal and customization of programmed settings will inevitably be necessary in the case of inappropriate shock or at some stage of subsequent patient follow-up. Thus, the average implanting physician should be aware of the different features, weak points, and advantages of each discrimination algorithm.

**Ventricular oversensing**

Apart from false detection of SVTs, another cause of inappropriate shocks is ventricular oversensing. This term pertains to a diverse array of situations (T-wave oversensing, electromagnetic interference, myopotential oversensing, oversensing due to sensing lead dysfunction, and double QRS detection) that result in over-counting of ventricular sensed events, thus satisfying the rate criterion and sometimes leading to inappropriate shocks. Recent retrospective studies have reported that ventricular oversensing resulted in inappropriate shocks in 2.3% and 3.9% of the ICD patient population. The phenomenon of T-wave oversensing is a rare cause of inappropriate shocks and may be triggered by electrolyte abnormalities and drugs. In order to prevent T-wave oversensing, newer generation ICDs automatically adjust the sensitivity threshold, increasing its value after ventricular events and then allowing a smooth decay with time. Particular caution is necessary in cardiac diseases associated with a low amplitude intracardiac ventricular electrogram (e.g. arrhythmogenic right ventricular cardiomyopathy and sarcoidosis), tall T-waves (e.g. short QT syndrome), and a long distance of T-wave from R-wave (long QT syndrome), which increase the risk of inappropriate therapy due to T-wave oversensing. Several manufacturers provide the option of specialized programmable parameters in order to overcome these caveats. Biotronik and St Jude Medical enable a programmable time delay before the decay in ventricular sensitivity as well as the possibility of customizing the initial value of ventricular sensitivity as a percentage of the R-wave amplitude.

Inappropriate therapy due to myopotential oversensing may occur in case of programming maximal sensitivity levels (lowest value for the sensitivity setting), although in most cases it is indicative of an insulation defect. When myopotential oversensing is suspected, a provocative test should be implemented, such as shoulder flexion with abduction against resistance.

A tool to prevent the occurrence of inappropriate shocks due to ventricular oversensing is the activation of available alert features triggered when the lead impedance value is out of a programmable range. In a few cases, the immediate patient alert gives the opportunity to the notified physician to proceed with timely lead revision, thus avoiding inappropriate therapy. However, ventricular oversensing is usually an early sign of lead dysfunction, preceding lead fracture and a rise in impedance values. In these cases, inappropriate therapy is the first clue to lead malfunction and its occurrence cannot be prevented by the activation of alert features.

**Optimal therapy programming for shock reduction**

Since the advent of tiered-therapy, non-committed ICDs, the therapeutic alternative of antitachycardiac pacing (ATP) is available for tachyarrhythmia termination. Several studies have shown that ATP successfully terminates ~90% of VTs having a rate <200 bpm, with an acceptable risk of VT acceleration. In the PainFREE Rx II trial, a single 8-pulse burst pacing train was effective in terminating 72% of fast VT episodes without impairing patient safety while in the EMPIRIC trial the consistent ATP application in the ‘empiric’ arm resulted in a significant reduction in the shocked episodes of monomorphic VT when compared with the ‘tailored’ arm, without an increase in the incidence of VT acceleration or syncope. This evidence-based tendency to reposition ICD therapy on a more ATP-oriented basis in order to decrease the number of shocks may also have a favourable impact on the rate of inappropriate shocks. Indeed, the programming of repetitive ATPs, especially in the slow VT zone where VT–SVT rate overlap is maximal, can prolong the time to shock delivery and thus provide the opportunity for some SVTs to self-terminate before shock administration. Furthermore, ventricular ATP may rarely terminate atrial tachycardias, as well as a considerable percentage of junctional tachycardias, although the latter group of SVTs represents a rare cause of inappropriate shocks.

Another decisive issue for the reduction of inappropriate therapies is the optimized programming of the number of intervals to detect (NID). Increase of the selected NID above the nominal values prolongs the detection window, thus allowing non-sustained VTs or short runs of pseudo-regularized atrial fibrillation to self-terminate before detection criteria are fulfilled and therapies delivered. The conferred benefit in inappropriate shock reduction has been shown not to be accompanied by under-detection of VTs or arrhythmic syncope.

**Pharmacological and interventional approaches**

The cornerstone for avoidance of inappropriate therapies is optimal device programming with the key issues of programming ATP therapies in slow as well as in fast VT zones, increasing the duration of the detection window and activating discrimination algorithms without time overrides. Furthermore, pharmacological and interventional measures can confer an incremental benefit. The dosage of the mortality-reducing β-blockers should be maximized in order to decrease the ventricular rates during supraventricular arrhythmias and thus to minimize the odds of SVT rates falling within VT/VF detection zones. Additionally,
antiarrhythmic agents can be used in certain cases in order to prevent supraventricular and non-sustained ventricular tachycardia occurrences that might lead to inappropriate therapies. When the use of antiarrhythmic agents is considered necessary, the first choice should be amiodarone, while sotalol or mexiletine can be a second choice when amiodarone either is ineffective or is discontinued because of adverse effects. However, the increased likelihood of drug-related cardiac and non-cardiac adverse events, especially during long-term administration, and the effect of amiodarone on the defibrillation threshold, which is minor but still clinically meaningful in a minority of cases, represent caveats that should be taken into consideration during clinical decision making.

Catheter ablation constitutes an alternative approach to antiarrhythmic agents, especially for easily amenable arrhythmias such as typical atrial flutter, atrioventricular nodal re-entry tachycardia, or atrioventricular re-entry tachycardias. In the rare case of failure to control ventricular rate with the above-mentioned measures, atrioventricular antiarrhythmic agents, especially for easily amenable occurrences that might lead to inappropriate shocks, are summarized in Table 2.

The strategies that can be implemented for the reduction of inappropriate ICD shocks are summarized in Table 2.

**Table 2. Strategies for decreasing the likelihood of inappropriate shocks**

<table>
<thead>
<tr>
<th>General strategies</th>
<th>Specific programming strategies (not applicable to all ICD models)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activate discriminators in all patients without permanent complete atioventricular block.</td>
<td>Activate alert features triggered when lead impedance is out of a programmable range.</td>
</tr>
<tr>
<td>Use multiple ATP programming in VT zone &lt; 200 bpm and at least one ATP sequence for VT rates from 200 to 250 bpm.</td>
<td>Avoid electrogram truncation in the morphology algorithm and activate the feature of automatic template update.</td>
</tr>
<tr>
<td>Prolong the tachyarrhythmia detection window by programming a number of intervals to detect higher than the nominal values.</td>
<td>Avoid morphology discriminators in patients with rate-dependent aberrancy.</td>
</tr>
<tr>
<td>Titrate β-blockers to maximal tolerated doses to decrease the likelihood of SVT rate falling within VT/VF detection zones.</td>
<td>Appropriately customize programmable sensing parameters to avoid T-wave oversensing in special circumstances (ARVC, short and long QT syndrome).</td>
</tr>
<tr>
<td>In case of inappropriate shock retrieve episode history and customize programming to avoid recurrence.</td>
<td>Consider catheter ablation for treatment of documented supraventricular tachyarrhythmias that may result in inappropriate shocks.</td>
</tr>
<tr>
<td>Exclude myopotential occurrence that may lead to inappropriate shock due to ventricular oversensing or due to distortion of the ventricular electrogram with subsequent erroneous detection of sinus tachycardia as VT.</td>
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### Future possibilities

Novel methods of rhythm discrimination have provided the rationale for the future development of promising algorithms. Proposed parameters that may be used for proper arrhythmia classification in ICD recipients are: the variability of the first post-pacing interval between consecutive bursts of different length, analysis of atrial response patterns during and after ATP, the response of the arrhythmia to simultaneous right atrial and ventricular pacing, and atrial impedance amplitude during the cardiac cycle. The ideal discriminator would be based on the detection of the impact of the tachyarrhythmia on haemodynamic stability and would postpone shock therapy irrespective of the tachycardia rate, as long as an adequate blood pressure level is maintained and pulmonary oedema is avoided. However, taking into consideration the gaping chasm between the ideal ICD and the current reality in everyday clinical practice, as well as the problematic availability of the recently developed technical capabilities, mainly for economic reasons, the above-mentioned discrimination scheme seems unlikely to come to fruition in the near future. Until then, detailed knowledge and use of all available programming options, guided by the special characteristics of each unique patient, provide the only feasible way to achieve the difficult task of reducing inappropriate shocks.

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### Conflict of interest

C.K. has received lecture fees from Biotronik, Medtronic, Sorin, and St Jude Medical. C.K. is an advisor to Biotronik and St Jude Medical.

### References


