

## REVIEW ARTICLE

**Temporary epicardial pacing after cardiac surgery:  
a practical review****Part 1: General considerations in the management  
of epicardial pacing****M. C. Reade***Instructor in Critical Care Medicine, University of Pittsburgh Medical Center, 605 Scaife Hall, 3550 Terrace Street, Pittsburgh PA 15261, USA***Summary**

Epicardial wires allow temporary pacing after cardiac surgery. Pacing is often the best, and sometimes the only method of treating temporary rhythm disturbances in this context. Temporary epicardial pacing has evolved from simple one-chamber systems to dual chamber, biatrial, and even biventricular systems. The first part of this two-part review provides an overview of the management of temporary epicardial pacing systems. Factors influencing the placement of the various types of epicardial wires and the routine care of a pacemaker-dependent patient are outlined, followed by a description of the diagnostic use of pacing wires, how to remove wires, and when to consider transition to permanent pacing. Special circumstances such as compatibility with magnetic resonance imaging and intra-aortic balloon pumps are also discussed. The second part of this review will describe the various pacing modes, and solutions to common pacing problems using various adjustable parameters.

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Knowledge of epicardial pacing is required for the intra- and postoperative management of patients undergoing cardiac surgery. While the majority of patients do not require pacing to facilitate separation from cardiopulmonary bypass, it is difficult to select those who may subsequently require pacing during their early postoperative course. Although decisions regarding placement of epicardial wires are seldom made solely by anaesthetists, and indeed much of the management of pacing systems is performed by nursing staff in the ICU, it is essential that anaesthetists have a sound understanding of the indications for, and management of, epicardial pacing. Optimisation of epicardial pacing systems can markedly affect cardiovascular stability, and so the pacemaker interacts with every other therapy controlled by the anaesthetist.

**Indications for temporary pacing**

Specific electrophysiological conditions that may benefit from temporary pacing are listed in Table 1. Whereas many

of these indications are universally accepted (such as third degree heart block), some have yet to achieve consensus. For example, in non-operative patients with congestive cardiac failure with intraventricular conduction delay, it has been recognised for some time that in permanent pacing there is benefit to delivering the pacemaker stimuli to both ventricles [1]. The relative timing of left and right ventricular pacing impulses is usually optimised using echocardiography. This technique has not been widely employed after cardiac surgery to date, but anecdotally can improve cardiac output after valve replacement surgery by 10–30% [2]. No currently available temporary pulse generator can differentially pace left and right ventricles. A satisfactory result can be obtained by connecting both left and right wires to the same output terminals of the pulse generator. As patients with increasingly small physiological reserve are considered for surgery, and as the technological challenge is small, this method of pacing may gain popularity. If so, a pulse generator capable of independently pacing each ventricle may become available.

**Table 1** Electrophysiological abnormalities that may benefit from temporary cardiac pacing [25, 26].

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<b>Conduction abnormality</b>	
Prolonged AV delay (common after cardiac surgery; artificially shortening this using AV sequential pacing may improve mechanical coupling between the atria and ventricles)	
AV block: third degree, or type II second degree	
During the insertion of a pulmonary artery catheter in a patient with left bundle branch block (although this is noted to be controversial)	
Bifascicular block with first degree block	
New onset bifascicular block (indicative of active ischaemia)	
Prolonged QT syndrome in the presence of significant bradycardia (to prevent torsades de pointes)	
<b>Tachycardia</b>	
AV junctional tachycardia (common after cardiopulmonary bypass): may be terminated by a brief period of pacing, which can then be discontinued	
To terminate re entrant SVT or VT	
Type I atrial flutter (rate <320–340 beats.min <sup>-1</sup> )	
<b>Prophylactic</b>	
Bradycardia-dependent ventricular tachycardia	
Prophylaxis of atrial fibrillation	
<b>Other</b>	
Sinus bradycardia (as an alternative to pharmacologic treatment)	
To restore AV mechanical synchrony in underlying third degree block, AV junctional or ventricular rhythms	
Hypertrophic obstructive cardiomyopathy (in particular if effective in reducing systolic anterior motion of the anterior mitral leaflet)	
Following heart transplantation	

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Another new potential role for temporary epicardial pacing is in the prevention of atrial fibrillation, which is extremely common in the period immediately following cardiac surgery (40% in some series). The incidence can be reduced by prophylactic simultaneous pacing of both right and left atria [3]. Bi-atrial pacing in this context was recently recommended by the American College of Chest Physicians [4], but has not yet gained widespread adoption.

Set against the physiological advantage and extra safety afforded by one or more epicardial wires is the small, but definite, risk they entail. Complications of epicardial wires include infection, myocardial damage, perforation, tamponade, and disruption of coronary anastomoses [5, 6]. Unfortunately, these risks have never been well quantified. Many studies have shown that the majority of patients never require pacing. In the light of this, some centres limit their use of epicardial wires to patients requiring pacing immediately prior to chest closure, for indications such as bradycardia with low cardiac output, nodal or junctional arrhythmias, or AV block [7]. Whereas in one study only 2.6% of patients without diabetes, pre-operative arrhythmia or the need for pacing to separate from bypass required pacing in the postop period [8], many centres find this risk unacceptably high, and

implant at least ventricular wires in all patients. Given the multiple inputs to surgical decision-making, this question is unlikely to be answered in a sufficiently powered randomised controlled trial.

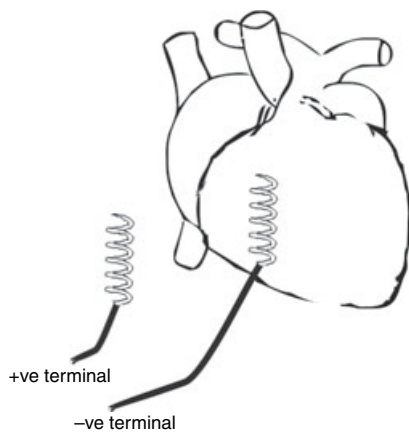
### **Epicardial pacing wires: atrial and/or ventricular placement**

Epicardial pacing wires were historically placed only on the right ventricle. In this position they allow ventricular stimulation, which is usually not as mechanically efficient as endogenous depolarisation. More importantly, there is no co-ordinated atrial contraction. Many patients, especially those with reduced ventricular compliance (as occurs in ischaemia), have a substantially reduced cardiac output in the absence of atrial contraction to assist in ventricular preloading. One study found a 25% increase in cardiac output with atrial or A–V sequential pacing compared to ventricular pacing [9], and the effect was particularly pronounced in patients with low ejection fractions [10]. For this reason, placing wires on the right atrium is often also desirable, but this must be balanced with the risks described above.

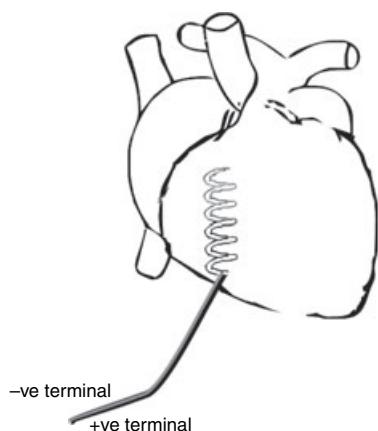
Epicardial wires are manufactured with a small needle on one end. This is used to embed the wire in the myocardium, after which the needle is cut off. Some wires are coiled to assist fixation; others can be clipped or loosely sutured in place. A larger needle on the other end of the wire is used to penetrate the body wall, bringing the wire to the surface. The lead should be sufficiently well anchored in the myocardium to avoid premature dislodgement, while still allowing eventual removal by gentle traction. Although the right ventricle is the most commonly used location, there is no agreement on optimal wire position, or even whether the intended position should be tested intra-operatively while there is still the opportunity for repositioning. There are competing influences: some positions give a better haemodynamic profile, and others preserve the longevity of the wires [11]. This question could form the subject of a separate review, and as the decision will seldom rest with the anaesthetist or intensivist, it will not be discussed further here.

### **Epicardial pacing wires: unipolar and bipolar**

Two epicardial wire systems are in common use: unipolar and bipolar (Figs 1 and 2). A unipolar system consists of a single wire (the negative anode) attached to the epicardium, with the positive electrode attached at a distance in the subcutaneous tissues. Which wire is which must be clearly marked at the ends protruding through the skin. The alternative bipolar system involves a single wire with two conductors insulated from one another, which both



**Figure 1** Unipolar epicardial pacing electrodes.



**Figure 2** Bipolar epicardial pacing electrodes.

run to the epicardial surface. The negative anode is usually the more distal. The ends of the conductors are 8 mm apart in one commonly used wire (the Medtronic bipolar coaxial 6495: Medtronic, Minneapolis, MN). As the current must travel a much shorter distance between electrode tips, the electrical potential required to bring the myocardium to threshold is less than in the unipolar system. This makes bipolar electrodes more suitable for use in dual chamber applications, as the likelihood of between-chamber interference is less when smaller potential differences are applied. As explained below, epicardial wires are also used by pacemakers to sense endogenous electrical activity. The smaller current path of bipolar electrodes makes them less susceptible to electrical interference when performing the sensing function. The larger current in a unipolar system creates much larger pacing spikes on the surface ECG.

By informal convention, wires attached to the right atrium are brought out through the skin on the right of the sternum, and those from the right ventricle emerge on

the left. Again, the wire that should be connected to the negative terminal of the pulse generator (epicardial for unipolar; distal epicardial for bipolar) should be marked; this is achieved by colour coding wires or with adhesive tags, according to local convention.

A major problem with all epicardial wires is the development of an inflammatory reaction around the wire/myocardium interface. Inflammation is accelerated when higher energy is applied, which is one reason to limit pacemaker energy output. Unfortunately, the only remedy for increased resistance is the application of increased current or voltage – which further increases the inflammation. As bipolar electrodes require less energy to begin with, they may have a greater longevity in pacing compared to a unipolar system [12, 13]. Epicardial wires usually fail to sense and capture after a few days. Increases in stimulation threshold typically occur after 4 days in both atrial and ventricular wires [14], and failure to pace is observed in >60% right and >80% left atrial wires after 5 days [15]. Other than minimising the initial energy delivered to the wire, techniques employed to extend wire longevity include variations in placement site (which must be balanced against haemodynamic optimisation) and the use of steroids. High dose systemic steroids are sometimes given to patients whose permanent pacemaker wires exhibit rapidly increased thresholds in the first few days. However, for patients with permanent pacing systems, this has largely been replaced by the use of steroid-eluting endovascular pacing wires. At present, steroid-eluting epicardial wires are only available for permanent placement in paediatrics. The efficacy of systemic steroids in extending the longevity of temporary pacing wires has not been studied.

### Diagnostic use of pacing wires

If not required for the transmission of a pacemaker impulse, atrial pacemaker wires can be used to create an atrial electrogram (AEG). Though seldom used, in some circumstances the atrial electrogram may be the best method of differentiating atrial and junctional arrhythmias, and in defining the nature of an AV block.

On many modern ECG recorders, there are three leads made specifically for this purpose: two for the bipolar atrial wires and a third for a skin electrode on the patient's flank. When the AEG channel is set to lead I, the potential between the tips of the two atrial electrodes is recorded (a 'bipolar' recording). This shows a large deflection with atrial depolarisation, but almost no signal with ventricular depolarisation. When set to lead II or III, the potential between one of the wires and the skin electrode is recorded (a 'unipolar' recording). In comparison to the bipolar recording, a larger ventricular signal is recorded. Alternatively, on an

ECG machine without specific AEG leads, the connectors that usually go to the right and left arm leads can instead be attached to the bipolar atrial pacing wires. In this arrangement, a bipolar AEG will be similarly recorded in lead I, and a unipolar AEG in leads II or III. The only disadvantage of this system is the inability to record simultaneously from the standard chest leads; for this reason some recommend connecting the pacing wires to the chest leads instead.

Analysis of the AEG is useful in a number of situations, particularly in some forms of heart block. Sinus node exit block (resulting in dropped P waves), second degree AV block, and third degree block with isorhythmic AV dissociation are all more easily diagnosed. The AEG allows timing of sinus depolarisation as opposed to P wave activity and also the identification of sinus or other atrial activity that might otherwise be lost within an ectopic depolarisation. A more detailed treatment of the use of AEGs is presented elsewhere [16].

### Alternatives to epicardial pacing wires

Epicardial wires are not the only means of temporary pacing after cardiac surgery. Alternative means of delivering the potential difference from the pacemaker box to the myocardium include a temporary transvenous wire, an electrode attached to an oesophageal probe, and transcutaneous electrodes. It is possible to pace the atrium using a temporary transvenous 'J-tip' wire lodged in the right atrial appendage, but this is technically difficult to place. Temporary transvenous wires are more commonly used to stimulate ventricular depolarisation. Oesophageal and transcutaneous pacing may depolarise large areas of the myocardium simultaneously, but the effect is usually similar to ventricular pacing. If pacing is an anticipated requirement after cardiac surgery, epicardial wires are the preferred technique. They more reliably sustain capture and are less prone to dislodgement and infection than a temporary transvenous wire, and do not require sedation as often do transcutaneous pacing or an oesophageal probe.

### General care of a patient with epicardial wires

Epicardial pacemaker wires are a low resistance connection to the heart. This creates the potential for microshock-induced arrhythmia, particularly ventricular fibrillation. Patients must be nursed in a cardiac-protected electrical environment, which implies adequately isolated electrical equipment and measures to prevent build-up of static electricity (absence of carpet, for example). Wires should only be handled with non-conductive gloves, and a large metal object (the bed, for example) should be touched first to discharge static potential prior to touching

the wires. The wires should be protected in a non-conductive container (for example, a plastic syringe barrel) when not in use.

To minimise unwanted electrical interference, by default, modern digital ECG monitors apply a high frequency filter to the incoming signal. In most cases this filters out the brief pacemaker spike, making it difficult to tell whether a pacing stimulus is being delivered. This can be overcome on most modern monitors by selecting the 'pacemaker' mode, which will record each spike, often highlighted with a marker. The small skin potentials created by bipolar leads in particular may be difficult to detect, and it may be necessary to inspect a variety of leads. Extracardiac, high frequency interference may become problematic, in which case the monitor can be returned to its usual mode after pacing diagnostics have occurred.

Electrical pacemaker output does not necessarily equate to mechanical capture of the myocardium, and as such it is helpful to have a monitor demonstrating the timing of cardiac contraction. An arterial pressure tracing or pulse oximeter waveform are the most readily available, and can usually be printed next to the ECG on a cardiac rhythm strip. This is much more helpful than attempts at analysing the moving screen image. If attempting to find pacing settings that produce optimal cardiac output, it is also helpful to have a high time-resolution monitor of cardiac output, such as echocardiography, continuous cardiac output pulmonary artery catheter, mixed venous oxygen, or one of the pulse contour analysis devices.

Pacemaker-dependent patients are at risk of pacemaker system failure or pacemaker-generated arrhythmia, and as a minimum should have continuous ECG monitoring and immediate access to a cardiac defibrillator with the capacity for transcutaneous pacing.

### Daily checks

Every day (and ideally with each change of nursing shift), a number of checks should be made on the pacing system. If the patient is cardiovascularly unstable for reasons unrelated to pacing, these other problems should be addressed before altering any pacing settings.

### Underlying rhythm

The need for ongoing pacing should be regularly reassessed. This is best done by turning down the pacing rate and allowing the endogenous rhythm to appear. This is a better strategy than turning down the pacing energy output until capture is lost, as there may be no underlying rhythm at all. It is occasionally impossible to re-establish capture once it has been lost –

leading to potential disaster if the underlying rhythm is inadequate.

### Sensitivity

The 'sensitivity' (as numerically represented on the pacing generator) is the minimum current that the pacemaker is able to sense. A lower number thus corresponds to a greater sensitivity. This paradox causes considerable confusion.

To check the sensitivity, the pacemaker rate should be set below the endogenous rate (if present), and placed in VVI, AAI or DDD modes. An explanation of the various pacing modes is presented in part 2 of this review. The sensitivity number is increased (making the pacemaker *less* sensitive) until the sense indicator stops flashing. Pacing should then occur asynchronously in the chamber being tested. This should not be allowed to persist for too long because there is a risk of precipitating atrial or ventricular fibrillation if the pacing spike is delivered late in the repolarisation phase (an artificial 'R-on-T'). The sensitivity number is then turned down (making the pacemaker more sensitive) until the sense indicator flashes with each endogenous depolarisation (in time with the P or R wave on the surface ECG). The number at which this first occurs is the pacing threshold. Most institutional protocols recommend leaving the pacing generator set at half the pacing threshold, to allow for detection of abnormally small signals, and for the possibility that perilead fibrosis over the course of the day will reduce the current transmitted to the pacemaker.

If there is no endogenous rhythm, it is impossible to determine the pacemaker sensitivity, in which case the sensitivity is typically set to 2 mV.

As explained in Part 2 of this review, if the sensitivity value is too low (i.e. the pacemaker is too sensitive), there may be inappropriate sensing of far field signals such as R or T waves, which may inappropriately inhibit pacing.

### Capture threshold

The capture threshold is the minimum pacemaker output required to stimulate an action potential in the myocardium. The capture threshold should not be checked if there is no underlying rhythm (which will have been established in the first step of these checks), for fear of losing and not being able to regain capture. If this is the case, careful continuous attention should be paid to the development of occasional missed beats, which (other causes having been excluded) will indicate a rise in the capture threshold and a need to increase the pacing output.

If it is safe to check the pacing threshold, the pacemaker rate should be set above the patient's endogenous rate, such that the chamber of interest is being consistently paced. The pacemaker energy output is then reduced

until a QRS complex no longer follows each pacing spike. This is the capture threshold. Typically, the output is left at twice the threshold, again to allow a margin of safety. However, if the threshold is  $> 10$  mA, the margin of safety is set to a lesser value, so as not to accelerate fibrosis at the lead/myocardium interface.

### Rate

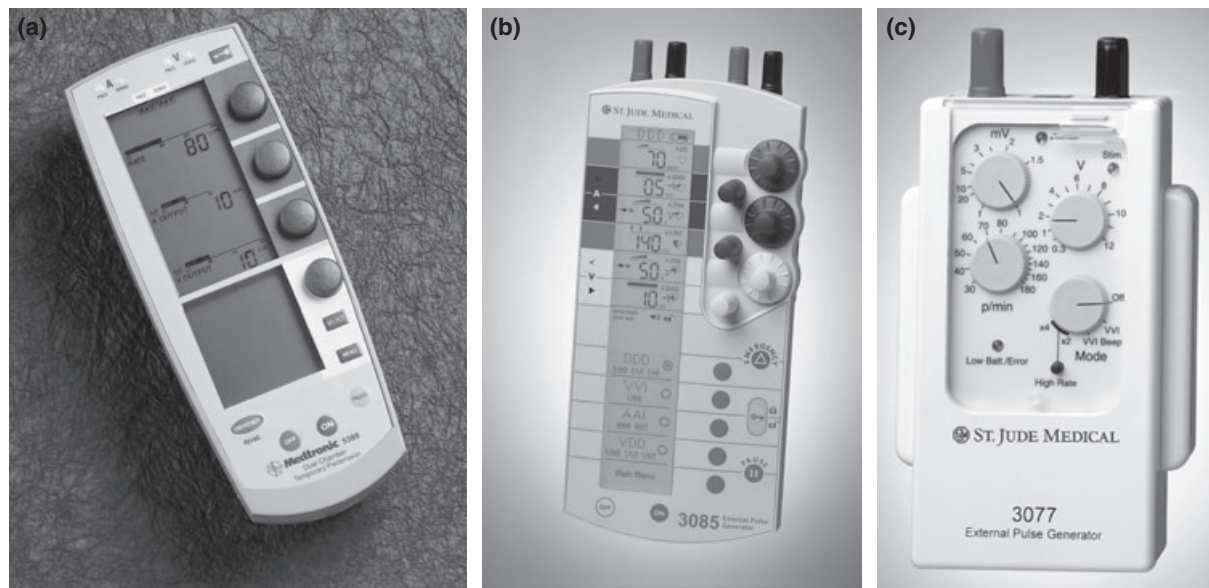
Cardiac output is the product of stroke volume and heart rate. After a point, as heart rate increases, stroke volume falls, so each patient will have an optimal heart rate for cardiac output. However, increased cardiac output driven by heart rate comes at the cost of increased oxygen consumption. In practice, the optimal heart rate is rarely accurately titrated to cardiac output and is usually left at  $80\text{--}90$  beats.min<sup>-1</sup> after the above adjustments are made. As a transition to complete reliance on endogenous rhythm, some advocate a period of 'backup' pacing (with the pacemaker set at around  $40$  beats.min<sup>-1</sup>), which allows the patient to remain in an endogenous rhythm until the point of significant haemodynamic compromise. This approach has the advantage of allowing the sensing threshold of the pacemaker to be continuously monitored. If full pacing is again required, it can be commenced with the confidence that the pacing threshold will not have become too excessive.

### Other pacing variables

The battery indicator should be checked. The appropriate pacing mode for the patient should be reassessed as described in part 2 of this review. The less commonly adjusted variables, such as the maximum tracking rate, AV interval, and post ventricular (pacing spike) atrial refractory period (PVARP) should be noted. These are also described in part 2. In practice, once these have been set (or left on automatic) and the pacemaker is functioning well in the desired mode, there is no reason to retest regularly whether they remain optimal.

### Pulse generators in common use

The Medtronic 5388 (Medtronic, Minneapolis, MN) and St Jude Medical 3085 (St Jude Medical, Sylmar, CA) are examples of currently marketed dual chamber temporary pulse generators, and the St Jude 3077 (St Jude Medical) and Medtronic 5348 (Medtronic) are single chamber devices (Fig. 3). The manufacturers' instructions for setting the various parameters are readily available in electronic format [17–19]. The different pacing modes and other variables that can be adjusted are the subject of the second part of this review. Typical settings are shown in Table 2.



**Figure 3** Commonly used temporary pulse generators. (a) Medtronic model 5388 (Medtronic, Minneapolis, MN, USA). (b) Medtronic model 5348 (Medtronic). (c) St Jude models 3085 (left) and 3077 (right) (St Jude Medical, Sylmar, CA, USA). Photographs provided by St Jude Medical and Medtronic.

### Removal of the epicardial wires

Pacing wires should be removed only after therapeutic heparin has been discontinued and before warfarin is commenced. They are removed by constant gentle traction, allowing the motion of the heart to assist dislodgement from the epicardial surface. Excessive traction should not be applied: occasionally the wires are caught by a tight suture either in the epicardium or somewhere along their course through the chest. In this case they should be pulled as far as is felt safe, and cut as close to the skin as possible. This will allow the cut ends to retract. There is no evidence that wires left like this have any adverse effect.

After lead removal the patient should be observed for a few hours, as there is a small (but ill defined) risk of tamponade at this point. Other complications noted with epicardial wire removal include ventricular arrhythmia [20] and damage to coronary anastomoses [21].

**Table 2** Typical pacemaker settings.

Atrial and ventricular output	10 mA or V (10–20 mA or 10–20 V)
PR interval/AV delay	150 ms (20–300 ms) or 'auto', determined by rate
Lower rate limit ('rate')	40 (backup); 80–100 (pacing)
Atrial overdrive stimulation	up to 800 ppm
Atrial sensitivity	5 mV (0.4–10 mV)
Ventricular sensitivity	5 mV (0.8–20 mV)
PVARP	250 ms or 'auto', determined by rate

### Considerations for transition to a permanent pacemaker

Rarely, a patient will remain dependent on epicardial pacing after cardiac surgery and may require implantation of a permanent pacemaker. The optimal timing for this decision will depend on the clinical course, but at 4–5 days it is reasonable to consider this option as by then many epicardial wires will have begun to fail. The patient should not be anticoagulated at the time of pacemaker box implantation.

Risk factors for requiring permanent pacing after cardiac surgery include age, pre-operative bundle branch block, prolonged cardiopulmonary bypass, and sub-optimal intra-operative myocardial protection [6]. Common indications for permanent pacing after cardiac surgery include complete heart block, sinus node dysfunction (sick sinus syndrome and other tachy-brady syndromes), slow ventricular response to atrial fibrillation, and second degree Mobitz type II heart block with an inadequate ventricular rate.

### Special circumstances

#### Magnetic resonance imaging (MRI)

MRI involves the application of both magnetic fields and radiofrequency pulses. A temporary pulse generator contains too much ferrous material to be allowed into the magnetic field with the patient. MRI is therefore not possible in a patient dependent on temporary epicardial

pacing. Whether a patient with epicardial wires in place, which are not being used, may have an MRI scan is more controversial. There is at least theoretical concern that a current could be induced in the epicardial wire by either the pulsating movement of the wire in the magnetic field, or the effect of the MRI radiofrequency pulse. Such a current could potentially precipitate an arrhythmia [22]. Energy transfer to the wire will also cause heating, with an increase of up to 20 °C at the electrode tip [23]. For this reason, most authorities agree that MRI is not advisable while epicardial leads remain in place. In contrast, patients with retained epicardial wires that have been cut off at the skin (and hence have no long ‘antennae’) have undergone MRI safely [24].

### Intra-aortic balloon pump (IABP)

If the IABP is timed according to a cardiac monitor with the high frequency filter disabled (to allow pacing spikes to become visible), the spikes may be misinterpreted by the IABP as QRS complexes. In the case of isolated ventricular pacing, the adverse effect of this small timing difference can be easily overcome by manual adjustment of the IABP timing parameters. However, if both atrial and ventricular spikes are misread as two QRS complexes, this will not be possible to correct. Either the IABP should be timed according to the arterial pulse, or the high frequency filter applied. This problem is lessened with bipolar leads, which have a smaller ECG representation than unipolar leads.

### Conclusion

The first part of this review has concentrated on the selection and routine management of temporary epicardial pacing systems. The second part will describe the indications for the various pacing modes and the optimal methods of troubleshooting the most common problems.

### References

- 1 Abraham WT, Fisher WG, Smith AL, et al. Cardiac re-synchronization in chronic heart failure. *New England Journal of Medicine* 2002; **346**: 1845–53.
- 2 Spotnitz HM. Optimizing temporary perioperative cardiac pacing. *Journal of Thoracic and Cardiovascular Surgery* 2005; **129**: 5–8.
- 3 Archbold RA, Schilling RJ. Atrial pacing for the prevention of atrial fibrillation after coronary artery bypass graft surgery: a review of the literature. *Heart* 2004; **90**: 129–33.
- 4 Maisel WH, Epstein AE. The role of cardiac pacing. American College of Chest Physicians guidelines for the prevention and management of postoperative atrial fibrillation after cardiac surgery. *Chest* 2005; **128**: 36S–8S.
- 5 Timothy PR, Rodeman BJ. Temporary pacemakers in critically ill patients: assessment and management strategies. *American Association of Critical-Care Nurses Clinical Issues* 2004; **15**: 305–25.
- 6 Bojar RM. *Manual of Perioperative Care in Adult Cardiac Surgery*, 4th edn. Malden, MA: Blackwell Publishing, 2004.
- 7 Puskas JD, Sharoni E, Williams WH, Petersen R, Duke P, Guyton RA. Is routine use of temporary epicardial pacing wires necessary after either OPCAB or conventional CABG/CPB? *Heart Surgery Forum* 2003; **6**: E103–E106.
- 8 Bethea BT, Salazar JD, Grega MA, et al. Determining the utility of temporary pacing wires after coronary artery bypass surgery. *Annals of Thoracic Surgery* 2005; **79**: 104–7.
- 9 Curtis JJ, Maloney JD, Barnhorst DA, Pluth JR, Hartzler GO, Wallace RB. A critical look at temporary ventricular pacing following cardiac surgery. *Surgery* 1977; **82**: 888–93.
- 10 Curtis J, Walls J, Boley T, et al. Influence of atrioventricular synchrony on hemodynamics in patients with normal and low ejection fractions following open heart surgery. *American Surgeon* 1986; **52**: 93–6.
- 11 Hurle A, Gomez-Plana J, Sanchez J, Martinez JG, Meseguer J, Llamas P. Optimal location for temporary epicardial pacing leads following open heart surgery. *Pacing and Clinical Electrophysiology* 2002; **25**: 1049–52.
- 12 Wirtz S, Schulte HD, Winter J, Godehardt E, Kunert J. Reliability of different temporary myocardial pacing leads. *Thoracic and Cardiovascular Surgeon* 1989; **37**: 163–8.
- 13 Yiu P, Tansley P, Pepper JR. Improved reliability of post-operative ventricular pacing by use of bipolar temporary pacing leads. *Cardiovascular Surgery* 2001; **9**: 391–5.
- 14 Elmi F, Tullo NG, Khalighi K. Natural history and predictors of temporary epicardial pacemaker wire function in patients after open heart surgery. *Cardiology* 2002; **98**: 175–80.
- 15 Daoud EG, Dabir R, Archambeau M, Morady F, Strickberger SA. Randomized, double-blind trial of simultaneous right and left atrial epicardial pacing for prevention of post-open heart surgery atrial fibrillation. *Circulation* 2000; **102**: 761–5.
- 16 Waldo AL, MacLean WAH. *Diagnosis and Treatment of Cardiac Arrhythmias following Open Heart Surgery*. Mount Kisco, NY: Futura, 1980.
- 17 Pace Medical. *Micro-pace temporary pacemaker Model 4570 Instruction Manual*, 4th edn. Waltham, MA, Pace Medical, 1998.
- 18 St Jude Medical. *St Jude Medical Dual Chamber Temporary Pacemaker Model 3085 Quick Reference Guide*. Sylmar, CA: St Jude Medical, 2003.
- 19 Scales G. *Medtronic Model 5388 Dual Chamber Temporary Pacemaker Technical Manual*. Minneapolis: Medtronic, 2001.
- 20 Carroll KC, Reeves LM, Andersen G, et al. Risks associated with removal of ventricular epicardial pacing wires after cardiac surgery. *American Journal of Critical Care* 1998; **7**: 444–9.
- 21 Del Nido P, Goldman BS. Temporary epicardial pacing after open heart surgery: complications and prevention. *Journal of Cardiac Surgery* 1989; **4**: 99–103.

- 22 Peden CJ, Collins AG, Butson PC, Whitwam JG, Young IR. Induction of microcurrents in critically ill patients in magnetic resonance systems. *Critical Care Medicine* 1993; **21**: 1923–8.
- 23 Luechinger R, Zeijlemaker VA, Pedersen EM, et al. In vivo heating of pacemaker leads during magnetic resonance imaging. *European Heart Journal* 2005; **26**: 376–83.
- 24 Hartnell GG, Spence L, Hughes LA, Cohen MC, Saouaf R, Buff B. Safety of MR imaging in patients who have retained metallic materials after cardiac surgery. *American Journal of Roentgenology* 1997; **168**: 1157–9.
- 25 Atlee JL, Bernstein AD. Cardiac rhythm management devices (Part I): indications, device selection, and function. *Anesthesiology* 2001; **95**: 1265–80.
- 26 Rozner MA, Frankina M. Cardiac pacing and defibrillation. In: Kaplan JA, Reich DL, Lake CL, Konstadt SN, eds. *Kaplan's Cardiac Anesthesia*. Philadelphia: W. B. Saunders, 2006; 827–43.