Successful Identification of and Discrimination Between Atrial and Ventricular Arrhythmia with the Aid of Pacing and Defibrillator Devices

Rahul K. Mukherjee 1,2, Manav Sohal,1 Nesan Shanmugam,1 Simon Pearse 3 and Fadi Jouhra 1

1. Department of Cardiology, St George’s University Hospital NHS Foundation Trust, London, UK; 2. Division of Imaging Sciences and Biomedical Engineering, St Thomas’ Hospital, King’s College London, UK; 3. Department of Cardiology, Kingston Hospital, London, UK

Abstract

The presence of supraventricular tachycardia is the leading cause of inappropriate shock in ICD recipients, and it can be a significant cause of morbidity, psychological distress and worsened clinical outcome. Modern pacing and ICD systems offer a number of discriminators that are integrated into algorithms to differentiate sustained ventricular tachycardia from supraventricular tachycardia. These algorithms can be adapted and optimised for each individual patient to ensure that only those arrhythmias that need treatment through the use of an ICD, are actually treated. This review summarises the single- and dual-chamber discriminators that can be used in the detection and classification of tachyarrhythmias.

Keywords

Supraventricular tachycardia, ventricular tachycardia, atrial fibrillation, discrimination algorithm

Supraventricular tachycardias (SVTs) other than AF are common in the general population at an estimated incidence of 73 per 100,000 and prevalence of 140 per 100,000 people.1 Meanwhile, AF is the most common cardiac arrhythmia with a lifetime risk of around one in four in the Western world.2 Ventricular tachycardia (VT) is a life-threatening cardiac arrhythmia and a major cause of sudden cardiac death, the incidence of which is estimated to range from 50 to 100 per 100,000 in the general population.3

ICDs are the mainstay of therapy for ventricular tachyarrhythmias (e.g. VT or VF) and the prevention of sudden cardiac death. However, when shocks are delivered inappropriately (i.e. for rhythm disturbances other than VT or VF) they can be associated with significant morbidity, psychological distress and worse all-cause mortality.4 Although ICD shocks may increase heart failure-related hospitalisations and potentially cause direct myocardial damage, it remains unclear whether the presence of non-lethal SVTs or VTs, which themselves may be related to worsening cardiovascular morbidity and mortality, might explain this association, in part.5 Based on historical data, over a 5-year period, up to 18% of ICD recipients may receive an inappropriate shock while 80% of inappropriate shocks are caused by SVTs such as atrial flutter, sinus tachycardia, atrial tachycardia, atrioventricular re-entrant tachycardia (AVRT), AV nodal re-entrant tachycardia (AVNRT) and AF.6 With contemporary programming of ICDs with delayed high-rate detection and the use of SVT discriminators, the rates of inappropriate shock and therapy can be reduced to around 3–4%.7

Robust discrimination of SVT from VT or VF is therefore critical for optimal functionality of an ICD. This is achieved through the use of various detection algorithms developed by device manufacturers that aim to balance sensitivity (detection of potentially life-threatening VT/VF) with specificity (avoidance of inappropriate therapy). There are also benefits in utilising the diagnostic capabilities offered by the presence of atrial intracardiac electrograms (EGMs) within implanted devices. Device-detected sub-clinical AF or atrial high-rate episodes (AHREs) are characterised by one or more runs of rapid atrial arrhythmia detected by a device without the presence of symptoms or clinical AF detected on routine monitoring with 12-lead ECG or ambulatory monitoring. The presence of AHREs has been associated with worsening heart failure, thromboembolism and more cardiovascular-related hospitalisations.8 There are studies currently underway to evaluate whether the initiation of oral anticoagulation in patients with AHRE can reduce the risk of stroke or cardiovascular death.9,10 In this article, we review the detection algorithms used by the major device manufacturers to classify cardiac rhythm and the discriminators that are used to help reduce inappropriate therapies.

Sensing, Therapy Zones and Detection Windows

The correct classification of cardiac rhythm and application of discrimination algorithms relies on accurate sensing and detection. Sensing refers to the determination of the timing of cardiac depolarisation signals using filters, amplitude thresholds and blanking periods. Detection refers to the interpretation of that signal by the device, which involves classification of a sequence of sensed signals to determine the nature of
the cardiac rhythm. Under-sensing occurs when there is a failure to detect a depolarisation, while over-sensing occurs when signals that are not part of local myocardial depolarisation are classified as such. Blanketing periods can help to prevent over-sensing (e.g. a post-ventricular atrial blanking period [PVAB] that could prevent incorrect classification of AF or atrial tachycardia). Under-sensing, particularly of ventricular depolarisation, may be important in VF, in which the EGM amplitude may be below the sensing threshold, but this is rare in practice.

Modern algorithms for delivery of ICD therapy involve a faster rate threshold and a longer duration of monitoring prior to therapy delivery, in order to prevent inappropriate or unnecessary shocks and allow some arrhythmia episodes to self-terminate. Tiered therapy ICD systems may have up to four VT detection zones that allow for zone-specific duration periods to help prevent over-sensing (e.g. a post-ventricular atrial atrial conduction). Rapid AF with apparent AV dissociation may be confused as VT.

Table 1: Single-chamber and Dual-chamber Discriminators of SVT and VT

| Discriminator                  | Description                                                                 | Disadvantages/Difficult Rhythms                  |
|-------------------------------|-----------------------------------------------------------------------------|--------------------------------------------------|
| **Single-chamber Discriminators** |                                                                             |                                                  |
| Stability                     | Enables discrimination of AF from VT based on R–R interval regularity        | AF with rapid ventricular rates (>170 BPM)       |
|                               |                                                                             | Rapid atrial flutter with regular R–R intervals  |
|                               |                                                                             | VT with irregular R–R intervals                  |
| Onset                         | Sudden changes in ventricular rate are more likely in VT while sinus tachycardia expected to have gradual rate increase | Lack of specificity                              |
| Ventricular EGM Morphology    | Analysis of QRS morphology in tachycardia to reference QRS template Presence of rate-related aberrancy with SVTs in sinus rhythm to identify VT |                                                  |
| **Dual-chamber Discriminators** |                                                                             |                                                  |
| Comparison of atrial versus ventricular rates | If ventricular rate > atrial rate, then VT is diagnosed | Atrial under-sensing or far-field R wave over-sensing is a potential source of error |
| AV association                 | AV dissociation is typically present in VT                                  | Rhythms with 1:1 conduction are not effectively distinguished e.g. AVRT and VT with 1:1 retrograde conduction Rapid AF with apparent AV dissociation may be confused as VT |
| Chamber of onset               | Determines whether a tachycardia initiates in the atrium with a short P–P interval or in the ventricle with a short V–V interval | Single episode of over-sensing could lead to erroneous classification |
| Atrial EGM morphology          | Could help distinguish atrial arrhythmias or identify retrograde conduction  | Far-field R waves could affect correct atrial sensing Changes from the reference atrial EGM morphology will affect correct classification |
| P–R relationship               | A consistent 1:1 P–R relationship may indicate VT                           | VT with 1:1 retrograde conduction AVRT            |

AV = atrioventricular; AVRT = atrioventricular re-entry tachycardia; EGM = electrogram; SVT = supraventricular tachycardia; VT = ventricular tachycardia.

The on-set criterion enables differentiation of VT from sinus tachycardia. VT tends to initiate with a sudden onset while in sinus tachycardia the rate usually increases gradually. A potential caveat is that exercise-induced VT may be preceded by sinus tachycardia and have a gradual onset, which may lead to erroneous classification using the on-set criterion. Analysis of ventricular EGM morphology has also been used to successfully discriminate between SVT and VT. The EGM source used for discrimination can be programmed to different available vectors. For example, the Wavelet morphology discrimination algorithm (Medtronic) can be programmable to one of six available vectors with the right ventricular (RV) coil–can as the nominal and RV tip–RV ring, RV tip–RV coil, superior vena cava (SVC) coil–RV coil, RV ring–can and SVC coil–can as available alternatives. A template is collected to analyse the QRS in sinus rhythm. If the ventricular rate exceeds the programmed detection cut-off, the tachycardia EGM is matched to the template. The morphological similarity of each tachycardia EGM to the sinus EGM is calculated and a resultant percentage match score derived, which is based on the differences of corresponding coefficients of their wavelet transforms. Using this algorithm as a single discriminator, inappropriate therapies for VT were reduced by 78% while the sensitivity for sustained VT was 98.6%.

The MorphMatch algorithm is used in Biotronic ICDs and is based on a beat-to-beat analysis of the QRS peak amplitude, QRS area and four major QRS deflections. QRS morphology is analysed in a 250-ms window.
around the peak of the QRS in the far-field EGM and the relative difference to a reference QRS is calculated for each beat. The reference QRS is continuously updated with normal beats and the mean variability of normal beats is calculated. The mean variability with the addition of a safety margin is used to program a threshold that can be used to declare a QRS complex as abnormal if the threshold is exceeded. 13

Boston Scientific ICDs use the vector and timing correlation algorithm, which compares the EGM signals of a stored reference template of normal sinus rhythm to an ongoing arrhythmia. Conduction vector analysis is performed of the far-field shock EGM and the local bipolar rate EGM, and inhibition of therapy occurs if analysis of QRS morphology at eight points in each EGM matches the QRS in sinus rhythm. 15

Contemporary devices manufactured by Abbott use the Far Field MD Morphology discrimination algorithm that applies the far-field vector (e.g. RV tip–can) and near-field vector (e.g. RV tip–RV ring) for alignment and correlation of the far-field QRS complex with the template. The template may be updated every 8 hours. A percentage match score is assigned and a nominal setting usually programmed whereby at least three out of ten QRS complexes have to match the morphology of the template by at least 90%. 20

Both patient-related or algorithm-related factors can lead to inappropriate detection of VT using the morphology criterion, with under-detection reported in up to 2% of VTs. 13 Algorithm-related factors that may prevent the accurate detection of VT using the morphology criterion include misalignment of the sinus template EGM with the tachycardia EGM, shock-induced EGM changes, signal clipping caused by incorrect signal filtering leading to EGM truncation, or EGM distortions caused by myopotentials. 15

A rate-related bundle branch block during SVT is an example of a patient-related factor that could inhibit the performance of the morphology criterion for accurate detection. Errors due to alignment or truncation issues could be prevented through programming steps including appropriate EGM source selection and gain adjustment. Morphology discrimination is also not applied during re-detection after a shock, in order to prevent misclassification. 15

**Dual-chamber Discriminators**

The addition of an atrial lead can increase the accuracy of rhythm identification given that additional parameters can be used in detection algorithms. These are also further summarised in Table 1. Broadly speaking, comparison of atrial and ventricular rates is a powerful discriminator because VT is expected if the ventricular rate exceeds the atrial rate (Figure 2). The AV association can also be used to distinguish VT from SVT given that VT is expected if AV dissociation occurs. However, this criterion does not distinguish between SVT and VT with 1:1 ventriculo-atrial (VA) conduction. In these settings, a chamber of onset criterion can be applied in which atrial tachycardia would be expected to be initiated with a short P–P interval while VT may initiate with a short R–R interval. This discriminator, however, is therefore prone to error if there is a single episode of under- or over-sensing. The single-chamber discriminators (that is, stability, onset, morphology) can also be used in conjunction, as part of the dual-chamber device detection algorithms, to ensure robust rhythm identification. 21

Medtronic devices use a hierarchical, rule-based algorithm (PR Logic<sup>TM</sup>) based on atrial and ventricular rate and regularity, P–R pattern and their associations. Pairs of R–R intervals and their associated P waves are used to determine ‘couple codes’ whereby the number and timing of P waves is associated with a letter of the PR Logic alphabet. Different sequences of couple codes are associated with the various SVTs and VTs. 18 When the algorithm classifies a rhythm as SVT, the device will withhold detection and therapy. Boston Scientific dual-chamber devices use the Rhythm ID<sup>™</sup> classification algorithm, which uses the comparison of atrial and ventricular rates in addition to the vector and timing correlation algorithm described earlier. 19

Biotronik uses the SMART<sup>™</sup> algorithm for dual-chamber detection. The first criterion is to determine whether the atrial and ventricular rate are different from each other, followed by calculation of stability on a beat-by-beat basis. The sudden onset criterion can then be applied to discriminate VT from slow-onset sinus tachycardia. Additional parameters for the algorithm include AV trend, whereby the strict order of AV intervals to identify consistent trends towards AV shortening or AV prolongation can be used to characterise AV dissociation. AV regularity and AV multiplicity (e.g. if the mean ventricular interval is a multiple of the mean atrial interval) can help establish whether atrial flutter (with 2:1, 3:1 conduction etc.) is present. 18

Abbott dual-chamber devices uses a rate branch algorithm together with other discriminators such as chamber onset, AV association, AV interval delta, stability and morphology match to classify a rhythm as SVT or VT. Rate branch compares the mean atrial and ventricular intervals to identify any differences, and if no difference is found then sinus rhythm is
Propensity-score matched analysis of registry data in primary prevention ICD recipients has also suggested that dual-chamber devices have a lower rate of inappropriate shock compared with single-chamber devices. In that analysis, independent predictors of inappropriate shock included a history of AF, chronic kidney disease and non-ischaemic cardiomyopathy, while PR Logic was the only discriminator that was included a history of AF, chronic kidney disease and non-ischaemic cardiomyopathy, while PR Logic was the only discriminator that was included.

There is some evidence that the addition of an atrial lead may have long-term benefits. The Dual Chamber and Atrial Tachyarrhythmias Adverse Events Study (DATAS) randomised patients with a conventional single-chamber ICD indication to a single-chamber ICD, dual-chamber ICD or a dual-chamber ICD programmed as a single-chamber ICD. The primary endpoint was a composite of all-cause mortality, invasive intervention, cardiovascular-related hospitalisation, inappropriate shock and sustained symptomatic AT lasting >48 hours. The primary endpoint was significantly lower in the dual-chamber ICD group (OR 0.31; 95% CI [0.14–0.67]; p=0.0028). There was also a reduced mortality in the dual-chamber ICD group. In patients with a dual-chamber ICD, improved rhythm interpretation could be facilitated at follow-up with the presence of an atrial lead, although a proportion of patients may require atrial pacing at a later date, which would necessitate a second procedure if only a single-chamber ICD had been implanted at the index procedure.

The performance of S-ICDs systems has previously been evaluated in the Subcutaneous versus Transvenous Arrhythmia Recognition Testing (START) study, in which arrhythmias were induced in patients with both S-ICDs and transvenous ICDs and the sensitivity and specificity of SVT–VT discriminators evaluated. Both ICD systems reported excellent detection of VT/VF episodes, while the S-ICD had improved specificity in the accurate classification of SVTs. This may have been due to the use of a far-field EGM source for the S-ICD, which provides greater information on global cardiac activation, as well as to the increased number of analysis points for each ventricular complex in the S-ICD (i.e. a higher resolution analysis of the signal). New discrimination algorithms to reduce T wave over-sensing have also been implemented to reduce inappropriate shock using a correlation of existing complexes to previous complexes. Recently, the multi-centre PRAETORIAN trial reported that in patients without a pacing indication, an S-ICD was non-inferior to the transvenous ICD with respect to device-related complications and inappropriate shock, with no difference in appropriate shock between the two arms.

**Challenging Arrhythmias**

Tachycardias that have a stable 1:1 AV relationship (e.g. AVNRT or VT with 1:1 retrograde conduction) may be difficult to discriminate using the stability and AV association criteria. In these circumstances, the chamber of onset criterion may be able to distinguish VT from an atrial tachycardia with rapid onset. Morphology may also be used for discrimination. AVNRTs typically have a 1:1 AV relationship with almost simultaneous atrial and ventricular depolarisation, with a VA interval <70 ms. The onset may be spontaneous and triggered by a premature atrial contraction and there may be a good match to the reference ORS morphology. AVNRT is a frequent cause of inappropriate ICD therapy given that the arrhythmia often conducts rapidly (>200 BPM), falling into the programmed VT or VF zones. Atrial activation may also occur in the PVAB period, which may lead to under-sensing of the atrial EGM and lead to incorrect classification of the rhythm as VT (given that tachycardia is classified as ventricular rate > atrial rate and therefore therapy will be delivered).
The response of the tachycardia to unsuccessful ATP can also be helpful in the differential diagnosis. An atrial tachycardia may terminate with ATP if the atrial rate is accelerated and resets the tachycardia circuit, while ventricular overdrive pacing may also terminate AVNRT. This response is not helpful in differentiation because VT may also terminate with overdrive pacing. However, if the tachycardia is entrained during ATP, the post-pacing response can help elucidate the mechanism, for example, in the case of a tachycardia with a 1:1 AV relationship that has not been successfully terminated by ATP and instead the atrial rate has been accelerated. Similar to a diagnostic electrophysiology study, an A-V response following cessation of pacing would rule in an atrial tachycardia, while a V-V-A response would be diagnostic of VT. A short post-pacing interval minus tachycardia cycle length (PPI – TCL < 30 ms) during ventricular overdrive pacing would also favour VT or an AVN over AVNRT, given that this suggests the ICD lead is in close proximity to the circuit. Occasionally, VA block may be seen during ATP, without termination of the tachycardia, which would favour VT. However, this response does not definitively exclude AVNRT with retrograde block.

The differentiation between AF and VF is usually made using the stability, AV association and morphology criteria. However, misclassification can occur if AF is particularly rapid and there is normalisation of the R–R intervals or if aberrancy with bundle branch block is present, which may make these discriminators uncertain. Inappropriate shock for AF or atrial flutter can be associated with an increased overall risk of mortality, particularly in younger patients (Figure 3).

Despite the use of ICDs in the primary and secondary prevention of sudden cardiac death, all-cause mortality remains high in ICD recipients over the medium to long term. In a large retrospective analysis of cause of death in >2,700 ICD recipients, congestive cardiac failure accounted for 30% of all deaths while sudden death occurred in 20% over a mean follow-up of 5.4 years. Based on available post-mortem investigations, >50% of sudden deaths in this cohort occurred due to ventricular arhythmias despite the presence of an ICD, which may have been due to inadequate recovery of myocardial output due to the underlying cardiovascular pathology, an acute myocardial ischaemic event or the presence of electromechanical dissociation.

Conclusion

There are a number of single-chamber and dual-chamber discriminators that can help distinguish SVT from VT and ensure that ICD therapies are applied appropriately. These discriminators are integrated into different algorithms that are used by the various device manufacturers. The performance of these discriminators is reliant on accurate atrial and ventricular sensing. In patients without a pacing indication, an S-ICD may be an option and has shown similar rates of device-related complications and inappropriate shock as a transvenous ICD, while avoiding the complications related to lead insertion and long-term lead-related complications. Despite these capabilities, the presence of SVTs remains a leading cause of inappropriate therapy in ICD recipients.

Clinical Perspective

- The majority of inappropriate shocks in patients with an ICD are caused by supraventricular tachycardias such as AF, atrial flutter, atrial tachycardia, atrioventricular (AV) re-entry tachycardia and AV nodal re-entry tachycardia (AVNRT).
- Modern pacing and defibrillator systems have a number of algorithms to enable reliable discrimination of supraventricular tachycardia from ventricular tachycardia, in order to limit therapies to those rhythms that definitively require them.
- It can be challenging to discriminate between tachycardias with a stable 1:1 AV relationship, for example ventricular tachycardia with 1:1 retrograde conduction or rapid AVNRT with a cycle length <300 ms, the latter of which may be a frequent cause for inappropriate ICD therapy.
23. Briongos-Figuero S, Sanchez A, Perez ML, et al. Single-brand dual-chamber discriminators to prevent inappropriate shocks in patients implanted with prophylactic implantable cardioverter defibrillators: a propensity-weighted comparison of single and dual-chamber devices. J Interv Card Electrophysiol 2019;54:267–75. https://doi.org/10.1007/s10840-018-0494-0; PMID: 30523511.

24. Friedman PA, Bradley D, Koester C, et al. A prospective randomized trial of single or dual-chamber implantable cardioverter-defibrillators to minimize inappropriate shock risk in primary sudden cardiac death prevention. Europace 2019;16:560–68. https://doi.org/10.1093/europace/euu022; PMID: 24928948.

25. Brisben A. How the S-ICD (subcutaneous implantable cardiac defibrillator) senses cardiac signals to minimize cardiac over-sensing and maximize rhythm discrimination. J Electrocardiol 2018;51:S38–S43. https://doi.org/10.1016/j.jelectrocard.2018.08.022; PMID: 30220546.

26. Gold MR, Theuns DA, Knight BP, et al. Head-to-head comparison of arrhythmia discrimination performance of subcutaneous and transvenous ICD arrhythmia detection algorithms: the START study. J Cardiovasc Electrophysiol 2012;23:359–66. https://doi.org/10.1111/j.1540-8167.2011.02999.x; PMID: 22035048.

27. Briongos AJ, Burke MC, Knight BP, et al. A new algorithm to reduce inappropriate therapy in the S-ICD system. J Cardiovasc Electrophysiol 2015;26:417–23. https://doi.org/10.1111/jce.12512; PMID: 25581903.

28. Enriquez A, Ellenbogen KA, Boies U, Baranchuk A. Atrioventricular nodal re-entrant tachycardia in implantable cardioverter-defibrillators: diagnosis and troubleshooting. J Cardiovasc Electrophysiol 2015;26:382–8. https://doi.org/10.1111/jce.12772; PMID: 26249214.

29. Knops RE, Østø Nordkamp UÅ, Delnoy PPHM, et al. Subcutaneous or transvenous defibrillator therapy. N Engl J Med 2020;383:526–36. https://doi.org/10.1056/NEJMoa1915932; PMID: 32707521.

30. Bennett MT, Leader N, Sapp J, et al. Differentiating ventricular from supraventricular arrhythmias using the postspacing interval after failed antitachycardia pacing. Circ Arrhythm Electrophysiol 2018;11:e005921. https://doi.org/10.1161/CIRCEP.117.005921; PMID: 29616476.

31. Arenal A, Otte M, Penado R, et al. Differentiation of ventricular and supraventricular tachycardias based on the analysis of the first postspacing interval after sequential antitachycardia pacing in implantable cardioverter-defibrillator patients. Heart Rhythm 2017;4:296–302. https://doi.org/10.1016/j.hrthm.2016.11.032; PMID: 27441396.

32. Chang PM, Powell BD, Jones PK, et al. Implantable cardioverter defibrillator programming characteristics, shocked rhythms and survival among patients under thirty years of age. J Cardiovasc Electrophysiol 2016;27:1183–90. https://doi.org/10.1111/jce.13038; PMID: 27334356.

33. Nagele H, Groene E, Sterle D, Nagele MP. Analysis of causes of death in patients with implanted defibrillators. Clin Res Cardiol 2021;110:895–904. https://doi.org/10.1007/s00392-021-01825-y; PMID: 33687520.