Pacemaker therapy of postoperative arrhythmias after pediatric cardiac surgery

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Objective: **To summarize the practical operation of temporary pacemakers in common use pertinent to the intensivist caring for the postcardiac patient. Pacemaker therapy is commonly required in the postoperative period after congenital cardiac surgery.**

Data Synthesis: **Monitoring the hemodynamic status and availability of equipment for resuscitation is always important in any patient requiring a temporary pacemaker. Two important scenarios to consider in the pediatric intensive care unit are: 1) the patient in whom pacing has been initiated to optimize cardiac function; and 2) the patient without demonstrable spontaneous electrical activity or with extreme bradycardia. A number of different models of temporary pacemaker are available. Management of the child requiring cardiac pacing requires an understanding of the indications for pacing, a thorough knowledge of the available pacemaker, and an ability to troubleshoot problems.**

Conclusions: **As the most common arrhythmias post congenital cardiac surgery involve either rate or conduction abnormalities, temporary pacemaker systems are a common form of electrical therapy in the postoperative period. (Pediatr Crit Care Med 2009; 10:000–000)**

KEY WORDS: emporary pacemaker; congenital heart disease; arrhythmia; postoperative; children

OVERVIEW

The objectives of this review are: 1) to provide a practical guide to the use of temporary cardiac pacemakers in the management of postoperative arrhythmias in pediatric patients; 2) to review alternative electrical therapies in the emergency management of arrhythmias in children (1).

Models

Single and dual chamber temporary external pacemakers are available from a number of manufacturers. Four such companies are Osypka (101H and 203H, Oscor), Biotronik (20/B, 30/B, and 30/BP), St. Jude (3085), and Medtronic (5348 and 5388). The general features and programmability are similar; however, there are specific differences. Default settings and available pacemaker modes differ, and programmable pulse width is not available in Medtronic models. The internal capacitance differs. In Medtronic models, the pacemaker is rated to continue pacing for 15 secs during a battery change at nominal settings of VVI 70/min, whereas it is rated for at least 30 secs in programmed mode in the Osypka models.

Basic Pacemaker Components

Temporary pacemaker systems consist of an energy source (battery), timing circuitry, and leads.

Leads

The usual interface between the pacemaker leads and the cardiac muscle in postoperative patients occurs on the outer (epicardial) surface of the heart. The pacemaker leads complete the electrical circuit—a negatively charged anode and a positively charged cathode—that is necessary for myocardial depolarization. Myocardial depolarization is more easily achieved with a negative electrical charge; therefore, anodal stimulation is preferred.

The options for temporary pacing leads in the cardiac intensive care unit are listed in Table 1. Epicardial pacing lead systems encountered in the cardiac pediatric intensive care unit are typically bipolar (two terminals in contact with and separated from each other by myocardium). Advantages of bipolar electrodes over unipolar are: 1) less between-chamber interference; 2) less electrical interference during sensing; 3) lower pacing thresholds; and 4) better sensing of local electrograms (2).

By convention, the two pacing leads attached to the anterior surface of the right ventricle exit the skin on the left side of the chest, and the two on the anterior atrial surface exit the skin on the right side of the chest. The timing and appearance of the electrograms in relationship to the electrocardiogram, and the chest radiograph, will help clarify the lead/chamber relationships if there is uncertainty. Caution should be exercised in cardiac malpositions.

An esophageal pacing lead might be used to establish atrial pacing in patients whose atrial leads are not functioning or not present (1). Tracking of the atrium is possible; however, the instability of the esophageal lead position makes this a temporary measure. Esophageal leads require a much higher output to capture the atrium (typically, a pulse width of 9 msecs and output of $\geq$10 mA) and a specialized generator is used. Esophageal pacing only captures the atrium and will not provide rescue therapy if ventricular pacing is required.

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Table 1. ●●●

Type	Leads	Generator	Typical Usage
Temporary epicardial	Placed at surgery, through skin, adherent to epicardium	External, temporary device or stimulator	Postoperative after heart surgery
Temporary transcutaneous	Adhesive pads placed on skin	Defibrillator with external pacing capability	Bradycardia during cardiac resuscitation
Temporary transvenous	Balloon electrode through venous sheath[a]	External, temporary device or stimulator	Bradycardia during resuscitation, especially in larger patient
Temporary esophageal	Esophageal electrode placed behind left atrium	External, temporary device or stimulator	Can be used for diagnostic purposes or post heart surgery for atrial pacing

[a]___.

Table 2. Causes of loss of pacemaker capture

Pulse generator
Battery
Programming to inadequate output
Leads
Lead dislodgment
Trauma or fracture
Lead myocardial interface
Myocardial
Ischemia
Scar
Metabolic
Acidosis/alkalosis
Hypoxemia
Hyperkalemia
Severe hyperglycemia
Infection
Medications
Apparent loss of capture
Pacing during refractory periods of cardiac action potential
Electromagnetic interference suppressing output
Oversensing
Crosstalk

Basic Temporary Pacemaker Function

The three main functions of the system are pacing, sensing, and timing.

Pacemaker Capture

The lowest depolarizing output current that causes contraction is the capture threshold. For permanent pacing systems, the output is usually set between two and three times capture threshold; however, this is often exceeded in the postoperative period because of the potential for many factors to contribute to unstable thresholds (Table 2).

The duration of the pacing impulse is known as the pulse width and is measured in milliseconds. In temporary pacemakers, the pulse width is either fixed or programmable. The amplitude is usually programmable over a wide range and is measured in either volts (Osypka, St. Jude, Biotronik) or mA (Medtronic).

Pacemaker Sensing

Sensing spontaneous myocardial depolarization is essential and depends on the integrity of the lead system as well as the vector of the electrogram in relationship to the leads. Bipolar sensing systems see more discrete signals resulting in less interference and noise than unipolar leads.

The sensing threshold is the highest programmable voltage level at which the pacemaker can still detect the intrinsic electrical depolarization of the chamber. Adjusting the threshold too high results in undersensing, and adjusting the threshold too low results in oversensing (Fig. 1). Oversensing can lead to inappropriate suppression of pacemaker activity. In permanent pacemakers, sensing is set at one half to one third of the sensing threshold to provide a safety margin. In postoperative temporary pacing, even with thresholds >5 mV, it may be prudent to program sensing at 2 mV to provide a safety margin in the uncertain conditions of the postoperative period.

Timing Intervals

Pacing Timing

Single chamber pacemakers can set a lower rate limit. Dual chamber pacemakers have programmable lower rates and upper maximum tracking rates, depending on the mode. The selection of the appropriate rate is based on age, an assessment of the underlying rhythm, and the required hemodynamic effect.

Sensing Timing (Fig. 2)

Blanking periods follow a paced or sensed event. The device ignores all electrical activity to prevent one lead from sensing a pacing artifact from another lead (cross-talk). Refractory periods (during which the device can sense but does not reset pacing timing) are either programmable or nonprogrammable. Each refractory period commences with the blanking period and prevents timing intervals from being started by signals, such as retrograde P waves or far-field R waves.

The atrial refractory period is initiated by an atrial sense or pace. The programmable postventricular atrial refractory period (PVARP) is initiated by a ventricular sense or pace event, and prevents the tracking of P waves that originate from retrograde conduction or loss of atrioventricular (AV) synchrony (e.g., failure to capture atrium). In dual chamber pacemakers the total atrial refractory period is programmable, and is the sum of two programmable intervals—the AV interval and the PVARP. There is a single ventricular refractory period initiated by a ventricular pace or sense that prevents sensing of the pacing stimulus and R wave.

Programming

In each pacemaker mode, there are certain items that are programmable and others that are not. Table 3 is a reference table for the usual pacemaker modes whereas Table 4 describes the basic steps in setting up the pacemaker in different patient conditions, using these basic programming profiles.

The base rate is determined by the reasons for pacing and the hemodynamics. The upper rate is usually selected based on age and hemodynamic needs, and it is designed to set the maximal ventricular pacing rate allowed at the same time tracking the atrium. At sensed atrial rates above the maximum upper tracking rate, the ventricular response resembles 2nd degree AV block. Default upper rate settings are set automatically based on the lower rate; however, these rates are usually too low

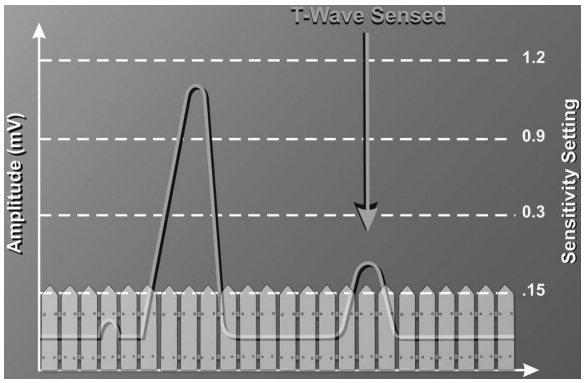

Figure 1. NEED FIGURE 1 LEGEND.

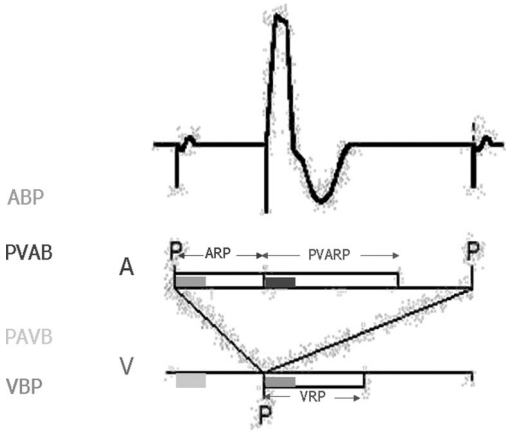

Figure 2. Refractory and blanking periods. *ABP*, ——; *PVAB*, ——; *PAVB*, ——; *VBP*, ——; *ARP*, atrial refractory period; *PVARP*, postventricular atrial refractory period; *VRP*, ventricular refractory period; *A*, ——; *V*, ——; *P*, ——. Courtesy of Medtronic.

Table 3. Features that require active programming decisions

	AAI	VVI	DDD	DVI	VDD
Rate (base)	Yes	Yes	Yes	Yes	Yes
Upper rate			Yes		Yes
A sense	Yes		Yes		Yes
A output	Yes		Yes	Yes	
V sense		Yes	Yes	Yes	Yes
V output		Yes	Yes	Yes	Yes
PVARP			Yes		Yes
AV interval			Yes	Yes	Yes

PVARP, postventricular atrial refractory period; AV, atrioventricular.

for children and manual selection is required.

The fixed or the default values are usually appropriate for pulse width. Most devices have the option for automatic adjustment of the PVARP (the PVARP decreases as the ventricular rate increases). The high tracking rates often required in the pediatric intensive care unit necessitate manually selecting an appropriate PVARP.

The AV interval begins with either a sensed or paced complex. In modes where there are both atrial pacing and sensing, the programmable AV interval refers to the postpacing AV interval. The postsensing AV interval is automatically set at a shorter interval (for example, 30 msecs). Therefore, a measured AV interval on an electrocardiogram may seem to be shorter than the interval set on the pacemaker. There is one AV interval in pacemaker modes in which the atrium is only sensed (VDD mode) or paced (DVI mode).

Pacemaker Nomenclature

To standardize pacing nomenclature, a code has been developed to identify different modes of operation for pacemakers (Table 5). All possible modes may not be available in temporary pacemakers.

Pacing Modes

There are many factors that influence the choice of pacing mode, including the potential effects of other therapies and the current status of the pacing system.

Generally

- Normal sinus rhythm and AV conduction at acceptable rates: inhibition of both atrial and ventricular pacing.
- Normal sinus rhythm with high-degree AV block: tracking of P waves with synchronized ventricular pacing.
- Sinus bradycardia with normal AV conduction: most often simply requires chronotropic support, and atrial pacing alone may be sufficient.
- Sinus bradycardia with AV block: pacing the atria and ventricles sequentially.

Single ventricular chamber pacing may be used in the absence of functioning atrial leads, if the atrial lead is not sensing appropriately or if chronic or persistent atrial arrhythmia makes atrial tracking contraindicated.

Single Chamber Pacing

Asynchronous Single Chamber Pacing: AOO, VOO

The atrium or ventricle is paced at a fixed rate regardless of intrinsic electrical activity and may result in asynchronous pacing (chamber may be paced when it is refractory or immediately after an intrinsic contraction). Temporary AOO may be used in overdrive pacing for atrial arrhythmias and temporary VOO may be considered during surgery in which electrocautery is being used.

Synchronous Single Chamber Pacing: AAI, VVI

These demand pacing modes will not pace when there is activity sensed in the respective chamber. Otherwise, fixed rate pacing will occur at the programmed lower rate. In VVI pacing, AV synchrony will not be maintained. AAI is a useful mode for sinus bradycardia provided AV conduction is intact (to maintain AV synchrony).

Synchronous, Sequential Single Chamber Pacing: VDD, VAT

In VDD mode, both atrium and ventricle are sensed but only the ventricle is paced. Sequential pacing is possible if atrial rate is greater than the lower (base) rate of the pacemaker. With no atrial activity, VDD functions as VVI. In

Table 4. Setting up the pacemaker for the first time

In either scenario, reduce the pacing rate before testing pacing threshold to reduce the likelihood of an asystolic pause	
Scenario A: Nonpacemaker-Dependent Patient	
Step 1: Reduce the pacing rate prior to testing pacing.	
Step 2: Manual Sensing Threshold—Dual Chamber Pacemakers	
With pacemaker on:	
Turn atrial and ventricular outputs to 0.1V or 0.1 mA	
Set rate control 10 beats/min (or less) than patient's intrinsic rate	
Access atrial sensing threshold field	
Turn control to maximum threshold	
Slowly reduce threshold	
Observing both patient monitor for atrial activity and atrial sensing indicator (visual or auditory) which will flash/beep synchronously with patients intrinsic rate at the sensing threshold	
Set the sensing control to at least one half the original sensing threshold to allow a margin of safety	
Typical atrial sensing thresholds <1mA	
Repeat procedure for ventricular threshold setting	
Typical ventricular sensing thresholds ~2–5mV	
Step 3: Capture threshold (patient has stable, acceptable intrinsic heart rates and conduction) Set rate control 10 beats/min above patient's intrinsic heart rate on ECG monitor	
Set atrial and ventricular outputs to minimum (e.g., 0.1 V or 0.1mA)	
Set AV interval less than intrinsic AV interval	
Slowly Increase Atrial Output Control	
Capture indicated by presence of atrial P wave post electrical spike on ECG monitor	
With intact A-V conduction, the AV interval can be set longer than patients AV interval and conducted heart rate will increase (indicated by rate monitor and arterial pressure tracing)	
With absent A-V conduction, there will be no rate increase	
Slowly increase ventricular output control	
Capture indicated by change in QRS complex to broad complex pattern, and increase heart rate, arterial pressure tracing and atrial waveform	
Once capture achieved, double the stimulation threshold to allow margin of safety	
Adjust A-V interval by observing ECG monitor and P-R interval on rhythm strip	
AV Sequential Pacing Indicated by	
Atrial spike immediately followed by P wave	
PR interval	
Ventricular spike immediately followed by paced QRS complex	Simultaneous arterial pressure waveform
Palpable pulse	
Biphasic right and left atrial waveform	
Scenario B: Pacemaker-dependent patient	
The procedures are the same except greater caution is required when ventricular noncapture occurs, as there may be no ventricular escape rhythm	
Reduce the pacing rate before searching for an intrinsic heart rate for sensitivity testing. If intrinsic heart rate does not appear at reasonably low rates (for the clinical situation), or if hemodynamic instability occurs at these low rates, testing sensing thresholds should be abandoned until a later time	

ECG, electrocardiogram.

VAT mode, ventricular pacing is triggered by a sensed atrial event. Reversing the atrial and ventricular leads produces AVT pacing as a method that may reestablish AV synchrony in patients with JET (3).

Dual Chamber Pacing

The benefits of dual chamber pacing in the immediate postoperative period generally relate to both chronotropy and AV synchrony as methods of increasing cardiac output (4).

DDD Pacing

Both chambers of the heart can be sensed and/or paced in DDD mode. A sensed atrial impulse will initiate an AV delay followed by either a ventricular sensed event or a ventricular paced event.

A sensed atrial event inhibits atrial output from the pacemaker and initiates blanking and refractory periods. A conducted impulse to the ventricle inhibits the ventricular output. The maximum possible rate that the pacemaker can track is determined by the total atrial refractory period (AV delay + PVARP). Once that atrial rate is exceeded, AV block occurs and results in sudden changes in heart rate. Too short an AV interval may be hemodynamically disadvantageous in the postoperative patient. Too short a PVARP increases the likelihood of a pacemaker-mediated tachycardia or oversensing.

DVI (AV Sequential) Pacing

In DVI mode, the atria and ventricles may be paced in sequence but only ventricular activity is sensed. Pacing is at the

Table 5. Pacemaker Code NASPE/BPEG

Position Category	I Chamber(s) Paced	II Chamber(s) Sensed	III Response to Sensing
	0 = None A = Atrium V = Ventricle D = Dual (A + V)	0 = None A = Triggered V = Ventricle D = Dual (A + V)	0 = None T = Triggered I = Inhibited D = Dual (T + I)

1. Position one refers to the chamber paced: A for atrium, V for ventricle, D for both.
2. Position two refers to the chamber sensed: A for atrium, V for ventricle, D for both.
3. Position three refers to the response to sensed intrinsic activity.
   a) I (inhibition)—a pacemaker's discharge is inhibited by sensed signal, e.g., VVI, where ventricular pacing is inhibited by sensed ventricular activity.
   b) T (triggering)—a pacemaker's discharge is triggered by a sensed signal, e.g., DDD, where ventricular pacing is triggered after a suitable atrioventricular delay.

programmed low rate only. The AV interval determines how much earlier than the low ventricular rate interval the atrium will be paced—regardless of intrinsic atrial activity. After an atrial stimulus, if AV conduction is successful, ventricular pacing is inhibited; otherwise, ventricular pacing occurs. If intrinsic heart rates are below the lower programmed rate, sequential AV pacing can result. Sequential pacing will be interrupted if the intrinsic atrial rate is above the programmed low rate, and is competing with the committed atrial pacing stimulus. Inappropriate stimulation may also precipitate atrial arrhythmias (atrial flutter or fibrillation).

Endless Loop (Pacemaker Mediated) Tachycardias

With DDD and VDD pacing, reentry pacemaker-mediated "endless-loop" tachycardia is possible if VA (retrograde) conduction is intact. These are commonly initiated by a ventricular premature beat. If the retrograde atrial beat is sensed by the atrial lead, it can initiate an AV delay, after which ventricular pacing will occur and conduction to the atrium can occur again. This type of tachycardia is an endless loop: the circuit's anterograde limb is the pacemaker, and the retrograde limb is via the AV node. Conversion to an atrial, nonsensing mode (DVI) or increasing the PVARP should prevent endless loop tachycardia.

Setting the Pacemaker in the Postoperative Patient

It is generally advisable to attach the leads to the pacemaker at the end of surgery regardless of the apparent integrity of the conduction system, and it is important to determine the patient's underlying rhythm and dependence on the pacemaker on arrival in the pediatric intensive care unit. Hemodynamic monitoring and availability of resuscitation equipment are important in patients requiring pacemaker modification. Two important clinical scenarios to consider when interrogating and programming the pacemaker are: 1) the nonpacemaker-dependent patient with intrinsic spontaneous electrical activity; and 2) the pacemaker-dependent patient without demonstrable spontaneous electrical activity or with extreme bradycardia (Table 4).

Pacemaker Function Troubleshooting

Failure to Capture (Table 2)

Steps to consider if failure to capture is noted are: 1) increasing the energy delivered; 2) reversing the polarity by reversing the wires connected to the pacemaker cable; and 3) converting the bipolar system to a unipolar system if there is failure of one of the leads. In this last situation, one electrode is connected to the myocardium at the same time the second is in contact with the body using a skin electrode. The epicardial lead should be connected to the negative terminal and the skin electrode should be attached to the positive terminal of the pulse generator.

Upper Rate Limitations

A dual chamber pacemaker cannot pace the ventricle above the maximum atrial tracking rate. This is determined by the AV interval plus the PVARP; and high heart rates require the manipulation of the AV interval and PVARP within acceptable parameters.

Overdrive Pacing

With overdrive pacing, the heart is temporarily paced faster than the underlying rate to either terminate or suppress an arrhythmia. Reentry type arrhythmias, such as those due to atrial flutter or an accessory pathway, may be terminated, whereas those due to enhanced automaticity, such as junctional ectopic tachycardia, may be transiently suppressed. Although ventricular arrhythmias may be terminated occasionally by overdrive pacing, it is rarely indicated due to the fragile circumstances in the immediate postoperative period. To pace at the high rates required, some temporary pacemakers are equipped with the capability for "burst" pacing.

Overdrive pacing involves depolarizing (capturing) myocardium within the reentrant circuit (the "excitable gap") which makes the tissue refractory, thereby interrupting the propagating wave front—with termination of the arrhythmia. The ability to enter the circuit depends on the location of the circuit, the site of pacing in relation to the circuit, and the tachycardia rate. In the case of atrial flutter, the pacing must occur faster than the atrial rate, not the ventricular rate. A pacing rate between 10% and 30% faster than the tachycardia rate may be required. Capture should appear as a change in the morphology of the P waves if one is pacing the atrium, or a change in the conducted RR intervals. After capture is confirmed, the pacing is stopped abruptly. If the tachycardia was reentrant, it may terminate. If the tachycardia was automatic, it may be suppressed briefly before resuming.

The effectiveness of overdrive pacing in the immediate postoperative period after heart surgery in children is unknown; however, overdrive pacing using permanent pacemakers converts 63% of atrial reentrant tachycardias, at mean cycle lengths 66% of the underlying arrhythmia (5).

Pacing at a rate slower than the tachycardia rate (underdrive pacing) is less likely to cause sudden deterioration; however, its overall effectiveness in the immediate postoperative period is unknown.

Troubleshooting Overdrive Pacing

Failure to terminate the arrhythmia could be caused by 1) nonfunctioning wires; 2) pacing too slowly; 3) the wrong diagnosis (actual atrial rate is faster than suspected; the tachycardia is automatic not reentrant); 4) inadequate output delivered; or 5) the excitable gap has not been entered in a reentrant tachycardia. Recurrence may also require concomitant antiarrhythmic therapy. Evidence of atrial capture with failure of termination over a range of pacing rates and durations are more indicative of a refractory underlying arrhythmia.

Multisite Pacing

Ventricular multisite pacing is a method that deals with situations where uncoordinated contraction (dyssynchrony) of the ventricles results in reduced cardiac output. By pacing the ventricle at multiple sites simultaneously (for example, the right and left ventricle), improved coordination may be obtained. Conflicting results have been obtained in the immediate postoperative period in both children and adults, and the method would not yet be considered as mainstream therapy (1, 6–8).

Transcutaneous Pacing

The use of transcutaneous cardiac pacing is relatively uncommon in the pediatric cardiac surgery population due to the routine use of temporary pacing wires. However, in the absence of pacing wires, it can provide a bridge to other therapy, such as a transvenous pacing wire or even Extra Corporeal Life Support and should be considered in any child when emergency ventricular pacing is necessary for rate support. This can be accomplished by using external paddles or appropriately sized disposable cutaneous skin electrodes. Monitoring during pacing must be performed through the device's three-lead electrocardiogram cable. Ventricular activity can be sensed; therefore, pacing can be either demand (VVI) or asynchronous (VOO). Transcutaneous pacing does not interfere with chest compressions. Pericardial effusions or pads placed on the scapula will interfere with capture.

Typical rates available range between 40 and 170 ppm, with pacing current outputs ranging from 0 to 200 Joules. Once the patient has been stabilized, plans should made be immediately for a more permanent mode of pacing or support.

Special Considerations

Many postcardiac patients require sophisticated imaging. Computed tomography scanning does not interfere with temporary pacemaker functioning or affect retained leads. On the other hand, magnetic resonance imaging uses magnetic fields and radiofrequency pulses to generate images and creates potential problems. Guidelines for magnetic resonance imaging in patients with cardiovascular devices have recently been published (9). Radiofrequency pulses applied to epicardial wires cause current induction that could precipitate either an arrhythmia or heating of the wires with myocardial injury; hence, magnetic resonance imaging is not advisable in these patients. In contrast, patients with retained epicardial wires that have been cut off at the skin have undergone magnetic resonance imaging safely (10).

Pacemaker Wire Removal

The wires are removed by constant gentle traction. If they cannot be removed easily by traction, they should be pulled as far as is felt safe and cut as close to the skin as possible, allowing the cut ends to retract. There is no evidence that retracted wires cause any harm. Bleeding of short duration from chest drains can be expected. There is a small risk of tamponade (11). Therapeutic anticoagulation should be held before wire removal.

CONCLUSION

Electrical therapies, in the form of temporary pacemaker systems and external pacemakers, are important components of the overall care of pediatric patient post cardiac surgery. Effective use of these therapies requires a comprehensive understanding of the patient's electrophysiology and of the available pacemaker equipment.

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