Cardiac device therapy 1: theory, technology and terminology

With advancing technology and ever-expanding indications for implantable cardiac pacing and defibrillation devices, this article reviews modern day practice in this field. This article focuses on topics pertinent not only to cardiologists but also to general physicians, medical trainees and allied medical specialties.

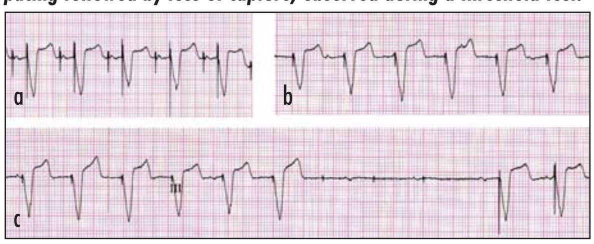
Since the first pacemaker was implanted by Senning in 1958, cardiac pacing has advanced immeasurably in both quantity and capability. The now more fashionable term 'device therapy' encompasses not only traditional pacing for bradycardia, but also pacing for tachyarrhythmia, implantable cardiac defibrillators (ICD) and biventricular pacing for heart failure (cardiac resynchronization therapy, CRT). As a result, a new subspecialty of cardiac device therapy is now maturing and destined to take on the additional workload posed by the looming number of heart failure patients deemed suitable for cardiac resynchronization devices and ICDs.

The theory

Pacing for bradycardia

The theory behind cardiac pacing is simple: an electrical stimulus (measured as current or voltage) is applied to the endocardium for a preset length of time (pulse width) in order to generate a stimulus capable of depolarizing and causing contraction within the specified cardiac chamber (capture) (*Figure 1*). The minimum amount of electrical energy needed to gain capture of the myocardium is called the threshold and is usually measured in mAmps or volts. These basic principles underlie even the most advanced of today's devices.

Figure 1. Electrocardiogram showing atrial and ventricular pacing. a. Dual chamber pacing. b. Ventricular pacing only. c. Ventricular pacing followed by loss of capture, observed during a threshold test.



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Once these basic principles are understood, then understanding the way modern devices work so well involves a detailed knowledge of so-called 'timing cycles' or the way the devices cause repeated stimulation in a timely fashion in conjunction with the patient's own heart beat (intrinsic rhythm). This involves a complex interaction of the pacemaker's ability to recognize the patient's 'intrinsic' rhythm (so-called 'sensing') while at the same time ignoring spurious electrical signals generated within the heart (made possible by refractory or blanking periods). While this may be relatively simple in a patient with a single chamber pacemaker and no underlying cardiac rhythm, it becomes infinitely more complex in patients with two or three pacemaker leads and competing intrinsic heart rhythms.

Certain bradycardia pacemakers also have an array of advanced functions to help deal with specific circumstances. Patients with paroxysmal atrial arrhythmias often receive dual chamber pacemakers with a mode switch facility to allow switching to single chamber mode when the atria start fibrillating. This prevents the pacemaker trying to pace the ventricle at the same rate as the sensed atrial fibrillation.

Rate drop response is another feature that signals a brief period of more rapid pacing when a sudden heart rate drop is noticed; this helps combat symptoms felt with neurocardiogenic syncope with sudden falls in heart rate and hypotension caused by vagal overstimulation and vasodilatation.

More recent advances have occurred in reducing the amount of time that the ventricles are paced. This may be particularly important given suggestions that patients who are ventricular paced over 40% of the time are at higher risk of developing heart failure and atrial fibrillation as a result of ventricular pacing (Wilkoff et al, 2002). Various algorithms are being developed to minimize ventricular pacing by dynamically extending the delay between atrial and ventricular pacing. Other features such as 'rate hysteresis' allow the intrinsic heart rate to drop below the base rate of the pacemaker before pacing ensues, thus minimizing the total amount of pacing.

A common yet advanced feature of most modern pacemakers is a rate response capability. Here the pacemaker uses an inbuilt sensor to detect an underlying physiological parameter (e.g. motion, vibration, QT interval, respiratory variation) in order to speed up the basic rate of pacing. Rate response proves invaluable in the chronotropically incompetent young patient with the inability to physiologically increase his/her own heart rate.

Newer generations of pacemakers are also available which help manage co-existing illness. An example of this is the daily monitoring of the intrathoracic pacing impedance (achieved by pacing from lead tip to generator – see part two of this article). Close correlation between impedance levels and total body water allows pre-emptive management of decompensating heart failure patients.

Pacing for tachycardias and sudden cardiac death

ICDs will generally use both basic pacing technology as well as a more advanced and high output form of energy delivery in the form of internal defibrillation. They have user-defined therapy 'zones' (*Figure 2*) which will deliver one of two basic therapies, depending on the rate of the 'sensed' tachycardia. Very rapid rates which are unlikely to sustain cardiac output are generally treated with one or more internal cardioversions (e.g. those seen in ventricular fibrillation), whereas slower and hopefully more sustainable rhythms are treated initially by anti-tachy pacing. This usually involves a series of eight paced beats, delivered at rates slightly faster than the tachycardia itself, designed to gain capture of the ventricle and therefore break the tachycardia circuit. In cases of failure to terminate the tachycardia with anti-tachy pacing, or where the anti-tachy pacing actually speeds up the tachycardia, internal defibrillation is usually the next resort. In most cases it is actually the pacing facility of the defibrillator devices that terminates most tachycardias, rather than defibrillation itself (*Figures 3* and *4*).

Anti-tachycardia therapy nowadays is largely reserved for ventricular arrhythmias such as ventricular tachycardia or ventricular fibrillation, but has previously been attempted in atrial arrhythmias. The advent of successful radiofrequency ablation therapies (Haissaguerre et al, 2000, Pappone et al, 2000) for atrial fibrillation, however, has largely rendered the practice of atrial anti-tachy pacing defunct.

Pacing for heart failure

The theory behind pacing for heart failure (CRT or biventricular pacing: BiV PPM) relies on the presence of delayed interventricular conduction or dyssynchrony, causing or worsening heart failure. Trials such as CARE-HF, COMPANION and MIRACLE have shown significant clinical benefits using CRT (Abraham et al, 2002; Bristow et al, 2004; Cleland et al, 2005). Bradycardia or pauses themselves are not a prerequisite.

Dyssynchrony is usually manifest as a broad QRS complex on the surface electrocardiogram, but can be diagnosed using specialist echocardiography techniques incorporating tissue tracking software (*Figure 5*) to follow ventricular wall movement (Cleland et al, 2005; Cazeau et al, 2008). Leads are placed to allow synchronized stimulation of both left and right ventricles. All the basic features of the delivered stimulus and timing cycles still apply, but are adapted to incorporate three pacing and sensing leads.

Importantly, tachycardia therapy devices can be combined with heart failure devices giving the so-called 'BiV ICD' or 'CRT-D'.

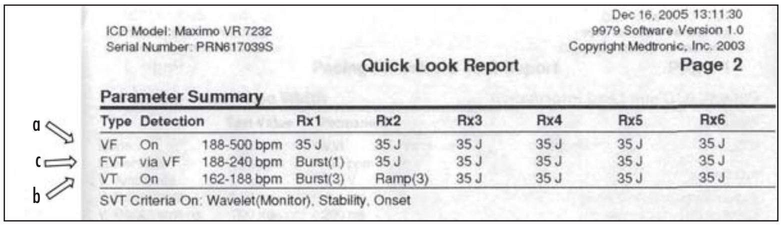
The technology

The systems generally consist of a generator (aka 'box', 'battery', 'can') and between one and three leads (aka 'wires', 'electrodes').

The generator

The generator is hermetically sealed and cannot be opened to replace failing components (e.g. the battery). It is composed of the header (where the leads attach), the

Figure 2. Interrogation of preset tachycardia therapy zones in Medtronic implantable cardiac defibrillator. Observe the three-zone setup with (a) a series of 35 J shocks for tachycardias above 188 beats per minute which is classified as the ventricular fibrillation (VF) zone, (b) a series of bursts of anti-tachycardia pacing followed by shocks for rates between 162 and 188 beats per minute which is classified the ventricular tachycardia (VT) zone, and (c) an intermediate fast ventricular tachycardia (FVT) zone between 188 and 240 beats per minute in which a single burst of anti-tachycardia pacing is given before shocks for ventricular fibrillation.


ICD Model: Maximo VR 7232
Serial Number: PRN617039S
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Quick Look Report
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Parameter Summary

	Type	Detection		Rx1	Rx2	Rx3	Rx4	Rx5	Rx6
a	VF	On	188-500 bpm	35 J	35 J	35 J	35 J	35 J	35 J
c	FVT	via VF	188-240 bpm	Burst(1)	35 J	35 J	35 J	35 J	35 J
b	VT	On	162-188 bpm	Burst(3)	Ramp(3)	35 J	35 J	35 J	35 J

SVT Criteria On: Wavelet(Monitor), Stability, Onset

Figure 3. Electrocardiogram showing termination of ventricular tachycardia by antitachycardia pacing; observe the initial eight antitachycardia pacing beats followed by four successive ventricular ectopic beats. Once the ventricular tachycardia terminates, intrinsic cardiac rhythm resumes after a couple of ventricular paced beats.

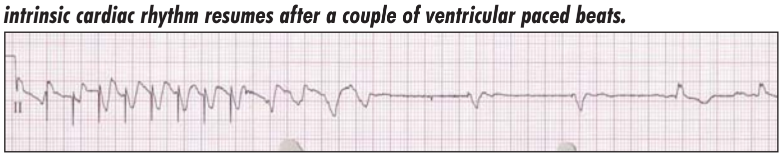
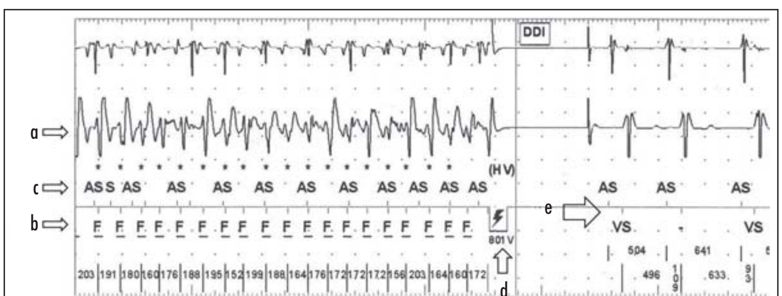


Figure 4. Intracardiac electrocardiogram taken during internal cardioversion of ventricular fibrillation. Observe (a) rapidly sensed signals from ventricular lead, (b) being interpreted by the device as fibrillation (F), (c) the relative paucity of atrial sensing signals (AS) in comparison to ventricular fibrillation signals implying that the ventricles are driving the rhythm, (d) the single high voltage (HV) internal cardioversion, followed by (e) appropriate atrial (AS) and ventricular (VS) sensing of sinus rhythm.



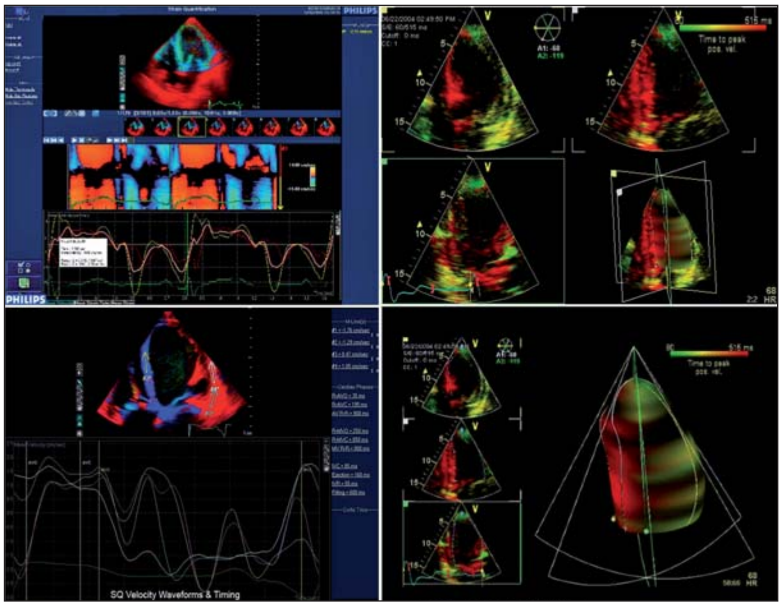


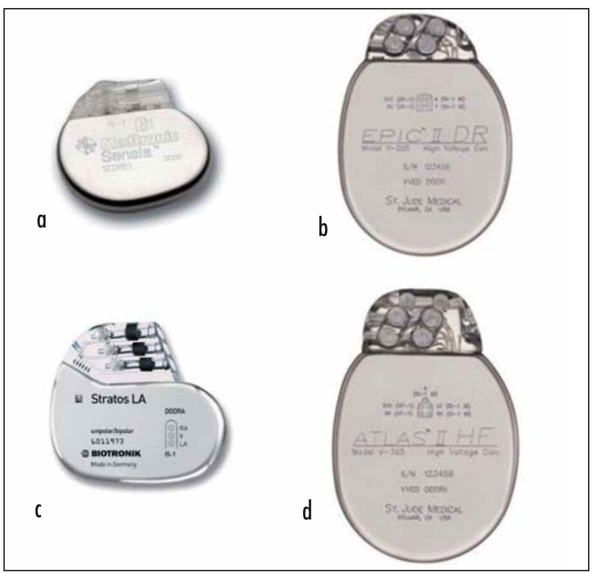
Figure 5. Tissue Doppler imaging in the assessment of left ventricular dyssynchrony.

battery and the internal electronic circuitry. The metal casing of the generator (usually made of titanium) can, if so desired, be used as an electrode in the pacing or defibrillation circuit (*Figure 6*).

Devices are small and light. Single chamber pacemakers weigh around 13 g and have a volume of 6 cc compared with ICDs whose average weight is 80 g with a volume of 40 cc. Defibrillators are larger and heavier as a result of the high energy charging circuitry.

Major companies in the devices market include Medtronic, Boston Scientific, St Jude, Vitatron and Sorin among others. Each company generally brands their device range (e.g. Adapta, Maximo, Atlas, Confient and Contak) according to the features supplied as standard.

Figure 6. Generators. a. Dual chamber pacemaker. b. Dual chamber implantable cardiac defibrillator. c. Biventricular pacemaker. d. Biventricular implantable cardiac defibrillator.



Most equivalent generators carry the same basic features; however, the more advanced models from each manufacturer have a number of extra specifications.

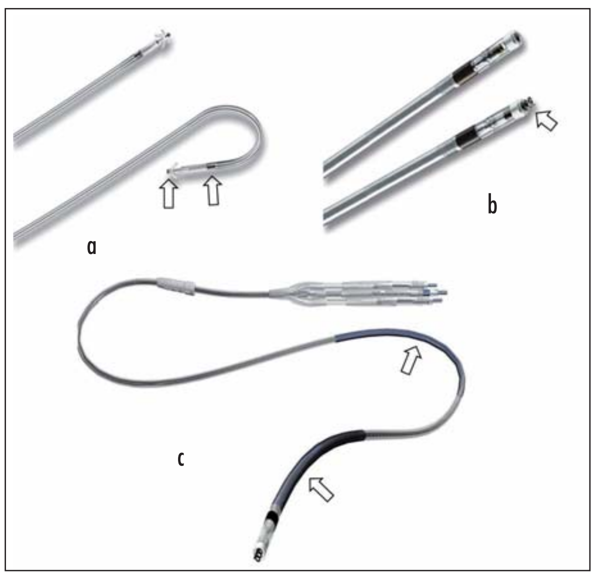
The longevity of a generator is largely dependent on battery life and battery drain, which in itself correlates with the amount of time the device spends pacing, the voltage at which the device is set to pace and the resistance to current leak (a function of lead type, placement and insulation). Figures quoted vary but range between 4–8 years. Owing to the higher output needed with defibrillation devices, longevity is still currently somewhat shorter at 2–6 years, and heavily influenced by the amount of defibrillation therapy.

The leads

Although pacing leads are commonly thought of as a single straight piece of wire, they are actually complex components designed to allow flexibility and strength with one or multiple conducting coils, within as thin and low profile a lead as possible (*Figure 7*).

Modern leads are almost always bipolar leads, meaning that they have two coiled conducting wires, intertwined yet insulated from each other, to allow the electric current to travel down one coil in the lead and back up the other coil. They have two electrodes at the lead tip, between which sensing or stimulation occurs. They can almost invariably be switched to a unipolar configuration where the heart is sensed or stimulated between the distal electrode and the metal case of the generator. From a practical point of view, bipolar leads tend to be slightly thicker and stiffer in profile, but suffer less in the way of stimulation or sensing outside the heart (e.g. from pectoral muscle, so-called myopotential inhibi-

Figure 7. The leads. a. Bipolar passive fixation leads with plastic tines at lead tip. Arrows denote the two electrodes at the lead's tip. b. Bipolar, active fixation lead with retractable helix at tip (arrow). c. Defibrillator lead with proximal and distal shocking coils seen as thicker portions of the lead (arrows).



tion). Also because the electrical impulse travels only a matter of 1–2 cm between electrodes in bipolar leads, the visible 'spike' on the 12-lead electrocardiogram is barely visible, sometimes making interpretation of the paced electrocardiogram difficult (*Figure 8*).

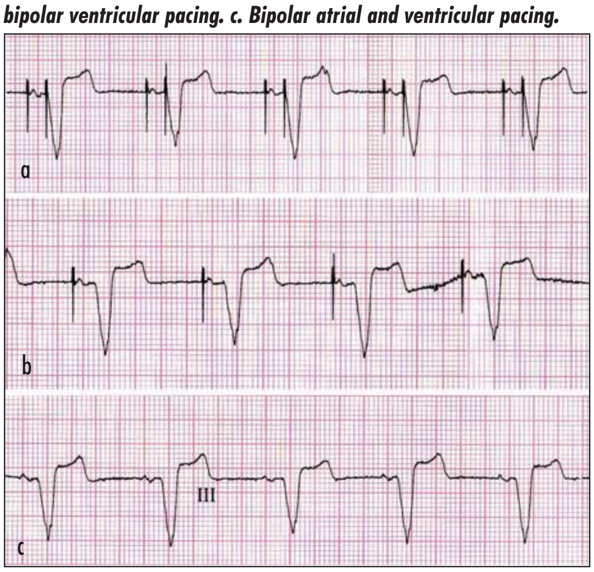
Defibrillator leads use this technology but in addition have one or two shocking coils, usually wrapped around the pace or sense leads and further insulated. Single coil leads will defibrillate the heart from coil to can, whereas dual coil leads can also defibrillate the heart between distal and proximal coil. A proximal coil, which incidentally can be added later as a separate lead, is generally positioned around the superior right atrium or superior vena caval junction.

Leads can be fixed to the endocardium in a number of ways, but are broadly described as active or passive fixation. Active fixation usually involves a retractable helix or 'corkscrew' on the distal portion of the lead which advances and buries into the endocardium by rotating a small bevel on the proximal end. Passive fixation leads use plastic tines or hooks which are designed to lodge in apical or appendicular trabeculae.

By 1 year, leads will generally become fixed to the endocardium as a result of chronic inflammation and fibrosis. This fibrosis used to be a frequent cause of premature lead failure by blocking the exit of the electric current from the lead rendering the lead non-functional (exit block), but widespread use of steroid-eluting pacemaker lead tips and improved tip design has considerably reduced this occurrence (Crossley et al, 1995).

Left ventricular leads used in biventricular pacing are generally thin unipolar leads to allow the intricate techniques used to negotiate tortuosities in posterolateral cardiac veins, although bipolar leads are available. Whereas surgically-placed epicardial leads directly onto the left ventricle were once the norm they are now reserved for difficult cases in which technical challenges preclude the lead being implanted percutaneously. Owing to the fragile nature of the coronary sinus walls, passive fixation leads were preferred, but high rates of left ventricular lead displacements has led to a newer generation of active fixation leads which use less intrusive techniques such as expanding coils and concertina-shaped anchors (Nagele et al, 2007).

Figure 8. Electrocardiogram showing difference in dual chamber pacing spikes with unipolar and bipolar pacing in the same patient. a. Unipolar atrial and ventricular pacing. b. Unipolar atrial and bipolar ventricular pacing. c. Bipolar atrial and ventricular pacing.



Programmer interrogation

This is the process by which the pacemaker is non-invasively checked, re-programmed and stored data is read once the device is implanted under the skin. Checks are generally performed by skilled cardiac physiologists. For some time this has been performed by placing an electromagnetic reader over the surface of the skin connected to a manufacturer-specific computer (*Figure 9*), but recent technological advances have discarded the magnetic reader in favour of wireless radiofrequency technology.

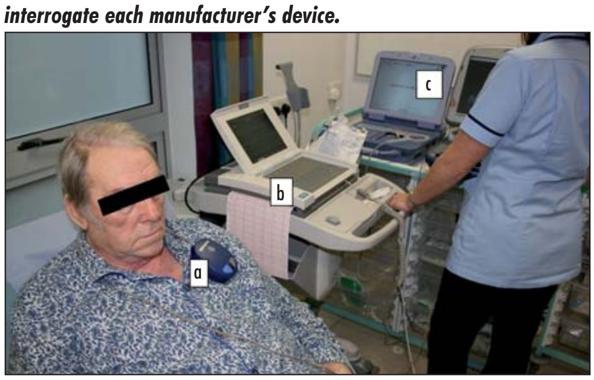
Traditionally this interrogation has required a hospital clinic visit, but technology has advanced sufficiently to allow this to be performed over a telephone line via a central computer server (transtelephonic) in centres with the necessary expertise.

Checks usually occur at implant, at 6–8 weeks post implant and subsequently annually for 'brady' pacemakers. These intervals can be shortened in cases of rising thresholds, painful implant sites or battery depletion. Batteries usually deplete slowly over time allowing for a reasonably accurate estimate of end of life. Most companies advise replacement allowing a 6–12-month safety margin, the so-called elective replacement interval.

The basic role of pacemaker interrogation is to ensure optimal pacing output and sensing parameters as well as to ensure adequate remaining battery life. Most modern devices will also have basic histograms to document the percentage of time spent paced or in intrinsic rhythm, as well as counters to pick up episodes of high heart rates.

With advances in solid-state memory modules, notably their increasing capacity and smaller size, more and more

Figure 9. Pacemaker interrogation using standard magnetic reader. Observe (a) programming head overlying skin and clothes, with (b) standard 12-lead electrocardiogram used to observe surface electrocardiographic changes. c. Specific programmers are used to interrogate each manufacturer's device.



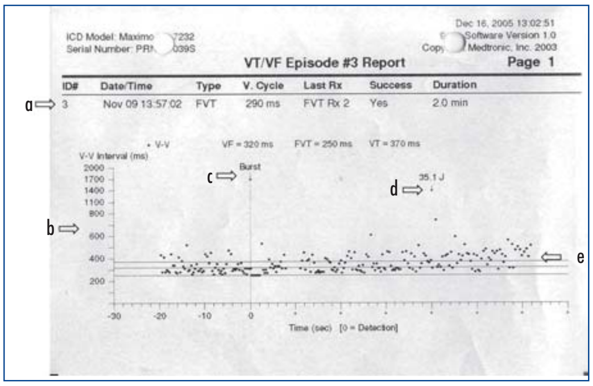
information can now be stored. Companies often market themselves and their devices on the post-implant usability of their software, together with the vast array of information obtainable at interrogation. Examples of advanced feature recordings include stored intracardiac tachycardia electrocardiograms, surface electrocardiograms derived from lead tip to generator signals, tachycardia cycle length 'dot plots', long-term lead integrity checks and duration of atrial fibrillation burden (*Figure 10*).

The terminology

Pacemakers are classified using a lettering system to indicate paced and sensed chambers together with additional features present within the device. This nomenclature has been used in recent years and works well when describing simple brady pacemakers. With the advent of biventricular pacemakers, defibrillators and increasingly complex bradycardia pacemakers, the lettering system has to a degree been abandoned in favour of a more descriptive phraseology.

Traditionally the first letter denotes the chamber paced (A=atrial, V=ventricular, D=dual, O=off), and the second the chamber sensed. The third letter tries to describe the response to an intrinsic cardiac stimulus, which works fine with a single chamber pacemaker that is inhibited (I) or triggered (T) by a sensed stimulus. When dual chamber systems are in place, however, it becomes difficult to describe the function of both leads with one letter and hence the common 'D' is used to denominate some form of dual lead response. The fourth letter has been used to describe additional features of the pacemaker, principally that of rate response (R) as described earlier. A fifth letter has been added to denominate devices with antitachycardia pacing (B) and defibrillation (D) capabilities. In practice this is rarely used because of the cumbersome nature of the acronym. Instead, most centres will describe a defibrillator as a function of its underlying bradycardia setup followed by 'ICD' (e.g. VVI ICD or DDD ICD). Biventricular pacemakers are generally referred to as CRT devices, followed by either 'D' if they have defibrillation capabilities or 'P' if they are merely pacing devices (e.g. CRT-P, CRT-D). The commonest pacing configurations are DDD(R), VVI(R) and AAI(R).

Figure 10. Advances in technology, particularly in solid state memory capacity, has allowed much more information to be recorded via the pacemaker or implantable cardiac defibrillator. Observe 'dot plot' of an episode of tachycardia graphing each interval between subsequent QRS complexes. a. The exact timing details of the event are recorded with (b) details of the intervals between each QRS complex mapped out (c) as dots against the y axis. d and e. Delivered therapies are also recorded allowing the user to interpret the effect of the therapy on the QRS interval and thus heart rate.



KEY POINTS

- Cardiac device therapy is an advancing cardiac subspecialty incorporating not only pacemakers for bradycardia but also implantable cardiac defibrillators and resynchronization devices for heart failure
- Modern day pacing devices are not only extremely programmable and capable of integrated multi-chamber cardiac pacing, but are also able to record valuable diagnostic data in various formats for clinician use.
- While the basics of most pacing systems remain relatively static, improved battery longevity, smaller lead and generator size and advanced memory features have created much more user-friendly and reliable systems.

Conclusions

The first part of this two-part article on cardiac device therapy should have demystified some of the basic principles underlying modern day cardiac pacing and defibrillation. This grounding is imperative in order to further advance one's knowledge and skill base in this field. Part two will concentrate on the current day indications for device therapy followed by a basic description of implant techniques and complications seen both early and late in the life of the implanted device. **BJHM**

Figure 5 *is reproduced courtesy of Philips and GE Healthcare,* Figure 7 *is reproduced courtesy of Medtronic.*

Conflict of interest: Dr Modi has received sponsorship and honoraria received from both Medtronic and Boston Scientific.

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