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REVIEW ARTICLE

Pacemakers and implantable cardioverter defibrillators

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Summary

An increasing number of patients are now treated cardiac pacemakers and implantable cardioverter defibrillators and the technology of these is constantly changing. It is vital to have a good understanding of how they function and what the real risks are. Understanding how the device should work when functioning normally, and the possible effects of electromagnetic interference, is paramount to their safe management in the peri-operative period. Knowing when a device should be disabled or reprogrammed requires careful consideration. Information from the patient's pacemaker clinic should be sought whenever possible and can be invaluable. In addition, the Medicines Healthcare products Regulatory Agency have published the first set of UK guidelines on the management of implantable devices in the presence of surgical diathermy and this will undoubtedly provide a firm foundation on which anaesthetists can base much of their practice.

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Since the development of the first pacemaker in the early 1950s, their use in the management of symptomatic bradyarrhythmias has become well established. In the UK over 30 000 patients will receive a pacemaker each year, with the total number in use exceeding 239 000 [1]. However, when compared with our European neighbours, the UK has very low levels of implantation, a circumstance that reflects inherent problems encountered within the infrastructure of our cardiac services [2].

Following the development of the implantable cardioverter defibrillator (ICD) in the late 1970s, patients susceptible to tachyarrhythmias, including malignant ventricular tachycardia and ventricular fibrillation, now have a greater chance of survival [3]. The number of ICDs in the UK currently exceeds 2000 and is likely to increase further following the most recent publication of guidance from the National Institute for Clinical Excellence (NICE) [4].

The majority of patients receiving pacemakers are elderly and the average age at the time of first implant has increased to 75 years. With an ever-increasing number of elderly patients presenting for surgical procedures, it is likely that anaesthetists will encounter patients with implantable devices more frequently. As a result, it is important to have a good understanding of device function and management in the theatre setting, particularly with the advent of newer devices with more complex technology, such as rate adaptive-pacing and cardiac resynchronisation therapy.

The modern pacemaker

At their most basic level, pacemakers work by delivering a very short (< 1.0 ms), low voltage (< 3.0 V) electrical current via an insulated pacing lead to the heart muscle at a preprogrammed rate. They are also able to detect the heart's native electrical impulses and respond accordingly. This ensures that the pacemaker only paces when required, thus eliminating the risk of the R on T phenomena and improving the battery life. The majority of pacemakers implanted today are either single chamber ventricular devices or dual chamber (atrial & ventricular) devices (Table 1).

Over the past 50 years there have been tremendous advances in both the design of the device and the software employed. The main features of what constitutes a modern pacemaker are shown in Table 2.

In the mid 1960s, transvenous leads were developed that could be inserted through a vein and thence into the heart, thus preventing the need for a thoracotomy and a

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Table 1 Percentage of new implants by pacemaker type in the UK in 2004.

Pacing chamber	Per cent of new implants
Atrial	1
Ventricular	43
Dual	54
Biventricular	2

Table 2 The development of the modern pacemaker.

	Features of the modern pacemaker
1960s	Transvenous pacing leads demand pacing
1970s	Pronged/screw-in leads Lithium iodine battery Titanium casing Radio-frequency programmability dual chamber pacing
1980s	Steroid eluting leads rate-responsive pacing defibrillator capability
1990s	Biventricular pacing data storage

general anaesthetic. The leads were, however, smooth tipped and reliable contact with the endocardium was not assured. The development of 'active fixation' leads ensured a better contact with the endocardium and the presence of a steroid eluting tip helped to reduce any inflammation that might result.

The introduction of the lithium iodine battery has dramatically increased the battery life to well over 10 years. Previously, mercury-zinc batteries needed replacement every 3–5 years. The titanium casing which surrounds the pulse generator and battery is strong, yet remarkably light, and assists greatly with the removal of outside electromagnetic interference (EMI), allowing patients safely to use appliances such as microwaves, shavers, mobile telephones and hairdryers. Additional EMI protection is afforded by the presence of complex EMI recognition software built into the device.

Radiofrequency programming became available in the 1970s, allowing simple adjustments to be made to the pacemakers settings without the need for surgery. Today, pacemaker and ICD checkups, together with any adjustments, can be completed within a matter of minutes using a nearby computer. Information regarding events such as periods of bradycardia, tachycardia or ventricular fibrillation can be stored within the memory of the device and accessed by specialist pacemaker physiologists during the routine checkup. The percentage of time that the patient has been dependent on the pacemaker is also recorded, allowing an estimation of remaining battery life.

To maintain atrio-ventricular synchrony, the concept of dual chamber pacing was introduced. This not only improved cardiac output by efficiently utilizing atrial systole, it also reduced the risk of significant mitral and tricusped regurgitation due to the mistiming of valve closure. In addition, several landmark studies, noteably the MOST, CTOPP and UKPACE have shown that patients with dual chamber pacing have a reduced risk of developing both heart failure and chronic atrial fibrillation [5–7].

In the late 1990s, pacemaker technology had improved to the extent that it now became possible to increase the pacing rate to match the patient's activity level. These devices are known as rate-adaptive and can employ a variety of different techniques to achieve this goal. Currently, in the UK, over 50% of devices have some form of rate-adaptive behaviour.

Pacemaker coding conventions

The North American Society of Pacing and Electrophysiology (NASPE) and the British Pacing and Electrophysiology Group (BPEG) first published a generic pacemaker code (NBG code) in 1987 [8]. In light of the developing technology, a revised code was produced and endorsed in September 2001 [9] (Table 3). Position I indicates the chamber in which pacing occurs and may be atrial (A), ventricular (V) or both (D). Position II indicates the chamber in which sensing occurs, and again may be asigned the letter A, V or D. The designation, O, may be used if the pacemaker discharges independently without sensing. Position III indicates the effect of sensing, which may be either to trigger a pacing stimuli or to inhibit a pacing stimuli. Position IV indicates the presence (R) or absence (O) of any rate-adaptive mechanisms. Position V is used to indicate whether multisite pacing is present in none of the chambers (O), one or both atria (A), one or

Table 3 The North American Society of Pacing and Electrophysiology (NASPE) and British Pacing and Electrophysiology Group (BPEG) pacemaker codes.

(I) Chamber paced	(II) Chamber sensed	(III) Response to sensing	(IV) Rate modulation	(V) Multisite pacing
O = no action	O = no action	O = no action	O = no action	O = no action
A = Atrium	A = Atrium	T = Triggered	R = Rate Modulation	A = Atrium
V = Ventricle	V = Ventricle	I = Inhibited		V = Ventricle
D = Dual	D = Dual	D = Dual		D = Dual

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both ventricles (V) or combinations of both (D). For a device to have multisite pacing the additional leads can either be placed within the same chamber (e.g. two leads pacing the right ventricle) or within opposite chambers (e.g. one lead pacing the right ventricle and another lead pacing the left ventricle).

Pacemaker codes most frequently encountered

The proportion of single chamber atrial pacing devices implanted each year is in the region of 1%. The main indication for isolated atrial pacing is sick sinus syndrome in the absence of atrio-ventricular block. It has been estimated, however, that in the region of 8% of patients with sino-atrial node disease will progress to atrio-ventricular block within 3 years [10]. As a result, a dual chamber device might, on balance, be the most appropriate choice.

In 2004, almost 95% of all newly inserted pacemakers were accounted for by only four different modes: VVI (16.9%), VVIR (24.8%), DDD (27.3%) and DDDR (25.4%). These modes will be discussed in more detail below.

VVI

In VVI mode, the pacemaker will both sense and pace the ventricle. If no intrinisic activity is sensed within the ventricle, the pacemaker will pace at a preprogrammed rate. If the electrical impulse generated by the sino-atrial (SA) node is able to pass through the atrio-ventricular (AV) node and depolarise successfully the ventricular tissue, pacing will be inhibited (Fig. 1).

VVIR

This mode is identical to VVI with the exception that a rate-adaptive mechanism has been installed, which will alter the pacing rate to match the physiological needs of the patient.

DDD

In DDD mode, both atrium and ventricle are sensed and paced. If both the SA node and AV node are functioning correctly, the pacemaker will do nothing more than sense this activity. If the atrium fails to produce a native beat, the pacemaker will pace the atrium at a preprogrammed rate. If either a native or paced atrial beat is not conveyed through into the ventricles after a preprogrammed PR interval, 'time out' occurs and the pacemaker will pace the ventricle (Figs 2a,b,c).

DDDR

This mode is identical to DDD with the exception that a rate-adaptive mechanism has been installed, which will alter the atrial pacing rate to match the physiological needs of the patient.

Rate-adaptive mechanisms

In the event of SA node dysfunction, any increase in oxidative requirements, as with exercise, illness or stress, may not be adequately met by a fixed rate pacemaker. As a result, additional sensors have been incorporated into pacemakers to detect 'secondary' stimuli that may indicate the need for a faster pacing rate. The ideal sensor would respond to circulating catecholamine levels or autonomic nervous system activity, which are directly responsible for controlling SA node activity. However, these sensors are still in development and are currently not available [11]. The majority of rate-adaptive sensors respond to stimuli such as movement (by using a piezoelectric crystal) or minute ventilation (by monitoring transthoracic impedance). In 2004, approximately 50% of all new implants in the UK had rate-adaptive capability, over 80% of which use the piezoelectric crystal and respond to patient movement.

Cardiac resynchronisation therapy

Patients with moderate to severe heart failure have a higher incidence of both interventricular and intraventricular asynchrony resulting from altered conduction throughout the His-Purkinje system. The effects on haemodynamic function have been well documented and include reduced diastolic filling and impaired cardiac

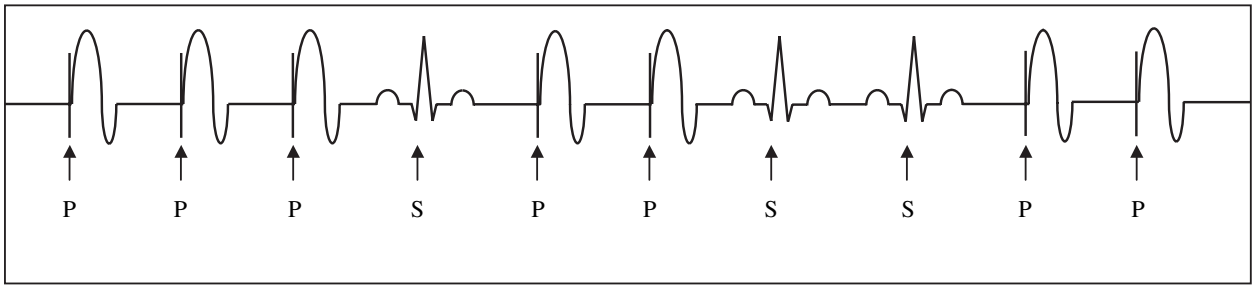

Figure 1 VVI pacing; S, sensed beat; P, paced beat.

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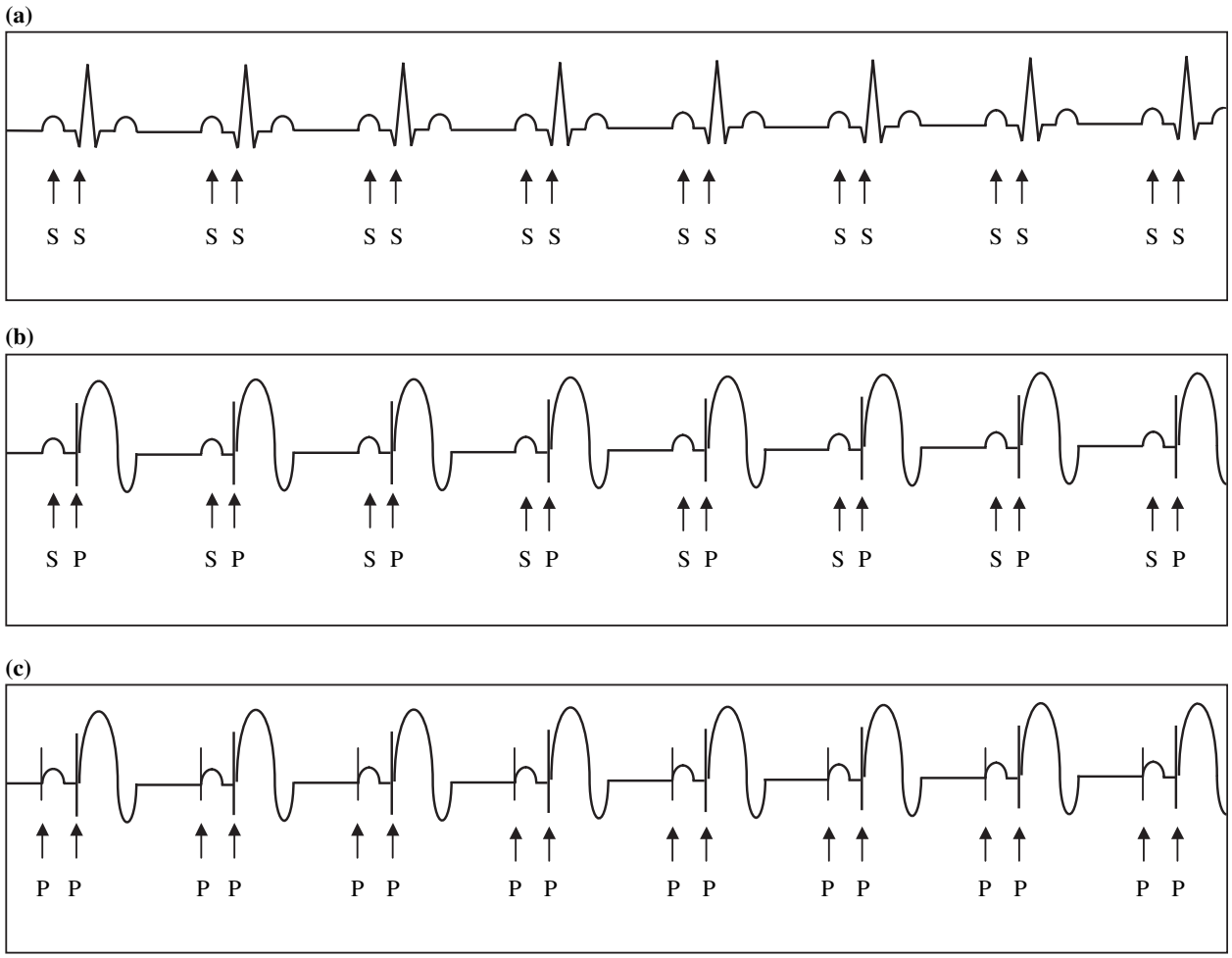

Figure 2 a) DDD pacing in a patient with normal SA node function and normal AV node function. b) DDD pacing in a patient with normal SA node function and abnormal AV node function. c) DDD pacing in a patient with abnormal SA node function and abnormal AV node function. S, sensed beat; P, paced beat.

output. Cardiac resynchronisation therapy (CRT), sometimes referred to as biventricular pacing, aims to improve this situation by using additional leads to pace multiple sites within the cardiac chambers. Further leads may be positioned within the right atrium or ventricle or, as in the case of true biventricular pacing, passed through the coronary sinus and veins to reach the left ventricle. Following placement of these additional leads, the patient's cardiac output can be optimised by altering the timing of each pacing lead whilst observing the effects under echocardiographic control.

Implantable cardioverter defibrillators

In the past, those at risk of sudden cardiac death from malignant tachyarrhythmias were managed pharmacologically with drugs such as amiodarone or sotolol. The outcome of these treatments was varied and often poor [12]. The first human to receive an implantable defibrillator, in 1980, was a young woman who had recurrent episodes of ventricular fibrillation [13]. The device, however, was only able to identify ventricular fibrillation and responded with an unsynchronised shock. Today, the devices used are far more complex and consist of individually tailored algorithms, which provide a series of management strategies for episodes of ventricular tachycardia and ventricular fibrillation.

The devices are based on the principle of 'tachycardia zones'. Each zone is defined according to the individual's clinical history and electrophysiology. The fastest zone (rate > 200) is known as the 'ventricular fibrillation zone' and is managed with unsynchronised, high energy (up to 30 J) shocks. Zones with rates less than 200 will be managed in one of four ways:

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1 observed with no further action;
2 anti-tachycardia pacing;
3 low energy (< 5 J) synchronised shock;
4 high energy unsynchronised shock.

Often the management is progressive, such that failed attempts at anti-tachycardia pacing will result in a set number of synchronised shocks being given, which would then, if unsuccessful, be followed by high energy unsynchronised shocks.

Rhythm recognition has now become very intuitive and includes rapid analysis of speed of onset, QRS morphology and width, beat-to-beat variability and atrial rate, thus allowing the device to instigate the correct course of action [12]. In addition, all ICDs now have pacemaker capability, allowing provision for antibradycardia pacing backup.

Defibrillator coding conventions

In addition to the NASPE/BPEG pacemaker code, in 1993 a four-position defibrillator code was devised [14] (Table 4). Position I indicates which chamber is shocked, position II indicates the chamber in which any anti-tachycardia pacing is administered, position III identifies the detection method and position IV indicates which chamber delivers anti-bradycardia pacing. In its most complete form, position IV is often used to specify the complete five-letter pacing convention. For example, a patient who has a ventricular defibrillator with anti-tachycardia pacing which uses a haemodynamic detection method, in combination with a biventricular, dual chambered, rate responsive pacemaker, might be coded as VVH-DDDRV.

Electromagnetic interference

A number of sources of electromagnetic interference (EMI) can be found within the hospital setting. For anaesthetists the main cause for concern undoubtedly lies with the use of diathermy. The effects of EMI on a pacemaker or ICD are unpredictable, but include inappropriate inhibition or triggering of pacing activity, asynchronous pacing (as seen with a VOO or VVI setting), reprogramming or software resetting of the device, damage to the internal circuitry and activation of anti-tachycardia pacing or even defibrillation shocks [11]. In addition, heat damage may occur in the myocardium at the point of contact with the electrodes of the device, although this has largely been documented following exposure to high-powered radiofrequency fields [15]. Protection from the various sources of EMI is afforded, in part, by the titanium casing of the implantable device, together with its built-in interference monitor, which is capable of filtering out certain unwanted electrical signals.

Unipolar diathermy is certainly more hazardous than its bipolar equivalent as, during the former technique, the current pathway on returning to the grounding plate may come into close contact with the pulse generator and leads of the implantable device. As a result, most manufacturers issue strong warnings against its use. However, there will obviously be times when the use of unipolar diathermy is unavoidable. In these circumstances the grounding plate should be placed as far away from the device as possible. For head and neck surgery the recommended placement is on the posterior aspect of the shoulder opposite the pulse generator.

It has been suggested that bipolar diathermy is generally safe in the presence of an implantable device [16, 17]; however, EMI will still be generated and a level of caution should be entertained.

Whenever diathermy of either type is required, it should be used in short, infrequent and irregular bursts, with the energy setting kept to a minimum. In many circumstances, pacemakers will not require reprogramming to an asynchronous mode and ICDs will not require disabling before surgery. However, where there is likely to be a high level of EMI generated, or where the intended site of surgery lies close to the pulse generator, expert advice regarding reprogramming should be sought.

Another, less obvious cause of pacemaker malfunction may occur in patients with a rate-adaptive function. There are reports of pacemakers with minute ventilation sensors interacting with cardiac monitors in which transthoracic impedance is used to measure respiratory rate [18–20]. The pacemaker may measure the summated impedance signals from the patient and the cardiac monitor, interpreting the information as a two-fold increase in minute ventilation. The effect would be to increase inappropriately the pacing rate.

Table 4 The North American Society of Pacing and Electrophysiology (NASPE) and British Pacing and Electrophysiology Group (BPEG) defibrillator codes.

Chamber shocked (I)	Anti-tachycardia pacing chamber (II)	Anti-tachycardia detection (III)	Pacing chamber (IV)
O = no action	O = no action	E = Electrogram	O = no action
A = Atrium	A = Atrium	H = Haemodynamic	A = Atrium
V = Ventricle	V = Ventricle		V = Ventricle
D = Dual	D = Dual		D = Dual

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Patients with an implantable device who require external defibrillation are at a very high risk of device damage or reprogramming due to the immense amount of EMI generated [21]. In addition, external defibrillation can induce high-energy currents through the device leads, resulting in serious burns to the myocardium. As a result, external defibrillation pads should be placed as far away from the pulse generator as possible and certainly more than 10 cm away. Placing the pads in an apex-posterior position may be advisable.

Magnets

In the past, patients with a pacemaker in whom EMI was likely were frequently managed by placing a magnet over their device to produce asynchronous pacing. As device technology has expanded, it has become less clear how each individual device will respond to a magnet, and there appears to be no universal effect, even between two otherwise identical devices. The response will depend largely on how the device has been programmed. For many pacemakers, the presence of a magnet will indeed induce continuous asynchronous pacing. For others, however, a very short period of asynchronous pacing might occur or there may be no effect at all. With the ICD, approximately 99% of them are programmed to have their anti-tachycardia function disabled in the presence of a magnet without affecting their bradycardia pacing.

In general, the routine use of magnets is not recommended and they should be used with caution. Information about the response of a device to the application of a magnet can be obtained from the pacemaker clinic responsible for the patient. In the event of a magnet ever being applied to an implantable device, its function and programming should be checked at the earliest opportunity.

Peri-operative management

At present there are no internationally agreed guidelines on the management of implantable cardiac devices in the peri-operative period. However, in 2005 the American Society of Anaesthesiologists published a practice advisory outlining recommendations for their management [15]. More recently, in March 2006, the Medicines and Healthcare products Regulatory Agency (MHRA) in collaboration with Heart Rhythm UK (HRUK) have released guidelines for the management of these devices when the use of electrical diathermy is anticipated [22]. Much of what these two documents recommend are outlined in more detail in the paragraphs which follow.

Pre-operative assessment

During the pre-operative assessment it is important first to identify whether a patient has an implantable device. This can be confirmed by taking a focused history, examining for scars and reviewing a chest X-ray or ECG. Next, one needs to ascertain whether the device is a pacemaker, ICD or a CRT and the nature of the underlying condition which led to its implantation. Many patients with an ICD might still refer to their device as a 'pacemaker'. Asking whether it has ever shocked them or has the potential to shock them might assist with clarifying this important point.

In the UK all patients with an implantable device should carry a device 'passport' or registration card, which will provide information such as the model, manufacturer and device serial number, as well as the programmed mode and set rate. Many patients may also carry emergency instructions and have access to their own magnet. Additional useful information includes when the device was implanted, when and where it was last checked and the results of the last check. If it has been checked within the past 3 months, there is probably no benefit in requesting a repeat check pre-operatively. If the battery life indicator (known as the elective replacement indicator, ERI) has reached its limit, the patient should have the battery replaced prior to considering any elective surgical procedure. In addition, the presence of more complex features such as rate-adaptive pacing or anti-tachycardia modalities should be elicited.

It is also important to determine the extent to which a patient is device dependent. This can be difficult, but indicative features include a previous history of symptomatic bradycardia or evidence of a successful therapeutic AV node ablation.

Much of this required information can be obtained from the pacemaker/ICD clinic responsible for regularly following up the patient. Indeed, the most recent guidance from the MHRA recommends contacting the patient's clinic as a matter of course, to determine these facts.

Recommended investigations include a 12-lead ECG together with a rhythm strip, which although it only provides a snapshot of the patient's cardiac electrical activity, may confirm the presence of pacing spikes and the baseline heart rate. A chest X-ray is not essential unless there is a paucity of information about the device. An X-ray would simply confirm device presence and lead positions. A pre-operative set of urea and electrolytes is important to identify abnormalities in the potassium level, which can result in pacing failure.

Finally, the decision as to whether a device requires reprogramming or disabling before surgery will need to take into account the following factors:

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- anticipated amount of EMI;
- device type (Pacemaker, ICD or CRT);
- pacemaker dependency;
- rate-adaptive features.

In the absence of unipolar diathermy or if the proposed surgery is remote from the pulse generator, the risk of malfunction will be minimal. In situations where the amount of EMI is likely to be high, or where the surgical site lies in close proximity to the device, consideration should be given to reprogramming patients with an ICD to 'monitor only' mode to prevent inappropriate defibrillation shocks. The pacemaker physiologist should perform this reprogramming in the theatre suite, immediately prior to surgery, and remain present throughout the surgical procedure in case the need arises to switch the defibrillator function back on. For those patients who are very much dependent on the correct functioning of their pacemaker or CRT, consideration should be given to reprogramming to prevent inappropriate inhibition or high rate pacing. It can achieve this goal by being programmed to monitor and not respond to the electrical interference. Rate-adaptive pacemakers that utilise the transthoracic impedance sensor should ideally be switched off. Again, it would be prudent to contact the patient's pacemaker/ICD clinic to seek their advice on the best course of action when considering reprogramming any implantable device.

Intra-operative management

During surgery, standard monitoring should be employed in the form of ECG, blood pressure and saturations. In the event of a patient having a functioning rate-adaptive device which utilises the transthoracic impedance sensor, the respiratory rate monitor should be switched off. ECG monitors which utilise the 'paced' mode of recognition will need to be used with caution as the monitor may interpret pacing spikes as continuing activity when the patient is in fact (albeit unlikely) asystolic.

If diathermy is essential, the bipolar system should be used wherever possible, and with short, intermittent and irregular bursts at the lowest possible energy setting. If obvious pacemaker inhibition occurs, the surgeon should be informed and diathermy discontinued or used judiciously.

Emergency pacing systems (internal or external) should be available, together with resuscitation equipment including an external defibrillator. Where an ICD is to be disabled, consider connecting the patient to the external defibrillator pads prior to commencing surgery.

There will, of course, be occasions when patients with implantable devices have to undergo emergency surgical procedures without having had the benefit of a thorough device assessment. In this situation, the above recommendations should be adhered to as much as possible. In addition, consideration can be given to the use of a magnet; however, magnets should be used with great care and preferably only when the magnet effect of the device is known.

Postoperative care

Whenever there has been concern about device failure, malfunction or the effects of EMI, the device should undergo a complete telemetric test at the earliest opportunity. Reprogramming back to the original settings should also occur, the timing of which will need to be discussed with the patient's pacemaker clinic. Anti-tachycardia and defibrillator modalities, must, of course, be switched on immediately postoperatively.

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