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Original Article

How implantable cardioverter-defibrillators work and simple programming

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Abstract Following the sudden death of a friend in 1966, Dr Michel Mirowski began pioneering work on the first implantable cardioverter-defibrillator. By 1969 he had developed an experimental model and performed the first transvenous defibrillation. In 1970 he reported on the use of a "standby automatic defibrillator" that was tested successfully in dogs. He postulated that such a device "when adapted for clinical use, might be implanted temporarily or permanently in selected patients particularly prone to develop ventricular fibrillation and thus provide them with some degree of protection from sudden coronary death". In 1980 he reported on the first human implants of an "electronic device designed to monitor cardiac electrical activity, to recognise ventricular fibrillation and ventricular tachyarrhythmias … and then to deliver corrective defibrillatory discharges". Through innovations in circuitry, battery, and capacitor technologies, the current implantable cardioverter-defibrillator is 10 times smaller and exponentially more sophisticated than that first iteration. This article will review the inner workings of the implantable cardioverter-defibrillator and outline several features that make it the wonder in technology that it has become.

Keywords: Implantable cardiovertor-defibrillator; ventricular fibrillation; ventricular tachycardia; defibrillation

Dissecting the implantable cardioverter-defibrillator

The four main components of the implantable cardioverter-defibrillator are the connector block, circuitry board, battery, and capacitor. The connector block, or "header", houses up to five DF-1 connectors for the atrial/ventricular/coronary sinus pacing leads, as well as the high-voltage right ventricular and superior caval vein, if present, coils. The number of ports decreases to three, or less, ports in the presence of the newer DF-4 ventricular lead that combines the right ventricular pacing lead and high-voltage coil through a single connector. It also contains the wireless antenna for telemetry as well as the suture sleeve.

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Within the device itself is the circuitry board, which includes microprocessors, ROM and RAM memory, telemetry controls, system management features, the radiofrequency link, pacing and implantable cardioverter-defibrillator timing functions, pacing and sensing amplifiers, high-voltage charging and switching circuit, and rate adaptive sensors. The batteries typically use lithium-silver oxide-vanadium chemistries, which support higher current drains for capacitor charging and high-rate anti-tachycardia pacing. The capacitor is used to store the high energy before delivery.

Sensing

As the myocardium depolarises, its electrical signal is recorded between the tip and ring electrodes – non-integrated – or the tip and high-voltage coil – integrated. This signal's frequency components are combined to create the signal, measured in millivolts, that the

device detects and to which it responds. This signal is measured from its amplitude's peak-to-peak and is monitored continuously. Because ventricular fibrillation waves often have much smaller amplitudes, the baseline R-wave electrogram should be >5 mV for optimal sensing at the time of implant. Moreover, to ensure that ventricular fibrillation is appropriately sensed, the ventricular sensitivity should be temporarily programmed at a higher value (1.2 mV) at the time of defibrillation threshold testing. In dual-chamber devices, it is also important at implantation to ensure adequate P-wave amplitudes, as atrial sensing is one means used to discriminate between supraventricular and ventricular tachydysrhythmias.

Sensing sources: near-field versus far-field sensing

Near-field sensing and far-field sensing are used for electrogram sensing. Near-field sensing occurs when electrodes are in close proximity to one another – e.g. tip-to-ring or tip-to-coil. This type of sensing usually results in a high frequency and relatively brief signal, because there is less myocardium in range; this signal is used for arrhythmia detection.

Far-field sensing occurs between electrodes that are farther apart in range – e.g. active can-to-right ventricular coil (HVA-HVB) or right ventricular coil-to-superior vena cava coil (HVB-HVX). With far-field sensing there is more myocardium between the electrodes, and the signal can mimic a surface electrocardiogram. This can be used to *confirm* the presence of an arrhythmia – e.g. in the presence of noise at the lead tip.

The sensing circuit

Upon detection, the electrogram is processed by the sensing circuit. The presenting electrogram is passed through an amplifier, which increases the amplitude of the signal by as much as 10-fold. It then passes through low- and high-band filters to eliminate non-depolarisation events, such as the T-wave. Finally, the signal is rectified, summing positive and negative components into a single positive electrogram. It is this signal that is presented for sensing based upon the sensitivity setting.

Determining the ventricular rate requires that every QRS complex is sensed, including low-amplitude ventricular fibrillation (VF) electrograms, while always avoiding detection of the subsequent T-wave. To accomplish this, some implantable cardioverter-defibrillator manufacturers use *automatic gain control* during which the sensitivity remains fixed but the gain is progressively amplified after tachycardia onset. Thus, very small electrograms, such as those from VF, are at a higher gain ensuring that they will exceed the fixed sensing threshold. Other manufacturers use auto-adjusting sensitivity during which the gain is fixed, but the threshold for sensing varies from beat to beat to avoid under-sensing VF.[1]

There are manufacturer-specific approaches to sensing. Boston Scientific has "nominal", "most", and "least" sensitivity settings that can be chosen. They also feature "fast" automatic gain control, which rapidly adjusts with each R-wave, and "slow" gain control, which adjusts the overall dynamic range of the gain. Medtronic has similar programmability but has no "slow" gain control. However, Medtronic does permit selection of specific sensitivity settings (nominal is 0.3 mV). St. Jude Medial allows programmable control over dynamic sensing during which the contour of the sensing envelope can be manipulated at multiple levels. This particular feature can be helpful to avoid T-wave over-sensing in patients with long QT syndrome.

Detection

Whereas "sensing" determines the timing of each atrial and ventricular electrogram, "detection" classifies the rhythm on the basis of a set of algorithms to determine whether therapy should be delivered. The detection rate is measured in beat-to-beat intervals or beats per minute. Once the rate is determined, the rhythm is classified by programmable detection zones – e.g. ventricular tachycardia versus ventricular fibrillation. The detection duration is measured in number of intervals to detect or length of time to detect. This is also programmable as consecutive beats or intervals – e.g. 16 beats within a detection zone – or as a percentage – e.g. 12 out of 16 beats within a detection zone.

Supraventricular tachycardia-ventricular tachycardia discriminators

The need for the implantable cardioverter-defibrillator to discriminate supraventricular tachycardia, including sinus tachycardia, from ventricular tachycardia in order to avoid unwanted shocks is well established in the literature. A review of ~1500 patients followed by the Latitude remote monitoring system demonstrated that the majority of shocks that occurred for heart rates between 160 and 190 bpm were for supraventricular tachydysrhythmias – e.g. atrial fibrillation, sinus tachycardia, or supraventricular tachycardia.[2] Thus, manufacturer-specific supraventricular tachycardia-ventricular tachycardia discriminators have been developed for both single-chamber and dual-chamber devices.

Single-chamber implantable cardioverter-defibrillators

Onset. *Onset criteria*[3] are based upon the premise that ventricular tachycardia has an abrupt onset, whereas sinus tachycardia typically warms up.

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Thus, therapy would be inhibited if tachycardia onset is gradual. This criterion has a high sensitivity (98%) for distinguishing between sinus tachycardia and ventricular tachycardia. However, it can misclassify abrupt-onset atrial fibrillation (as ventricular tachycardia), abrupt-onset supraventricular tachycardia (as ventricular tachycardia), exercise-induced ventricular tachycardia following sinus tachycardia (as not ventricular tachycardia), and ventricular ectopy that precedes ventricular tachycardia (as not ventricular tachycardia). Once onset criterion is applied, there is no superceding correction.

Stability. *Stability criteria*[2] seek to inhibit therapy if the ventricular rate is variable. This is based on the reasoning that ventricular tachycardia has stable R-R intervals whereas atrial fibrillation has irregular R-R intervals. Using this criterion and rates <170 bpm, there is a high sensitivity for discriminating ventricular tachycardia from atrial fibrillation. However, *stability* can misclassify stable supraventricular tachycardia/atrial flutter (as ventricular tachycardia), rapid atrial fibrillation with less R-R variability (as ventricular tachycardia), and irregular ventricular tachycardia (as not ventricular tachycardia).

Morphology. *Morphology criteria*[2] inhibit therapy if the intracardiac electrogram matches a stored ventricular electrogram template, because ventricular tachycardia morphology should be different than the baseline stored QRS template. This criterion is the most accurate of the single-chamber algorithms. It is continuous and can be applied to heart rates >200 bpm. It can misclassify supraventricular tachycardia with aberrancy (as ventricular tachycardia) and supraventricular rhythm electrogram truncation or malalignment (as ventricular tachycardia). *Morphology* cannot be applied on re-detection.

Sustained rate duration. *Sustained rate duration* limits the time that therapy can be withheld during a high ventricular rate episode by over-riding inhibitors after the duration timer expires. This will prevent ventricular tachycardia under-detection, particularly when the supraventricular tachycardia-ventricular tachycardia discriminator has no correction – e.g. *Onset*. Of course, this feature increases the risk of being shocked for supraventricular tachycardia, and it is nominally programmed "off" in most devices.

Dual-chamber implantable cardioverter-defibrillators

In addition to those criteria used for single-chamber devices, dual-chamber implantable cardioverter-defibrillators have features that allow comparison of atrial and ventricular relationships[4] in order to discriminate supraventricular tachycardia from ventricular tachycardia. Supraventricular tachycardia-ventricular tachycardia discrimination using atrial and ventricular rates is based upon the fact that most ventricular tachycardia will develop some degree of atrioventricular dissociation. Therefore, in the presence of reliable atrial sensing, this method has a sensivity of up to 90% for ventricular tachycardia. However, if there are atrial sensing problems, such as far-field R-wave over-sensing, the atrial rate will appear to exceed the ventricular rate and ventricular tachycardia could be misclassified as supraventricular tachycardia and therapy withheld.

There are manufacturer-specific algorithms to enhance supraventricular tachycardia-ventricular tachycardia discrimination in dual-chamber implantable cardioverter-defibrillators[5] e.g. Boston Scientific's *Rhythm ID*, Medtronic's *PR Logic*™, Biotronik's *Smart*® algorithm, and St. Jude Medical's *Rate Branch*™ Logic – that are beyond the scope of this article.

Tachycardia therapies

Anti-tachycardia pacing

Anti-tachycardia pacing consists of short pacing sequences delivered as *bursts* – same cycle length within a sequence – or *ramps* – cycle length shortens within a sequence – to terminate tachydysrhythmias without the need for shocks. In ventricular tachycardia, pacing at an accelerated rate can introduce impulses within the circuit that collide with the reciprocating tachycardia wavefront, thereby extinguishing re-entry. Anti-tachycardia pacing can be quite effective, terminating up to 95% of tachycardia events, up to 80% with the first anti-tachycardia pacing attempt. Anti-tachycardia pacing sequences are typically delivered at 69–88% of the tachycardia cycle length. It has been shown that burst pacing is more effective at terminating ventricular tachycardia than ramp, with less chance of accelerating the tachycardia cycle length.[6] To prevent syncope or tachycardia acceleration, anti-tachycardia pacing should be programmed for only – one to two sequences for fast ventricular tachycardia (>188 bpm), as data have shown that 90% are terminated within the first two anti-tachycardia pacing bursts (88% cycle length, eight pulses).[7]

Defibrillation

Current implantable cardioverter-defibrillator systems can deliver 25–36 J/shock and up to 8 shocks/sequence. This therapy is >98% effective in terminating VF. All current systems deliver energy in a biphasic mode; typically the energy is first delivered from the active can (A) to the right ventricular coil (B) or A > B for the first portion of the shock, followed by B > A. When there is an additional superior

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vena cava (SVC) coil (X) present, the initial pathway can be Can-SVC coil (AX) to right ventricular coil (B) or AX > B. The initial polarities may be reversed to deliver B > A or B > AX. In fact, newer data suggest that delivery from the right ventricular coil (B) to the active can (B > A) may be more effective.

The need for defibrillation threshold testing at the time of implantation has come into question. The argument is that with pectoral active can systems, higher output devices (>35 joules), and biphasic waveform shocks, the need for routine defibrillation threshold testing has been eliminated. However, defibrillation threshold testing carries with it the benefits of ensuring the integrity of the system, the reliability of sensing, and the assurance that the patient can be successfully defibrillated should they develop VF.[8] This author also believes that there are conditions associated with an inherently high defibrillation threshold testing, including hypertrophic cardiomyopathy, for which defibrillation threshold testing should still be considered.

In patients with CHD, the shock vector may be atypical, making defibrillation threshold testing necessary. In young patients having an abdominal implantable cardioverter-defibrillator and a subcutaneous and/or pericardial high-energy conductor, the shock vector may change as the patient's torso lengthens and girth increases; repeat defibrillation threshold testing may be warranted as the body habitus changes with growth.

Simple programming

Primary prevention

For primary prevention indications, implantable cardioverter-defibrillators should be programmed as a single VF zone defined by heart rates ranging from 200 to 240 bpm, depending on the patient's age and underlying substrate. The detection zone should be of sufficient duration to allow spontaneous termination of non-sustained events, usually 5–9 seconds. Anti-tachycardia pacing during charging is now a constant feature of these devices and should be programmed "on". Shocks should be programmed at maximal output, and supraventricular tachycardia-ventricular tachycardia discriminators should be programmed "on". A "monitor zone" comprising a slower rate can be programmed "on" to identify slower pathological, but haemodynamically tolerated, tachydysrhythmias; or ascertain that anti-arrhythmic drugs have sufficiently suppressed the sinus rate.

Secondary prevention

For secondary prevention, implantable cardioverter-defibrillators may be programmed "on" for both a ventricular tachycardia zone (e.g. 170–200 bpm) and a VF zone (e.g. >200 bpm). This decision should be based on the underlying arrhythmic condition, underlying haemodynamic status, known tachycardia rates, and the patient's age. For example, monomorphic ventricular tachycardia worthy of anti-tachycardia pacing is not a realistic possibility in patients having long QT syndrome. Some implantable cardioverter-defibrillators permit the programming of a fast ventricular tachycardia zone (e.g. 188–200 bpm) as well. During the ventricular tachycardia zone, supraventricular tachycardia-ventricular tachycardia discriminators should be turned "on", and multiple anti-tachycardia pacing burst or ramp sequences may be programmed, under the belief that the patient will tolerate the lower ventricular tachycardia rates and hence the longer period required for anti-tachycardia pacing to be effective. During the fast ventricular tachycardia zone, only one to two anti-tachycardia pacing sequences should be programmed "on" since the faster ventricular tachycardia rate will be less well tolerated than the rates in the ventricular tachycardia zone. Generally, following failure of anti-tachycardia pacing to treat ventricular tachycardia, direct current cardioversion for at least one shock is more appropriate than defibrillation. During the VF zone, anti-tachycardia pacing is permitted only during charging and all shocks are maximal. A "monitor zone" may also be programmed for the reasons described above.

Summary

Modern-day implantable cardioverter-defibrillator systems are a wonder in technology. With simple programming, ventricular tachydysrhythmias can be appropriately detected, discriminated from supraventricular tachycardia, and successfully converted into a stable, perfusing rhythm with a life-saving shock.

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Conflicts of Interest

None.

Ethical Standards

The authors assert that all referenced work contributing to this review complies with the ethical standards of biomedical or medicolegal investigation.

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