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REVIEW

Pacing device therapy in infants and children: a review

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Abstract The number of pediatric pacemakers implanted is still relatively small. Children requiring pacing therapy have characteristics that are distinct from those of adults, including physical size, somatic growth, and cardiac anomalies. Considering these features, long-term follow-up of pediatric pacemaker implantation is necessary. Selection of appropriate generators, pacing modes, pacing sites, and leads is important. Generally, epicardial leads are commonly used in small infants. On the other hand, the use of endocardial leads in children is increasing worldwide because of their benefits over epicardial leads, such as minimal invasiveness, lower pacing threshold, and longer generator longevity. Endocardial leads are not suitable for patients with intracardiac shunts because of the high risk of systemic thrombosis. Venous occlusion is another significant problem with endocardial leads. With the increase in the number of pacing device implantations, the incidence of infection from such devices is also increasing. Complete device removal is sometimes recommended to treat device infection, but experience in the removal of endocardial leads in children is still scarce. This article gives an overview of pacing therapy in the pediatric population, including discussions on new pacing systems, such as remote monitoring systems, magnetic imaging compliant pacemaker systems, and leadless pacing devices.

Keywords Pacemaker · Child · Pacing lead

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Introduction

Pacing device implantations in young patients comprise only <1 % of all pacemaker implantations. Complicated issues are involved in pacing device implantation in children, such as their small physical size, somatic growth, and the presence of cardiac anomalies. Furthermore, pacing therapy in children requires long-term follow-up, and their treatment with pacing devices differs from that in adults. All of these issues should be considered when deciding whether to treat a child using pacing therapy and when selecting an appropriate pacing system. Generally, epicardial leads are commonly used in small infants. However, pacemaker implantation using epicardial leads is invasive because a thoracotomy is required and sometimes the leads are problematic. Recently, the use of endocardial leads is increasing worldwide due to their various benefits over epicardial leads, such as minimal invasiveness, lower pacing threshold, and longer generator longevity. Endocardial leads are not suitable for patients with intracardiac shunts because of the high risk of systemic thrombosis. Venous occlusion is another significant problem with endocardial leads in small children, because the diameters of their vessels are smaller than those of adults. The use of epicardial leads has the advantage that it avoids the risks of venous occlusion and systemic thrombosis associated with the use of endocardial leads. The incidence of pacing device infection is increasing as the number of pacemaker implantations in children increases. Complete device

removal is sometimes recommended to treat pacing device infection, but there is a paucity of reports on the removal of endocardial leads in children.

This article provides an overview of pacing therapy in the pediatric population, including discussions of new pacing designs such as remote monitoring systems, magnetic imaging compliant pacemaker systems, and leadless pacing devices.

Indications for pacing therapy in children

Children differ from adults in many ways, not only physique. Pacing therapy in children must take into account several unique pediatric issues: (1) small physique; (2) somatic growth; (3) presence of intracardiac shunts; and (4) a complex anatomical heart structure. It is important to understand these features when deciding whether pacing is indicated, as well as when selecting the time to implant and how to implant.

The 2008 Guidelines of the American College of Cardiology (ACC)/American Heart Association (AHA)/Heart Rhythm Society (HRS) summarize indications for pacing treatment in children (Table 1) [1]. Atrioventricular block including congenital atrioventricular block associated with cardiac surgery or a natural history of complex congenital heart disease such as corrected transposition of the great arteries are the most important indications for pacemaker implantation in children [1–6]. In pediatric patients, atrioventricular block that does not recover within 7–10 days after cardiac surgery is associated with a risk of sudden cardiac death in the future, so pacemaker implantation is recommended. However, atrioventricular conduction may be restored spontaneously in some patients with postoperative heart block; therefore, the patient's condition and anatomical features should be considered when deciding whether implantation is required [7]. Villain and colleagues [6, 8] searched for predictors of the late occurrence of advanced atrioventricular block among pediatric patients who developed transient block after cardiac surgery. They demonstrated that patients with an extended His to ventricle interval on intracardiac electrocardiogram were at high risk of atrioventricular block in the future. An infra-His conduction disturbance observed in a pediatric patient with postoperative transient atrioventricular block may be an indication for pacing therapy.

Table 1 Indications for pacemakers in children

1. Advanced second- or third-degree atrioventricular block associated with symptomatic bradycardia, ventricular dysfunction, or low cardiac output
2. Sinus node dysfunction and correlation with symptoms during age-inappropriate bradycardia. The definition of bradycardia varies with the patient's age and expected heart rate
3. Postoperative advanced second- or third-degree atrioventricular (AV) block that is not expected to resolve or that persists at least seven days after cardiac surgery
4. Congenital third-degree AV block with a wide QRS escape rhythm, complex ventricular ectopy, or ventricular dysfunction
5. Congenital third-degree AV block in an infant with a ventricular rate of <55 bpm or with congenital heart disease and a ventricular rate of <70 bpm
6. Acquired heart block in myopathies
7. Long QT syndrome with conduction disorder

Selection of epicardial leads and endocardial leads

Types of pacing leads

There are two types of pacing leads: epicardial and endocardial. The former is placed on the surface of the heart through a thoracotomy or sternotomy, whereas the latter is placed in the endocardial layer via a transvenous approach. Important factors for selection include body size, venous diameter, presence of intracardiac shunt, and risk of thrombosis. In general, endocardial leads are recommended for bigger children, while epicardial leads are used in small infants and older children with difficult venous access.

Body size

In Japan, an epicardial lead is currently commonly used in a child with a small body size (weighing <20 kg) because of the risks of venous obstruction and thrombus formation when using an endocardial lead. On the other hand, there is a global trend towards using endocardial leads in younger patients. Some institutes actively implant transvenous leads in children weighing <15 kg [4, 9–11]. Implantation of pacemakers using a transvenous lead in infants weighing 10 kg or less has been reported [9, 10, 12]. Stojanov et al. [9] implanted endocardial leads in 105 children (mean age 5.7 years) weighing 15 kg or more, with 25 % of them <10 kg, and reported no lead trouble, infection, or sensing failure during a mean follow-up of 6.7 years. Kammeraad et al. [10] reported endocardial pacing lead implantation in 39 infants with a median weight of 4.6 kg (range 2.3–10 kg) and median age of 3.3 months (range 2 days–35 months). During a median follow-up period of 4.3 years, 11 lead extractions were attempted in 9 patients because of venous thrombosis and device infection.

Complications such as symptomatic atrial pacemaker lead thrombosis, pulmonary thromboembolism, and superior vena cava syndrome have been reported [13–19]. The incidence of symptomatic pulmonary thromboembolism is 0.6–3.5 % when an endocardial lead is used in patients

without intracardiac shunt [20]. However, the risk of systemic thrombosis is high in patients with heart abnormalities and a large intracardiac shunt. In these patients, the use of an epicardial lead is recommended. Khairy et al. [21] reported that implantation of transvenous leads in patients with intracardiac shunts was associated with a lower threshold and a lower frequency of pacemaker exchange compared to epicardial leads, while the risk of systemic thromboembolism was twice as high. They also found that the use of warfarin and aspirin did not completely prevent thromboembolism [21]. Systemic thromboembolism has been reported not only in right-to-left shunt cases but also in left-to-right shunt cases such as small ventricular septal defect and atrial septal defect [22, 23]. In patients with an intracardiac shunt, epicardial leads are indicated, but an endocardial lead may be selected in a patient at high risk for thoracotomy, such as those with severe heart failure, severe cardiac dysfunction, a history of frequent open heart surgery, and multiple organ failure.

Venous occlusion and tricuspid valve regurgitation

Venous obstruction is a major complication of pacemaker implantation using an endocardial lead, especially in infants whose veins have small calibers. After endocardial lead implantation, venous occlusion occurs in approximately 15–30 % of adult cases [24–28] and in 20 % of pediatric cases [29].

Haghjoo et al. [27] reported that a large number of leads is a risk factor for venous obstruction in adults. Thrombus formed as a result of lead–endothelial interaction and neointimal proliferation may culminate in venous obstruction. Animal experiments have shown that thrombogenicity is due to the reaction of polyurethane and silicone lead insulation with the vascular endothelial surface [30]. In humans, however, no association between thrombogenicity and lead insulation material has been demonstrated [31].

The few studies that have investigated risk factors for venous obstruction in children implanted with transvenous pacing leads have reported controversial results. Bar-Cohen et al. [32] observed total venous occlusion in 13 % and partial venous occlusion in 12 % of 85 children and young adults (median age 15 years). They found that age, body size, growth, and lead-related factors such as lead duration, number of leads, number of procedures, history of lead extraction, and INDEX (lead size divided by the body surface area) did not significantly predict venous occlusion. On the other hand, Figa et al. [28] observed venous obstruction in 21 % of 63 children with transvenous leads, and demonstrated that patients with obstruction had a significantly higher mean INDEX than those with no obstruction. Nevertheless, choices of pacing system and vein need to take into account future growth and prevention of venous obstruction [30]. To estimate vein dimensions in growing children, Sanjeev and Karpawich [33] reported that the diameter of the innominate vein and superior vena cava and the lengths from the innominate vein to the superior vena cava junction and the superior vena cava to the right atrium junction were positively correlated with child height. Moreover, expansion of the venous diameter is age dependent up to ten years of age [33].

To address the change in venous length as infants grow, it is necessary to estimate the lead length and make a loop (Fig. 1) [33–36]. Generally, the loop of endocardial lead is created in the atrium and inferior vena cava. However, this strategy does not always solve the problem. A child developed pacing failure five years after pacemaker implantation because the ventricular endocardial lead was firmly attached to the endothelium of the inferior vena cava. Emergency revision showed that even though a loop was formed within the inferior vena cava during implantation, the expected lead release had not occurred [34]. Transvenous ventricular pacing leads across the tricuspid valve may cause or exacerbate tricuspid regurgitation (TR). Most cases of TR associated with transvenous ventricular leads are associated with minimal change in and little impact on hemodynamics [37]. However, cases requiring tricuspid valve operations for severe symptomatic TR due to ventricular pacing leads have been reported [38]. Careful observation of changes in TR should be considered after inserting transvenous ventricular leads across the tricuspid valve in growing children or patients with right-side structural heart disease.

Lead problems and reintervention

Table 2 compares endocardial and epicardial leads. Lead problems included lead fracture, insulation break, dislodgement, and abnormalities in pacing sensing or pacing. There is a high incidence of lead troubles in pediatric pacing patients. The reported incidence has been shown to be 15 % [39] and 27 % [40] of implanted leads. In younger patients (<12 years), congenital heart disease and epicardial lead systems are reported to be independent risk factors of lead problems [39]. Lead fracture is more common in children than in adults. Many factors, such as lead stretching due to somatic growth, compression of epicardial leads caused by the small space between ribs or between the clavicle and ribs for the endocardial lead, and other factors, contribute to lead fracture susceptibility. Short durability of pacemaker leads and limited access, including the small diameter of subclavian veins for the endocardial lead and a transthoracic or transsternal approach for the epicardial lead, may cause a serious problem in the future for children, given their much longer life expectancies than adult patients.

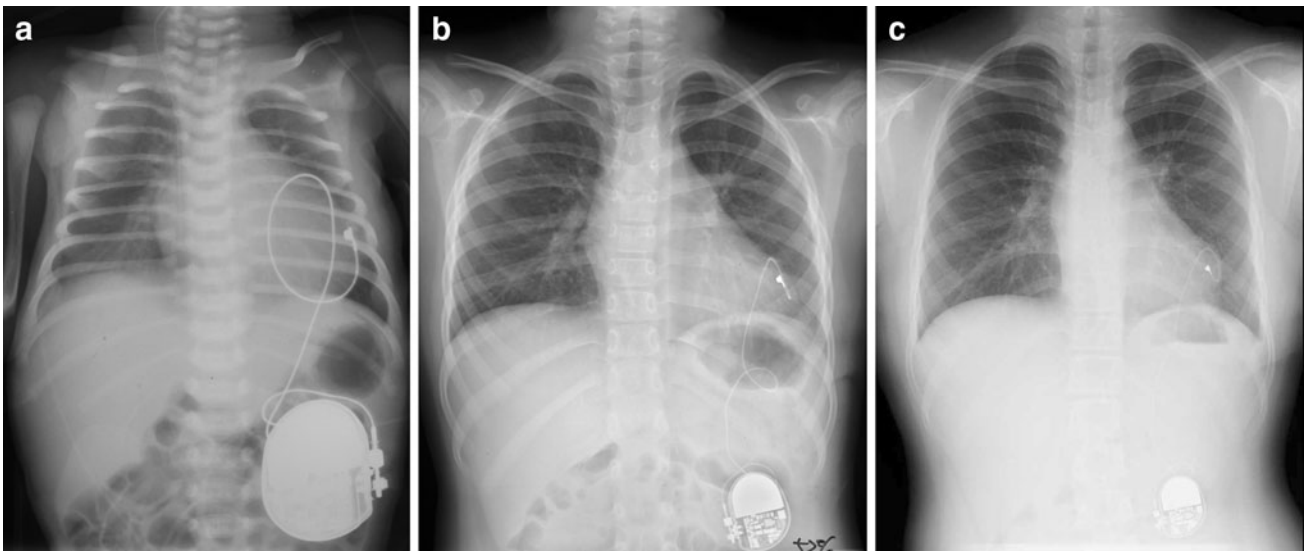

Fig. 1 Growth and change in a loop of an epicardial lead. A 16-day-old newborn with congenital atrioventricular block underwent pacemaker implantation using an epicardial lead. Radiographs at 16 days of age (**a**), 7 years later (**b**), and 12 years later (**c**) are shown. Note the change in the loop of the lead as the child grows

Table 2 Comparison between epicardial and endocardial leads

	Epicardial lead	Endocardial lead
Invasiveness	Maximum (thoracotomy or sternotomy is required)	Minimum
Incidence of high threshold and lead troubles	Higher than endocardial lead, but steroid-eluting epicardial lead reduces the risk of lead troubles	Comparatively few
Systemic thrombosis	None, even with intracardiac shunts	High risk in a patient with an intracardiac shunt
Venous occlusion	None	Possible
Lead removal due to device infection	Thoracotomy or sternotomy is required	Transvenous lead extraction, but there is still little experience of this procedure in children. Open heart surgery with extracorporeal circulation is sometimes required in cases with difficult lead extraction

Epicardial leads are affected by fibrosis and pericardial adhesion from prior surgery, and often result in failure due to an increase in threshold [41–44]. Moreover, because of the high pacing threshold, frequent generator exchange is necessary [21, 44]. Epicardial leads consist of stub-in leads, screw-in leads, and steroid-eluting suture-on leads. Each type of epicardial lead is unipolar or bipolar. The durability of stub-in and screw-in leads is considered to be shorter than that of the suture-on type. Steroid-eluting epicardial leads prevent threshold increase in the long term, reducing lead troubles as a result. In newborns and older infants, steroid-eluting epicardial leads have been used with excellent long-term outcome [45–49]. Currently, the suture-on type of endocardial lead (such as Capture Epi, Medtronic Inc., Minneapolis, MN, USA) is mainstream in Japan. However, the screw-in type (such as Myodex, St. Jude Medical Inc., St. Paul, MN, USA) became available in Japan in June 2012, which increases the range of devices obtainable. In children and adults with congenital heart disease, there are increasing reports of selective-site pacing using the SelectSecure lead (Medtronic Inc.). This system involves placing a 4.1 Fr lumenless steroid-eluting pacing lead (SelectSecure lead model 3830, Medtronic Inc.) inside an 8 Fr changeable delivery catheter (SelectSite model C304S-59 cm or C304L-69 cm, Medtronic Inc.) and advancing to the target site. This system allows arbitrary pacing at the selected site. The lumenless lead has a small diameter that reduces lead fracture and improves creep resistance [50–52]. Since the diameter of an 8 Fr delivery catheter is too large for small children, a 5 Fr delivery catheter (CheckFlo Performer® Introducer Set with the Children's Hospital Boston Modification, Cook Medical Inc., Bloomington, IN, USA) can be used in an infant [52].

Body size and generator size

For an infant with a small body size, a pacemaker with minimal thickness and a generator that is as small as possible should be chosen. Especially for newborns and premature infants weighing 4–5 kg or less, the smallest pacemaker generator available should be used. The smallest pacemaker generator that is currently commercially available is the Microny II 2526T (St. Jude Medical Inc., St. Paul, MN, USA). This is a single-chamber pacemaker measuring 33 mm × 33 mm, with a thickness of 6 mm, a volume of 5.9 cm^3, and a weight of 12.8 g. In comparison, a standard single-chamber pacemaker has a volume of 8–11 cm^3 and a weight of 17–23 g.

The Microny II is a bipolar sensing and single-chamber pacing device. The basic pacing rate can be adjusted to 40–160 beats/minute (bpm). However, output is limited to 4.5 V [53–55]. It is equipped with an "autocapture" function that automatically measures the pacing threshold. The pacemaker battery life can be extended by using the autocapture function with epicardial and endocardial leads [48, 53].

Pacing mode

Dual-chamber (DDD) pacemakers are often selected for adult patients with atrioventricular block. DDD pacing requires two endocardial leads. In infants, this presents a problem because the venous diameter is small and may cause venous obstruction. A VDD pacemaker instead of a dual-chamber pacemaker is a good alternative choice in children with complete atrioventricular block and normal sinus node function, because it requires only a single lead and may reduce the possibility of venous occlusion. When epicardial leads are used, atrial lead implantation via a subxiphoid approach is not possible, and either an invasive median sternotomy or a left thoracotomy must be performed. The high heart rate of infants is another issue. The mean heart rate of an infant is 100 bpm or faster, increasing to 180–200 bpm or above when crying. In an infant with atrioventricular block, the atrial rate becomes so rapid that it may exceed the maximum programmable upper tracking rate, which is limited by the postventricular atrial refractory period and atrioventricular delay. Under the condition where the atrial heart rate exceeds the maximum programmable upper tracking rate, symptomatic 2:1 atrioventricular block may occur. Therefore, in infants with a small body size and a rapid ventricular rate, single-chamber ventricular pacing (VVI) or single-chamber ventricular pacing with rate response (VVIR) should be selected.

Patients on DDD pacing with epicardial leads may lose the DDD pacing when the amplitude of the atrial wave is low [56]. Because of dyssynchrony in the ventricles caused by ventricular pacing, cardiac function may deteriorate in both children and adults with congenital heart disease [57–62]. In a Danish study that compared single-chamber ventricular pacing and single-chamber atrial pacing in patients with sick sinus syndrome, atrial pacing is associated with a significantly higher survival, less atrial fibrillation, fewer thromboembolic complications, less heart failure, and a low risk of atrioventricular block [63, 64].

A pacing mode selection trial reported that in patients with sinus node dysfunction, the lower the ventricular pacing rate, the lower the rate of atrial fibrillation and cardiac failure [65, 66]. In patients with sinus node dysfunction, unnecessary right ventricular pacing deteriorates cardiac function and increases atrial fibrillation, and also induces electrophysiological remodeling and repolarization instability, which may lead to proarrhythmia [67]. In patients with a preserved atrioventricular conduction system, such as those with sick sinus syndrome or first-degree atrioventricular block, algorithms that minimize unnecessary ventricular pacing are recommended [1, 68–75]. In patients with atrioventricular block and a well-maintained narrow QRS escape rhythm, when the lower pacing rate interval in ventricular pacing is set at a higher level, the ventricular pacing ratio increases and cardiac function is lowered. Therefore, care must be taken when adjusting the pacemaker.

In patients with high-grade atrioventricular block, ventricular pacing is indispensable, and the pacing site of the ventricular leads is a critical issue. Right ventricular apical pacing can worsen cardiac function for both endocardial and epicardial lead pacing [69, 71, 76–79]. His bundle pacing or para-Hisian pacing is preferable for endocardial leads. However, this pacing mode has various issues, such as technical difficulty with lead placement, a high pacing threshold, and a high energy requirement. Consequently, long-term stability cannot be obtained easily. Right ventricular septal pacing is favorable because it is an easy technique and can maintain a low pacing threshold compared with His bundle or para-Hisian pacing [77, 80, 81]. Left ventricular apical pacing is the best mode for epicardial leads in children, and left ventricular lateral wall pacing is also useful [82–84]. In children with lowered cardiac function caused by right ventricular pacing, changing to biventricular pacing or His bundle pacing is useful to improve cardiac function and reverse left ventricle remodeling [85–88].

Patients with congenital heart disease after cardiac surgery who have undergone pacemaker implantation due to sick sinus syndrome are sometimes associated with atrial flutter and intraatrial reentrant tachycardia. A pacemaker

with atrial antitachycardia pacing ability is useful for controlling both atrial tachycardia and bradycardia [89–91].

Site of device implantation

In general, when implanting endocardial leads via a transvenous approach, the generator is placed in the subclavicular region. Infants have thin subcutaneous tissue at the chest wall, so the leads are often placed above the posterior sheath of the rectus muscle of the abdomen. Since some people feel uneasy about implantation scars in the subclavicular region, the device pocket is made in the axilla region for cosmetic purposes [92, 93]. For newborns or infants who have gastrointestinal diseases such as necrotizing enterocolitis or are scheduled for abdominal surgery or peritoneal dialysis, the pacemaker is implanted in the chest or axilla [4]. Intradiaphragmatic pacemaker implantation was performed in a premature infant with a very low birth weight (1.3 kg) [55].

Cardiovascular implantable electronic device infection

The incidence of pacemaker lead infection is high in young patients [94]. Infection is one of the most severe complications of pacemaker implantation in children, because long-term management is required. Deep pacemaker pocket infections have been reported in 1–2 % of adult patients, and often require removal of the infected generator and lead or leads [95–97]. There are only a few reports on pacemaker lead infections in children, and the reported incidence was 5 % [10], 2 % [98], and 7.8 % [99]. Cohen et al. [99] reported a series of 385 pacemaker implantations (224 epicardial leads, 161 endocardial leads) in 267 patients over 20 years. Device infection occurred in 7.8 % of the patients (superficial infections 4.9 %, pocket infection 2.3 %, and isolated positive blood culture 0.5 %). Trisomy 21 and pacemaker revisions were significant risk factors for infection after pacemaker implantation. There was no difference in infection rate between epicardial and endocardial leads. Treatment of pacemaker lead infections should follow the 2010 update of the American Heart Association guidelines [100]. When cardiovascular implantable electronic device infection is accompanied by sepsis, infective endocarditis, bacteremia, vegetation, and device exposure, complete device removal including the endocardial lead is recommended [100]. The presence of an epicardial lead necessitates extensive surgical procedures for complete device removal, including a full or limited sternotomy or thoracotomy. Therefore, the suspicion of device component infection must be balanced against the risk associated with surgical removal [100].

Lead removal

Pacemaker lead removal is strongly recommended in patients with device infections and lead trouble. Zartner et al. [101] reported that transvenous leads were successfully removed in 89 % (25 of 28) of infected leads in 22 young patients (mean age 12.9 years). Using a laser sheath, Moak et al. [102] reported successful removal of transvenous leads in 91 % (39 of 43) of infected leads in 25 young patients (median age 13.9 years). However, two patients had major complications (pericardial tamponade and left subclavian vein thrombus). Cecchin et al. [103] reported that lead removal was successful in 80 % (162 of 203) of all infected leads in 144 pediatric and congenital heart disease patients, and in 94 % (103 of 109) of the leads undergoing complex extractions, including a radiofrequency-powered sheath [103]. They also found complications in eight patients (major in four, minor in four) but no procedural-related death. Open heart surgery with extracorporeal circulation is sometimes required to remove transvenous leads in cases of difficult lead extraction due to severe adhesion of the lead to the venous system, tricuspid valve or right ventricle. An increasing number of young patients have received transvenous pacemaker implantation. The number of patients who need lead removal is expected to increase in the future.

Epicardial leads are used in young children. When device infection occurs, removal of the epicardial lead is also required. After open heart surgery for congenital heart disease, complete removal of epicardial leads may be difficult because of strong adhesion.

Remote monitoring system

In recent years, remote monitoring systems have become available. Using these systems, physicians can receive pacemaker information, including battery status, pacing threshold, lead impedance, and cardiac events, from patients' devices while they are at home. The quality of the data collected by these systems is the same as that collected by manual interrogation by telemetry in the outpatient clinic. In Japan, CareLink Network™ (Medtronic Inc, Minneapolis, MN, USA), Home Monitoring™ (Biotronik GmbH & Co. KG, Berlin, Germany), Merlin.net™ (St. Jude Medical Inc., St. Paul, MN, USA), and the Latitude® Patient Management system (Boston Scientific, Natick, MA, USA) have been launched since February 2012. A remote monitoring system is beneficial in that it provides continuous monitoring and detects trouble with leads. As a result, it is possible to reduce severe lead complications, increase the patient's sense of security, and obtain high satisfaction of the patient [104–107]. When the number of

patients increases sufficiently, implantation of a pacemaker with a remote monitoring system should be profitable for epicardial leads that often have problems, as well as for detecting atrial arrhythmia that may occur in postoperative patients with congenital heart disease.

Cardiac resynchronization therapy

Cardiac resynchronization therapy (CRT) is an established management in adults with heart failure. The role and effectiveness of CRT remain unclear in children and patients with congenital heart disease. Pediatric patients who undergo CRT are a heterogeneous population, including those with cardiomyopathy, secondary cardiac dysfunction due to chronic ventricular pacing, and congenital heart disease. Heart failure associated with congenital heart disease can be divided into three subgroups according to ventricle anatomy: systemic left ventricle, systemic right ventricle, and single ventricle failure [108–110]. In small children, patients with congenital heart disease and intracardiac shunt, and patients with complex congenital heart disease after the Glenn procedure or a Fontan-type operation, epicardial lead placement is required due to limited transvenous access and the risk of systemic thrombosis.

Corrected transposition of the great arteries (CTGA) and a postatrial switch operation for transposition of the great arteries (Mustard or Senning procedure) are major physiological conditions in which the anatomical right ventricle functions as the systemic right ventricle. In CTGA, some variations of right coronary venous anatomy [111] may pose difficulties when placing a lead on the systemic right ventricle via a transvenous approach. In patients who received an atrial switch operation in which the orifice of the coronary sinus is cut back into the pulmonary venous chamber, transvenous lead placement on the systemic right ventricle is also impossible. In these instances, epicardial lead placement on the systemic right ventricle via a thoracotomy is required.

The criteria for CRT in adult populations are: NYHA functional class III or IV despite optimal pharmacological therapy, left ventricular ejection fraction <35 %, and QRS duration >120 ms. However, many pediatric patients undergoing CRT do not comply with the above criteria. A large proportion (62–70 %) of the pediatric and congenital heart disease patients who were enrolled in CRT trials were NYHA functional class I or II, indicating mild heart failure [88, 112, 113]. Van der Hulst et al. [110] suggested that a substantial proportion of pediatric chronic heart failure patients had concomitant indications for cardiac surgery (15–32 %), ICD implantation, or antibradycardia pacing (55–77 %), which may have accelerated the decision-making of CRT implantation during the same procedure in patients with only mild heart failure. When response was defined as an improvement in the ejection fraction of the systemic ventricle or NYHA functional class, the response rates after CRT ranged from 65 to 75 % [88, 112, 113]. The proportion of CRT conducted for systemic right ventricle or single ventricular failure ranged from 23 to 37 % [88, 112, 113]. Reverse remodeling by CRT seems to be less severe in systemic right ventricle than in systemic left ventricle cases [108, 113].

Other systems

Pacemaker system designed for the magnetic resonance environment

Great advances have been made in the field of imaging diagnostic technology in recent years. Magnetic resonance imaging (MRI) of the whole body has become popular. For patients with an implanted pacing device, it is important to know whether they can safely undergo an MRI examination.

Recent reports have indicated that an MRI examination can be performed without complications in patients with a pacemaker. Nevertheless, the presence of a pacemaker is conventionally considered a contraindication to MRI examination [114–119]. In 2011, the US Food and Drug Administration approved the Revo MRI SureScan Pacing System (Medtronic Co. Minneapolis, MN, USA) for MRI use. This system consists of a generator (Revo MRI SureScan implantable pulse generator) and a lead (CapSureFix MRI lead: model 5086 MRI lead) that are specifically engineered for MRI safety. The results of a clinical trial showed that this system was safe to use with MRI equipment of up to 1.5 T [119]. MRI is increasingly being used to examine multiple internal organs in children, particularly due to a trend for avoiding exposure to unnecessary radiation doses during computed tomography. The development of a pediatric pacing device for MRI use is desirable.

Leadless pacing device

Recent research has progressed to the development of a "leadless pacing system." A small receiving device is placed at the target pacing site, and pacing energy is provided by a stimulating device external to the heart in the form of either ultrasound-mediated waves or an alternating magnetic field generated by a transmitter that are/is converted into a voltage pulse by a receiver unit [120–122]. Before clinical application, the following problems must be solved: the method of placing the electrode, interference

from external noise, and the effect of electrodes surrounding the myocardium. If these issues can be solved in the future, this pacing treatment will be beneficial for small patients with small venous calibers and complex cardiac anomalies.

Conclusion

Pacing treatment has been given to only a small number of infant patients, so its use is still limited. Several pediatric issues with pacing therapy such as small physique, body growth, and concurrent cardiac anomalies with or without intracardiac shunt, together with the patient's pathophysiological conditions, should be taken into consideration in pacing treatment. Careful long-term management is necessary. Using the latest technology and choosing the optimal pacing method by considering patient-specific factors and pacemaker features are desirable approaches.

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