Introduction

Since the first implantation of an implantable cardioverter defibrillator (ICD) 1980 by Mirowski et al. [1], significant development of hardware and software has taken place in ICD therapy. Initially, devices were implanted abdominally, using epicardial patch electrodes for adequate defibrillation. Currently, dual-chamber systems with significantly reduced device size provide concomitant atrial therapies, rate adaptation, and are implanted conventionally, as a pacemaker is. Even additional electrodes inserted in left ventricular veins via the coronary sinus for biventricular stimulation are now available, and can be integrated into these complex systems.

Arrhythmia Detection

One relevant clinical problem remaining in ICD therapy is the frequency of inappropriate therapies due to non-malignant tachyarrhythmias. Because inappropriate shocks have a significant negative impact on quality of life, and a potential proarrhythmic effect, sinus tachycardias, atrial flutter, and atrial fibrillation (AF) must be distinguished from malignant ventricular tachyarrhythmias. As the predominant cause for inappropriate ventricular therapies, AF hemodynamically compromises patients with heart failure and severely depressed left ventricular function, and constitutes a significant risk factor for the development of thromboembolism. The improvement of the initial simple algorithms to the more sophisticated ones used today is presented below.

Single-chamber Implantable Cardioverter Defibrillators

In current ICDs, at least two or more zones for the detection of tachyarrhythmias can be programmed. In the ventricular fibrillation (VF) zone, due to the risk of hemodynamic deterioration, immediate detection and a sensitivity of 100% is essential. A simple algorithm that counts a programmable ratio of RR intervals in the detection zone (x out of y type of criterion; e.g., 12 intervals out of 16 in the VF zone) decides between therapy delivery or inhibition. Application of this single algorithm on additional detection zones, i.e., for slower ventricular tachycardias (VT), leads to a high number of inappropriate therapies. The possibility of programming slower detection zones (e.g., between 100 and 220 beats/min) leads to a significant overlap with sinus tachycardias, AF, and atrial flutter. For a better discrimination to prevent inappropriate therapies, additional algorithms that are only active in this VT zone have been introduced. The initial algorithms were the onset and stability criteria. The first identifies sudden changes in the cycle length of the ongoing rhythm. An abrupt reduction of the cycle length above the programmed onset value is interpreted as initiation of a VT. Sinus tachycardias, which enter the VT zone gradually, are therefore excluded from therapy by the onset criterion. Systematic analysis shows that an onset of 9% to 12% of the preceding cycle length reduces inadequate therapies for sinus tachycardias. This algorithm is not effective in the case of AF or atrial flutter, which characteristically present with a variability of beat to beat cycle lengths. Detection of this variability of the RR inter-
vals is implemented in the stability criterion. Variations of consecutive tachycardia cycle lengths must vary above a programmed value (eg, 40 msec) to be identified as supraventricular origin, and to withhold therapy delivery. This algorithm primarily addresses AF and atrial flutter with intermittent varying atrioventricular conduction. Both algorithms show ineffective classifications, for example, in VTs developed during exercise or emotional or mental stress, with an elevated sinus rate preceding the beginning of the VT (onset criterion, approximately 5%–13% of VTs) [2–4]. Potential reasons for misdiagnosis by the stability criterion are supraventricular arrhythmias, which present with a stable conduction to the ventricles, thus imitating a ventricular origin.

The relevant number of inadequate therapies in single-chamber ICDs initiated further development of algorithms. The characteristically broader QRS complexes of tachycardias with ventricular origin are analyzed in the electrogram (EGM) width criterion. Analysis of the intracardiac EGM during sinus rhythm is stored as reference information. Detection of a certain amount of broad classified complexes (eg, six of eight) classifies the tachycardia as wide complex tachycardia, and initiates the programmed therapy in the VT zone (EGM Width Criterion; Medtronic, Minneapolis, MN). Another morphology algorithm stores a template of the small QRS complex during sinus rhythm. The number of polarity changes and amplitudes of QRS complexes, and the area under the curve, are calculated. Each complex in the tachycardia detection zone is compared with the initially stored pattern. If a programmable percent-value of accordance falls short, the VT therapy is delivered (MD Criterion; St. Jude Medical, Sunnyvale, CA) (Fig. 1). With the combined use of the morphology criterion (≥ 60%) with sudden onset and stability, an improved sensitivity (96.7%) in the diagnosis of VT can be maintained. The specificity is only in combination with the onset criterion in the lower range, and was improved in a sub-group analysis for sinus tachycardias and atrial flutter (60.6% and 66.7%) [5]. Potential misdiagnosis analyzing the QRS complex is due to bundle branch block, exercise-induced, or rate-dependent bundle branch block and morphology changes of the QRS complex over time. It may also occur when class I drugs are used.

**Dual-chamber Implantable Cardioverter Defibrillators**

Further improvement in rhythm classification has been made by the incorporation of atrial sensing information in more complex algorithms. Apart from the hemodynamic improvement, made by synchronizing atrial and ventricular contraction in patients with atrioventricular (AV) nodal conduction abnormalities by dual-chamber pacing in ICDs, the sensing information can be used to differentiate between atrial and ventricular origin of the tachycardia. The use of the atrial information must meet the requirements of the signal quality. The atrial sensitivity must be high enough, and stable over time. Under-detection would favor diagnosis of VTs in most algorithms. The detection of other potential signals would be reduced, such as myopotentials (contraction of the upper thorax muscles and diaphragm), or far-field R-wave sensing. Such oversensing could lead to an incorrect classification of atrial tachycardias (ATs), inappropriate treatment if the option of atrial therapies is available, and potential under-detection of VTs [6]. Far-field sensing is either suppressed by algorithms in some devices, or by changing atrial sensitivity or postventricular atrial blanking times (Figs. 2 and 3). The best electrode position to reduce far-field R-wave sensing is at the lateral free wall of the right atrium [7–9]. It should be routinely tested intraoperatively and during follow-up. Oversensing can be diminished by elevating the atrial sensitivity. Apart from loss of AV sequential stimu-