2
Rhythm Classification by Arrhythmia Management Devices

Summary
A reliable ICD needs both sensing of the endocardial signal and detection algorithms for arrhythmia diagnosis. Initially, the only target was ventricular fibrillation, but with the possibility of rate detection ventricular tachycardia could be detected as well. This led to the development of tiered-therapy devices with arrhythmia zones. Simple arrhythmia discriminators as stability and sudden onset became available, and proved to be very useful. The place of more complex algorithms is still unclear.

The ability of an ICD to reliably detect life-threatening ventricular arrhythmias is one of the most essential features of a device. It involves both sensing of the endocardial signal and the application of detection algorithms for arrhythmia diagnosis [1, 2]. The ICD must consistently sense all ventricular depolarizations to accurately determine the heart rate during sinus rhythm and tachyarrhythmias (Figure 2.1). The challenge is to reliably sense low amplitude signals during ventricular fibrillation and to avoid sensing of T waves or extracardiac signals (Figure 2.2).

Actually, two different endocardiac lead designs for sensing, either dedicated bipolar or integrated bipolar, are used. Bipolar epicardiac signals are only exceptionally necessary (pediatric patients, congenital heart disease) and pose specific problems (Figure 2.3). Sensing with a dedicated endocardiac bipolar system is accomplished between the tip electrode and a second ring electrode, approximately 10 mm from the tip. With the integrated bipolar configuration, sensing is accomplished between the tip electrode and the right ventricular shocking coil. Both dedicated and integrated bipolar lead sensing concepts are effective for sensing low amplitude signals during ventricular fibrillation.

Other sensing configurations have been used in different conditions or for specific devices, as a unipolar lead with a patch, or a can. Sensing of the left ventricular signal is now introduced for biventricular approaches (resynchronization).
2. Rhythm Classification

**Figure 2.1.** Different levels of sensitivity result in recognition (black vertical bars) of only the normal complexes (low sensitivity); recognition of normal complexes and ventricular premature beats (normal sensitivity); recognition of normal complexes, ventricular premature beats, and ventricular fibrillation (high sensitivity). The drawback in the last situation is that T-waves are sensed as well (grey bars).

**Figure 2.2.** Current ICDs utilize either automatic gain control or auto-adjusting threshold to ensure reliable sensing. In automatic gain control, the sensing threshold is fixed while continuous adjustment of the gain is performed to ensure maximum sensing. With this method, the gain is increased when the amplitudes of the R wave decrease from large to small. In auto-adjusting threshold, the gain is fixed and the threshold is adjusted. Auto-adjusting threshold uses a constant amplification of the amplitude of the R wave, which becomes the starting amplitude of the time-decay threshold. The figure shows how the ventricular arrhythmia is correctly recognised because the threshold (dotted line) is adjusted after the QRS complexes, while the T-wave is not sensed.

**Verification of Signals During Implantation**

The lead electrogram and markers should be checked during implantation for evidence of correct sensing. Loose connections and oversensing of intracardiac or extracardiac signals should be recognized in this stage (Figure 2.4). If the patient had a previously implanted or abandoned ventricular lead in place, it is important to check for mechanical lead ‘chatter’ that can generate signals mimicking ventricular tachyarrhythmias. If lead ‘chatter’ is observed on the electrograms, a reposition of the lead is necessary. It seems wise to remove redundant leads. Connectors and adaptors are predisposed to additional noise, and should be avoided.
Early Devices: Detection of Ventricular Fibrillation

The original detection algorithm in the automatic implantable defibrillator (AID™) was the probability density function (PDF), conceived to detect sinusoidal rhythms (Intec Systems) [3]. The PDF processed the electrical signal to define the proportion of the cardiac cycle that this signal was deviating from the baseline (Figure 2.5).

The algorithm was based on the observation that the signal during ventricular fibrillation spends the majority of its time away from the isoelectric...
baseline as compared to the signal during sinus rhythm. CPI shortly proposed a so-called ‘turning point morphology’ criterion (TPM), derived from the electrogram recorded between the shock leads. The principle was that electrograms with a certain percentage of isoelectric time and a high slew rate would not satisfy the TPM criteria. It was felt that these morphology criteria postponed intervention [4].

**Rate-only Detection**

The basic goal of the ICD is to detect and subsequently terminate life-threatening ventricular tachyarrhythmias. The most fundamental criterion for the detection of ventricular tachyarrhythmias is based on rate. This is measured by assessing the duration of the cardiac cycle length (time divided by rate) on a beat-to-beat basis. Each detected ventricular interval is compared with the programmed detection zones. This basic detection algorithm measures and counts ventricular intervals to detect a tachyarrhythmia if it fulfils the criteria of ventricular rate over a certain, predefined duration. With correct sensing, this method ensures 100% sensitivity of ventricular tachyarrhythmias with rates above the programmed detection rate. However, rate-only detection has a poor specificity in arrhythmia discrimination. The reported incidence of inappropriate therapy ranged between 16 and 41% [5–8]. This incidence may have been underestimated due to the lack of electrogram storage. The definition of ‘appropriate’ therapy relied on concomitant ECG monitoring. The fact that atrial tachyarrhythmias contributed to the incidence of inappropriate therapy was established.

With tiered-therapy devices (providing antitachycardia pacing for slower tachycardias), the inappropriate detection of atrial tachyarrhythmias became a greater problem [9]. This is due to the increased probability of rate overlap between the target ventricular tachyarrhythmias and atrial tachyarrhythmias, as lower detection zones can be programmed.
Detection Zones

In modern ICDs, the range of ventricular rates is divided into a bradyarrhythmia, a normal, and up to three tachyarrhythmia detection zones (Figure 2.6). In all ICDs, the highest detection zone is called the ‘fibrillation’ zone. In order for a tachyarrhythmia to be detected and assigned to a given detection zone, it must exhibit a certain number of intervals (duration). For this duration criterion different methods of counting are used (consecutive interval counting, probabilistic counting, or a combination of these).

Probabilistic counting algorithms are used for the detection of ventricular fibrillation. This algorithm requires a defined proportion of ventricular intervals within a sliding window to be shorter than the programmed detection interval for fibrillation (X of Y counter). This method reduces the chance of underdetection of ventricular fibrillation due to the irregularity of ventricular intervals and the continuously changing amplitude of the signal. In Medtronic ICDs, for example, 75% of consecutive intervals must be within the fibrillation detection zone. In the Guidant algorithm, a fixed window width of 10 intervals is used. Initially, 8 of 10 intervals are required within the fibrillation detection zone for rate detection to be met, and at least 6 of 10 intervals must remain in the detection zone for a programmed detection time.

The counting algorithm for ventricular tachycardia may be either probabilistic or consecutive in design. The consecutive-interval algorithm diminishes the risk of inappropriate therapy for atrial fibrillation, without compromising the sensitivity for detection of ventricular tachycardias. In consecutive-interval algorithms, the counter increments every time when an interval is measured within the detection zone. An interval outside the detection zone will reset the counter to zero. For patients with both slow and fast ventricular tachycardias, the programming of two tachycardia detection zones allow zone-specific detection and therapies. The programming of slow tachycardia detection zones increases the risk of inappropriate therapies for atrial tachyarrhythmias [9, 10].

![Detection and therapy zones. The detection and assignment of ventricular tachyarrhythmias into a specific zone is dependent on the programming of the range of ventricular rates into non-overlapping zones. Abbreviations: FDI = fibrillation detection interval; FTI = fast tachycardia interval; TDI = tachycardia detection interval; Tach A, VT, or VT-1 = slower tachycardia limit; Tach B, VT-1, or VT-2 = faster tachycardia limit.](image)
Interval-based Discriminators

One of the most important limitations of ICD detection is inappropriate therapy delivered for atrial tachyarrhythmias. Interval-based discriminators as ‘sudden onset’ and ‘stability’ were developed to improve the specificity of arrhythmia discrimination [11–13].

The discriminator ‘sudden onset’ aims at distinguishing sinus tachycardia (gradual onset) from VT (abrupt onset) (Figure 2.7). Sudden onset has a high specificity for rejecting sinus tachycardia [11, 13]. Despite this high specificity, this discriminator may cause underdetection of VT originating during atrial tachyarrhythmias and VT starting with a rate below the programmed detection rate [11]. The risk for underdetection of VT is increased with higher programmed values for ‘sudden onset’ [13].

The discriminator ‘stability’, or rate regularity, uses an interval variability threshold to differentiate VT characterized by stable intervals from atrial fibrillation with irregular ventricular response. Stability has proven to be reliable in the rejection of atrial fibrillation with a mean ventricular rate \(<170\) min\(^{-1}\) [12, 14]. However, the performance of ‘stability’ is dependent on the rate of the ventricular response, as the degree of interval variability decreases at faster rates [14]. The reported incidence of inappropriate therapy ranged between 6 and 21% on a per-patient basis [15–17].

Figure 2.7. Panel A, interval plot showing a tachyarrhythmia with a gradual onset. Panel B, interval plot showing a tachyarrhythmia with a sudden onset. (Medtronic, model GEM 7271 DR). □ A-A: AA intervals; • V-V: VV intervals; FVT = fast ventricular tachycardia; VF = ventricular fibrillation; VT = ventricular tachycardia.
Initially, both discriminators have been used infrequently because physicians were concerned about underdetection of VTs. Serious underdetection was observed in only a minor proportion of the episodes.

The addition of a safety timer (duration) may prevent underdetection of VT. If a tachyarrhythmia satisfies the ventricular rate criterion and the discriminators indicate SVT, the safety timer will override the discriminators and therapy will be delivered. However, this feature ensured 100% sensitivity for VT but at the price of decreased specificity for rejection of SVT [18].

In a case control study, the interval-based discriminators ‘sudden onset’ and ‘stability’ reduce inappropriate therapies due to atrial fibrillation and sinus tachycardia [17]. The major limitation of ‘sudden onset’ and ‘stability’ is the inefficiency to reject sudden onset atrial tachyarrhythmias with a consistent atrioventricular (AV) relation, e.g. atrial tachycardia or atrial flutter. Complex algorithms with the addition of atrial information might improve the specificity of arrhythmia discrimination.

**Dual-chamber Discrimination**

An early plea for the addition of atrial sensing to improve arrhythmia discrimination was proposed by Furman as early as in 1982 [19]. The comparison between atrial and ventricular rates is a simple and effective arrhythmia discriminator. In the majority of VTs, the ventricular rate is faster than the atrial rate. Limitations of this simple criterion are the underdetection of VTs with 1:1 VA conduction and ventricular tachyarrhythmias during atrial fibrillation. To address this limitation, the analysis of the AV relationship was postulated as a feature of interest to discriminate sinus tachycardia from VT [20]. Measurement of the AV relationship provides a reliable diagnostic tool for AV association. Further, timing relationships between atrial and ventricular electrograms can be used to identify atrial tachyarrhythmias with stable AV conduction.

All dual-chamber algorithms comprise both single- and dual-chamber discriminators (Table 2.1). Dual-chamber discrimination algorithms include comparison of atrial and ventricular rates and/or measures of the AV relationship. The algorithms in dual-chamber devices can be roughly divided into two groups: (1) Comparison of atrial and ventricular rates (rate branches) and (2) Hierarchical analysis of the atrioventricular relationship.

**Dual-chamber Algorithms Based on Analysis of the Atrioventricular Relationship**

A hierarchical structure of single- and dual-chamber arrhythmia discriminators is applied in the algorithms PARAD, PARAD+ (ELA Medical), and PR Logic (Medtronic). The PARAD algorithm (P And R Based
Arrhythmia Detection) first analyses the stability of the rhythm, then atrioventricular association, onset, and finally the chamber of origin (Figure 2.8) [21]. The chamber of origin is used to discriminate between ventricular tachyarrhythmias and atrial tachyarrhythmias with 1:1 AV relation by identification of atrial activity preceding ventricular activity or vice versa. In PARAD+, the additional criterion ‘long cycle search’ can be activated to inhibit therapy for atrial fibrillation with fast ventricular response.

The PR Logic algorithm (Figure 2.9) is based on the timing relationship of atrial activity with respect to ventricular activity. For atrioventricular relationship analysis, each RR interval is divided into four zones. Arrhythmia classification is based on PP and RR findings. An episode receives a code, which is compared with templates in a library of arrhythmias. PP intervals and

**Table 2.1. Arrhythmia discrimination components in dual-chamber algorithms.**

<table>
<thead>
<tr>
<th></th>
<th>Biotronik</th>
<th>ELA Medical</th>
<th>Guidant</th>
<th>Medtronic</th>
<th>St. Jude Medical</th>
</tr>
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<tbody>
<tr>
<td>Single-chamber detection</td>
<td></td>
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<tr>
<td>Stability</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<td>Sudden onset</td>
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<td>+</td>
<td>+</td>
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<tr>
<td>Sustained duration</td>
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<td></td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dual-chamber detection</td>
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<td></td>
</tr>
<tr>
<td>Atrial vs ventricular rates</td>
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<td></td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AV association</td>
<td>+</td>
<td></td>
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<td>+</td>
<td></td>
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<tr>
<td>Timing relationship</td>
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<td></td>
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<tr>
<td>Chamber of origin</td>
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</table>

**AV = atrioventricular**
AV relation are used for identification of atrial tachyarrhythmias. Stability of RR intervals and AV dissociation are used to identify ventricular arrhythmias when atrial fibrillation is present [22].

In both algorithms therapy is delivered unless a discriminator identifies an atrial tachyarrhythmia.

**Dual-chamber Algorithms Based on Rate Branches**

Comparison of atrial and ventricular rates is applied in several algorithms. The dual-chamber algorithms in Biotronik (Figure 2.10) and St. Jude Medical initially divide tachyarrhythmias into three rate branches: ventricular rate > atrial rate, ventricular rate < atrial rate, and ventricular rate = atrial rate. In the latter two branches, applicable single- and dual-chamber arrhythmia discriminators are applied to classify the arrhythmia [23]. In case of the ventricular rate = atrial rate branch, the onset criterion and analysis of the
atrioventricular relationship are applied. The association or dissociation of the rhythms is monitored based on the stability criterion. If the ventricular rhythm is stable and the atrial rhythm is unstable, the tachyarrhythmia will be classified as ventricular. If both rhythms are stable, the stability of the atrioventricular relationship is analysed to exclude atrioventricular dissociation. In Guidant dual-chamber devices (Figure 2.11), priority is given to the single-chamber detection criteria onset and stability. An aggressive programming of single-chamber detection criteria in these devices will decrease the sensitivity but increase the specificity of arrhythmia discrimination. The dual-chamber detection criterion ‘ventricular rate > atrial rate’ can be applied to prevent underdetection of ventricular arrhythmias. The ‘Afib threshold’ criterion cannot prevent inappropriate arrhythmia classification as priority is given to the stability criterion.

Performance of Dual-chamber Algorithms

The majority of studies conducted with dual-chamber ICDs were restricted to one manufacturer [21–24]. These studies mainly focused on the feasibility and safety of dual-chamber devices, and provided data for improved specificity of arrhythmia detection without compromising the sensitivity for ventricular tachyarrhythmias. The specificity ranged between 66.7 and 93.3% with positive predictive values for ventricular tachyarrhythmias between 87.4 and 98.4%. These data support an actual benefit of dual-chamber devices over single-chamber devices.
Randomized studies comparing single-chamber and dual-chamber ICDs have been performed [25–29]. However, conclusive evidence of the superiority of dual-chamber over single-chamber discrimination has not been proven [30]. The functionality of dual-chamber algorithms is influenced by the accurate determination of the atrial rate [31]. The presence of atrial sensing errors and atrial blanking can result in either misclassification of ventricular arrhythmia as atrial arrhythmia or inappropriate rejection of ventricular arrhythmias.

The Atrioverter: Detection of Atrial Tachyarrhythmias

The philosophy of the atrioverter was different from a conventional ICD [32]. While ICDs had to recognize all ventricular tachyarrhythmias and were prompted to shock when in doubt, the atrioverter was allowed to wait until atrial fibrillation was diagnosed with absolute certainty. A specific device for atrial fibrillation, the Metrix atrioverter system (Incontrol Inc., Redmond, WA, USA), was developed with a two-step detection algorithm. The first algorithm discriminated between a sinus and a non-sinus rhythm, based upon the presence or absence of a ‘quiet interval’. The second algorithm, the baseline crossing test (Figure 2.12), was performed on the electrogram obtained between the right atrial electrode and the coronary sinus lead (Figure 2.13). The result of both algorithms was a high sensitivity (100%) for the detection of non-sinus rhythm with a specificity of 96% for atrial fibrillation.

The standalone atrial defibrillator was safe, but required the implantation of a ventricular sensing lead. Mainly under influence of the industry, a dual-chamber device was developed that provided detection and treatment for atrial fibrillation, atrial tachycardia, and ventricular tachyarrhythmias [33].

In the majority of these devices, the detection of atrial arrhythmias is mainly based on rate (with sometimes overlapping zones for atrial tachycardia, flutter, and fibrillation). Evidently, this is not related to real physiology or pathology. For a more accurate classification of atrial tachyarrhythmias, another advanced atrial detection algorithm was developed [34]. This algorithm uses the maximum atrial rate, the standard deviation, and the dispersion of atrial rate to classify unstable and stable atrial arrhythmias.

![Figure 2.12. Atrial fibrillation, as the number of baseline crossings is high.](image)
Some morphology-based algorithms existed in early devices (PDF, Intec and TPM, CPI) as mentioned earlier on. They were never widely used in this era. Medtronic based an algorithm on width of the intracardiac EGM and the slew rate. The ventricular EGM is then classified as narrow or wide by comparing the measured actual width to the programmed value for width threshold value (Figure 2.14). The optimal EGM source for measurements of the EGM width is a far-field configuration between can and coil. The efficacy of the EGM width criterion has been studied by several investigators (Table 2.2). The reported overall sensitivity for detection of ventricular tachycardia was 64.1% [35]. When the data was corrected for stable QRS-complexes in the 12-lead electrocardiogram, the sensitivity was higher on a per-episode basis than on a per-patient basis [35].

The EGM width criterion has several limitations. The criterion cannot be applied in patients with a pre-existing complete bundle branch, which results in underdetection of ventricular tachycardias. Rate-related changes of the electrogram width may result in false-positive detections of ventricular tachycardia. The EGM width is also affected by additional antiarrhythmic drug treatment (class Ic drugs and amiodarone).

Recently, arrhythmia discrimination in the ICD included more advanced morphology algorithms. These algorithms are based on more complex
comparisons of electrograms. The ‘morphology discrimination’ algorithm constructs a quantitative representation of each ventricular complex [36]. This representation is determined by the peak amplitudes, polarities, number of peaks, and the order of peaks. Each ventricular complex during tachycardia is compared to a stored template during the patients’ baseline rhythm. The other morphology-based algorithms are the ‘vector timing and correlation’ algorithm and the ‘wavelet transform’ algorithm, which are both under clinical investigation [37, 38].

**Table 2.2.** Efficacy of the EGM width criterion.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Year</th>
<th>Sensitivity %</th>
<th>Specificity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gillberg <em>et al.</em></td>
<td>1994</td>
<td>100</td>
<td>–</td>
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<td>Brachmann <em>et al.</em></td>
<td>1996</td>
<td>96</td>
<td>76</td>
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<tr>
<td>Duru <em>et al.</em></td>
<td>1999</td>
<td>–</td>
<td>74</td>
</tr>
<tr>
<td>Spehl <em>et al.</em></td>
<td>1999</td>
<td>100</td>
<td>66</td>
</tr>
<tr>
<td>Unterberg <em>et al.</em></td>
<td>2000</td>
<td>96.7</td>
<td>98.6</td>
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</table>

**Figure 2.14.** Ventricular tachycardia with bipolar ventricular electrogram and marker channel. The QRS complexes are similar to the template which is shown in the lower part. Three out of eight complexes preceding the ATP episode are coded as ‘Wide’. The criterion was only ‘passive’ in this case, as detection occurred because of the high rate.
2. Rhythm Classification

References


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