PEDIATRIC CARDIOLOGY and CARDIAC SURGERY VOL. 26 NO. 3 (200–205)

Review

Arrhythmias after the Fontan Operation

Martin J. LaPage and J. Philip Saul

Division of Pediatric Cardiology, Department of Pediatrics, Medical University of South Carolina, South Carolina, USA

Key words:
congenital heart disease, Fontan, arrhythmia, intra-atrial reentry tachycardia

Arrhythmias are a common cause of morbidity in patients with palliated single ventricle pathology. The relative risk of arrhythmia in Fontan patients strongly favors the development of intra-atrial reentry tachycardia (IART) or sinus node dysfunction (SND). More than 50% of Fontan patients will develop atrial tachycardias over long term follow-up. This review focuses on the characteristics and treatment of IART and SND. In general, IART is an arrhythmia specific to post-atriotomy atria; and is frequently a non-cavotricuspid isthmus dependent circuit, especially in the Fontan patient. Drug therapy alone is often inadequate for prevention of IART. Atrial antitachycardia pacing has not been reliable in patients with congenital heart disease. Radiofrequency (RF) ablation has shown increasing success rates as new technologies are implemented. Knowledge of both the anatomy and physiology are critical for successful ablation. Surgery is appropriate with significant hemodynamic abnormalities or failed arrhythmia management. Most importantly, recurrences are common and optimal therapy should include a combination of the discussed techniques.

Introduction

The Fontan operation has undergone significant modification since its initial description in 1971.[1] While conversion to total cavo-pulmonary connection and addition of the fenestrations have improved clinical outcomes, other variations such as extracardiac conduits instead of lateral tunnels still have not established superiority. Persistent throughout the evolution of the Fontan has been the high risk of developing arrhythmias and the daunting task of treating those arrhythmias given their high risk of recurrence.

Arrhythmias are a common cause of morbidity in patients with palliated single ventricle pathology. The relative risk of arrhythmia in Fontan patients strongly favors develop of intra-atrial reentry tachycardia (IART) or sinus node dysfunction (SND), with a lesser risk of atrial fibrillation (AF) or ventricular tachycardia (VT).[2] This review will focus on the characteristics and treatment of IART and SND.

Sinus node dysfunction

SND, defined as resting heart rate (HR) <5th percentile, peak HR 75% predicted, or non-sinus rhythm on electrocardiogram (ECG),[3] is common in Fontan patients due to the effects of multiple right atriotomies over several operations, in addition to the chronic high pressure state of the right atrium. Cohort and cross sectional studies have shown a predominance of sinus rhythm on ECG in 63–71% of Fontan patients, dependant on age.[3, 4] Twenty-four hour Holter monitoring in patients nearly 8 years after Fontan operation showed a normal mean heart rate and low maximum heart rate.[5] Studies comparing the extracardiac conduit Fontan and the lateral tunnel have reported conflicting results regarding improvement in SND.[6, 7] In addition to baseline heart rhythm, Fontan patients perform below normal on exercise testing with peak HR <75% predicted in 41%[3] and VO_2 max only 69% of normal.[5] There is a weak association

Received November 10, 2009
Accepted January 21, 2010

Reprint requests to: Martin J. LaPage, M.D.
Division of Pediatric Cardiology, Department of Pediatrics, Medical University of South Carolina
165 Ashley Avenue, PO Box 250915, Charleston, SC 29425, USA
E-mail: lapage@musc.edu

between lower resting HR and higher peak HR with higher functional status.[3] Specific risk factors for developing SND within the Fontan population are still being defined; however, importantly, SND is associated with a higher risk of IART.[8]

Intra-atrial reentry tachycardia

More than 50% of Fontan patient will develop atrial tachycardias over long term follow-up.[9] Animal and human electrophysiologic studies have established the reentrant nature of these tachycardias, leading to the common usage of the term IART. In general, IART is an arrhythmia specific to post-atriotomy atria, differentiating it from atrial flutter, which is typically dependent on the cavo-tricuspid isthmus (CTI). IART is frequently a non-CTI dependent circuit, especially in the Fontan patient. Diagnosis may be elusive as classic flutter waves on surface ECG are uncommon and reentry cycle lengths are usually slower than typical atrial flutter.

The specific factors predisposing Fontan patients to atrial reentry include: 1) atrial scarring from atriotomies and pericardial inflammation, 2) high atrial wall stress and hypertrophy due to increased pressure and chamber size, and 3) changes in atrial refractoriness associated with SND and concomitant bradycardia. Fontan patients have a longer P-wave duration and greater P-wave dispersion; and among Fontan patients, IART patients have a longer P-wave duration and greater dispersion.[10, 11]

Additional risk factors for development of IART include: age <3 or >10 years, systemic atrioventricular valve (AVV) replacements,[12] duration of Fontan circulation,[9] and the presence of SND.[8] Type of Fontan, extracardiac conduit vs lateral tunnel, has also been evaluated, with one study showing no difference[9] and another demonstrating less IART with the extracardiac conduit.[7] A shorter time to development of IART has been found when the Fontan is performed after 10 years of age, after a prior pulmonary artery (PA) reconstruction, and with an atrial baffle.[8] Predisposition to IART may even be present before the Fontan operation, with demonstrated inducibility of IART in 27% of patients studied prior to the Fontan.[13]

The underlying congenital lesions and the surgical procedures that create the substrate for development of this arrhythmia are often associated with marginal hemodynamic status, which exacerbates the effects of the tachycardia. Fontan patients with IART are significantly more likely to develop congestive heart failure, right atrial thrombus, and have moderate to severe systemic atrioventricular valve regurgitation; however, no differences in survival have been attributed to the presence of IART alone.[14] Of note, although atrial fibrillation can be observed in Fontan patients, a cohort study evaluating congenital heart disease (CHD) patients with IART and/or atrial fibrillation found no evidence of progression from IART to AF over time.[15]

IART can be treated with medication, pacing, catheter ablation, or surgery. Each approach has its varied successes and risks. In fact, the most successful treatment regimens usually include a combination of various techniques. Despite rapid progress in this area, recurrence rates remains higher than desirable.

1. Drug therapy

There are no prospective studies on drug therapy for IART. Retrospective experience shows <40% of IART patients treated with drug therapy are free from recurrence at 1 year post-presentation regardless of the antiarrhythmic drug used.[16] Antiarrhythmics can be proarrhythmic, aggravate SND and compromise ventricular function. One important drug therapy to utilize is prophylactic anticoagulation with aspirin or vitamin K antagonists to prevent the up to 19% incidence of thromboembolic events.[17]

2. Pacing

Pacing therapies target two methods for reducing IART: pacing to prevent bradycardia-mediated tachycardia, and antitachycardia pacing to treat episodes of IART. Current guidelines consider pacing to be reasonable for the prevention of recurrent episodes of IART in patient with CHD;[18] however, benefits have varied across studies. Although pacing has been shown to be useful in preventing bradycardia-mediated tachyarrhythmias,[19] rates of IART specifically did not differ with pacing. Studies concerning optimal mode of pacing have also shown variable results. One study showed atrial or dual chamber pacing was significantly more successful for prevention than single chamber ventricular pacing,[19] while another showed no difference in development of IART between single chamber ventricular pacing and dual chamber pacing.[20] Neither study was specific to the Fontan population.

Atrial antitachycardia pacing has not been reliable in patients with CHD.[21] Effective use of this modality requires accurate sensing of atrial activity, a sometimes challenging task, due to the abnormal anatomy and electrophysiology,

and the multiple prosthetic patches placed at the time of surgery. False detection is not uncommon and delivered therapy is successful only ~50% of the time.[21, 22)]

Pacemaker implantation obviously carries its own risks beyond those intrinsic to the Fontan. Pacemaker implantation appears to occur relatively early in the pediatric Fontan population with 11–13% of patients <15 years old having a pacemaker, increasing to only 20% of patients ≥15 years old.[4)] Generator replacements are required every 5 to 10 years; and may include lead replacements and extractions. Nearly 50% of operations in Fontan patients are pacemaker related.[23)] Because of the anatomic separation of systemic venous and intracardiac spaces, most Fontan patients require epicardial implantation which requires a more invasive approach than transvenous implantations. Implantation of transvenous leads in Fontan patients have been reported with leads placed in both the atria and the ventricle via trans-baffle delivery including 1 patient with an extracardiac conduit Fontan.[24, 25)] Lead performance was nominal at mid-term follow-up. Transvenous leads increase the risk of thromboembolus when an intracardiac shunt is present.[26)] Additionally, anti-tachycardia pacing may exacerbate the tachycardia. This has been reported in one case[22)] where anti-tachycardia pacing caused an increase in the IART rate subsequently leading to a rapid ventricular response and degeneration into ventricular fibrillation (VF) and sudden death.

3. Ablation

The techniques for ablation of IART have evolved considerably over the past two decades. Early studies on treatment of IART in patients with congenital heart disease demonstrated poor outcomes and high recurrence rates.[27)] Fontan patients are at especially high risk of recurrence as demonstrated in a more recent study where 53% recurred compared to a 21% recurrence in other repaired CHD.[28)] The biggest barriers to ablation of IART in the Fontan patient are the combination of a very thick atrial wall and a multiplicity of circuits. Two important technologies have greatly improved outcomes: cooled-tip catheters and 3D mapping systems.

Cooled-tip catheters allow for the application of more power to the tip, which causes deeper tissue heating and larger lesion formation; sometimes critical for success in the thickened Fontan atrium.[29)] Tip cooling can be achieved with an irrigated tip catheter or can also be accomplished passively using a catheter tip with larger mass (8 mm, 10 mm) or more conductivity (gold). Studies on irrigated tip catheters have shown that a lower number of lesions are necessary for successful ablation.[30)] A prospective randomized study to determine if irrigated radiofrequency (RF) increased ablation success rates found no difference between standard and irrigated RF during the limited randomized period although cross over from standard to irrigated resulted in better success overall.[31)]

The evolution, interpretation, and use of 3D mapping systems has been reviewed in detail elsewhere.[32–34)] Current 3D mapping systems localize catheter position using magnetic fields (CARTO, Biosense Webster, Inc, Diamond Bar, CA, USA), ultrasound ranging (Boston Scientific, Natick, MA, USA), and impedance (EnSite NavX, St. Jude Medical, St. Paul, MN, USA). Electroanatomic mapping is performed by direct catheter contact with the endocardium or via non-contact mapping in the Ensite / NavX system which creates derived endocardial electrograms based on far field signal strengths detected by a basket catheter wrapped around a balloon.

Preliminary studies demonstrated the utility of 3D mapping for ablation of IART.[35, 36)] Additionally, 3D mapping allowed for the demonstration of the diversity of circuits in patients with IART.[37)] A comparison of electroanatomic and noncontact mapping systems to map IART circuits in Fontan patients showed that electroanatomic contact mapping identified a much lower surface area of abnormal endocardium compared to non-contact mapping; and reconstructed electrograms created by the non-contact mapping system were significantly different from local electrograms accurately represented with contact mapping.[38)] In that study, successful arrhythmia mapping was superior with electroanatomic mapping in 58% and superior with non-contact in 19%. However, the two techniques are in many ways complimentary with electroanatomic mapping being better for consistent IART circuits and non-contact being better for changing circuits.

IART circuits in Fontan patients are anatomically distinct. Successful ablation requires a simultaneous consideration of both the anatomy and electrophysiology. Two studies have evaluated IART circuits after various cardiac operations.[39, 40)] In both studies, Fontan patients had statistically different circuit locations, most commonly involving the right atriotomy scar. Successful ablation locations in the Fontan patients were lateral right atrium (RA) wall 53%, anterior RA 25%, isthmus 15%, atrial septum 7%.[40)] Circuits

involving the atriotomy rotate in either direction on the lateral right atrial wall, typically with one arm of the circuit passing between the atriotomy and the crista terminalis. Lines of block from the atriotomy to the inferior vena cava (IVC), superior vena cava (SVC), crista terminalis, and tricuspid valve (TV) annulus all may be effective in blocking these circuits. The CTI may harbor the slow region of the circuit even in the presence of tricuspid atresia when there is a tricuspid "dimple". Peri-caval reentry has been identified as an atypical mechanism of CTI-dependent arrhythmias in Fontan patients,[41] when circuits rotate around the IVC and through the CTI, between the IVC and right AVV or dimple. The atrial septal defect may also serve as central foci for reentrant circuits.

The target for ablation of IART is the critical slow region of the circuit which exists between two conduction barriers. A complete ablation line between these barriers prevents further reentry using this site. The slow region can be identified by concealed entrainment, low amplitude fractionated electrograms, or by the location of the typical anatomic barriers. Electroanatomic mapping can be used in sinus rhythm to define these anatomic barriers and identify successful ablation sites even if IART cannot be induced.[42] Once ablation is performed, it is important to attempt to document the presence of electrical block across the ablation target zone and to document non-inducibility of all sustained IARTs. The combined use of 3D mapping and tip cooling techniques has improved acute success to approximately 90%.

4. Surgical therapy

Operative intervention is perhaps the most successful intervention for preventing recurrences of IART. Early techniques consisting of single ablation lines across the CTI[43] or between the atriotomy and the AVV showed no improvement in recurrence rate compared to no intervention.[44] Currently, the modified right atrial maze procedure is the preferred and most successful approach, combining a series of atrial incisions and intraoperative cryoablation lesions detailed in prior publications.[43, 45–47] One center has reported a late recurrence rate of 12–14% with this approach to treatment;[43] compared to the 33% recurrence after simple isthmus ablation.

The risks of such a procedure are considerably higher than for catheter procedures. Thus, a reasonable approach is to attempt at least one catheter ablation in Fontan patients who do not have hemodynamic reasons for revision and to move to surgical revision with a right atrial maze procedure for patients who fail catheter-based procedures or who have hemodynamic reasons for surgery.

Summary

Despite improvements in the palliation of single ventricle CHD, arrhythmias remain a common and serious complication after conversion to Fontan anatomy. Drug therapy alone is often inadequate for prevention of IART. RF ablation has shown increasing success rates as new technologies are implemented. Knowledge of both the anatomy and physiology are critical for successful ablation. Surgery is appropriate with significant hemodynamic abnormalities or failed arrhythmia management. Most importantly, recurrences are common and optimal therapy should include a combination of the discussed techniques.

【References】

1) Fontan F, Baudet E: Surgical repair of tricuspid atresia. Thorax 1971; **26**: 240–248
2) Walsh EP: Interventional electrophysiology in patients with congenital heart disease. Circulation 2007; **115**: 3224–3234
3) Blaufox AD, Sleeper LA, Bradley DJ, et al: Functional status, heart rate, and rhythm abnormalities in 521 Fontan patients 6 to 18 years of age. J Thorac Cardiovasc Surg 2008; **136**: 100–107, 107. e. 1
4) Anderson PA, Sleeper LA, Mahony L, et al: Contemporary outcomes after the Fontan procedure: a Pediatric Heart Network multicenter study. J Am Coll Cardiol 2008; **52**: 85–98
5) Robbers-Visser D, Kapusta L, van Osch-Gevers L, et al: Clinical outcome 5 to 18 years after the Fontan operation performed on children younger than 5 years. J Thorac Cardiovasc Surg 2009; **138**: 89–95
6) Dilawar M, Bradley SM, Saul JP, et al: Sinus node dysfunction after intraatrial lateral tunnel and extracardiac conduit Fontan procedures. Pediatr Cardiol 2003; **24**: 284–288
7) Nürnberg JH, Ovroutski S, Alexi-Meskishvili V, et al: New onset arrhythmias after the extracardiac conduit Fontan operation compared with the intraatrial lateral tunnel procedure: early and midterm results. Ann Thorac Surg 2004; **78**: 1979–1988; discussion 1998
8) Fishberger SB, Wernovsky G, Gentles TL, et al: Factors that influence the development of atrial flutter after the Fontan operation. J Thorac Cardiovasc Surg 1997; **113**: 80–86
9) Weipert J, Noebauer C, Schreiber C, et al: Occurrence and management of atrial arrhythmia after long-term Fontan circulation. J Thorac Cardiovasc Surg 2004; **127**: 457–464
10) Wong T, Davlouros PA, Li W, et al: Mechano-electrical interaction late after Fontan operation – relation between P-wave

duration and dispersion, right atrial size and atrial arrhythmias. Circulation 2004; **109**: 2319–2325
11) Tuzcu V, Ozkan B, Sullivan N, et al: P wave signal-averaged electrocardiogram as a new marker for atrial tachyarrhythmias in postoperative Fontan patients. J Am Coll Cardiol 2000; **36**: 602–607
12) Durongpisitkul K, Porter CJ, Cetta F, et al: Predictors of early- and late-onset supraventricular tachyarrhythmias after Fontan operation. Circulation 1998; **98**: 1099–1107
13) Law IH, Fischbach PS, Goldberg C, et al: Inducibility of intra-atrial reentrant tachycardia after the first two stages of the Fontan sequence. J Am Coll Cardiol 2001; **37**: 231–237
14) Ghai A, Harris L, Harrison DA, et al: Outcomes of late atrial tachyarrhythmias in adults after the Fontan operation. J Am Coll Cardiol 2001; **37**: 585–592
15) Kirsh JA, Walsh EP, Triedman JK: Prevalence of and risk factors for atrial fibrillation and intra-atrial reentrant tachycardia among patients with congenital heart disease. Am J Cardiol 2002; **90**: 338–340
16) Triedman JK: Atrial reentrant tachycardias, In Walsh EP, Saul JP, Triedman JK, (eds): Cardiac Arrhythmias in Children and Young Adults With Congenital Heart Disease. Philadelphia, PA, USA, Lippincott Williams & Wilkins, 2001, pp137–160
17) Monangle P, Chan A, Massicotte P, et al: Antithrombotic therapy in children: the Seventh ACCP Conference on Antithrombotic and Thrombolytic Therapy. Chest 2004; **126** (3 Suppl): 645S–687S
18) Epstein AE, DiMarco JP, Ellenbogen KA, et al: ACC/AHA/HRS 2008 Guidelines for Device-Based Therapy of Cardiac Rhythm Abnormalities: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Writing Committee to Revise the ACC/AHA/NASPE 2002 Guideline Update for Implantation of Cardiac Pacemakers and Antiarrhythmia Devices): developed in collaboration with the American Association for Thoracic Surgery and Society of Thoracic Surgeons. Circulation 2008; **117**: e350–e408
19) Silka MJ, Manwill JR, Kron J, et al: Bradycardia-mediated tachyarrhythmias in congenital heart disease and responses to chronic pacing at physiologic rates. Am J Cardiol 1990; **65**: 488–493
20) Walker F, Siu SC, Woods S, et al: Long-term outcomes of cardiac pacing in adults with congenital heart disease. J Am Coll Cardiol 2004; **43**: 1894–1901
21) Stephenson EA, Casavant D, Tuzi J, et al: Efficacy of atrial antitachycardia pacing using the medtronic AT500 pacemaker in patients with congenital heart disease. Am J Cardiol 2003; **92**: 871–876
22) Rhodes LA, Walsh EP, Gamble WJ, et al: Benefits and potential risks of atrial antitachycardia pacing after repair of congenital heart disease. Pacing Clin Electrophysiol 1995; **18** (5 Pt 1): 1005–1016
23) Petko M, Myung RJ, Wernovsky G, et al: Surgical reinterventions following the Fontan procedure. Eur J Cardiothoracic Surg 2003; **24**: 255–259
24) Hansky B, Blanz U, Peuster M, et al: Endocardial pacing after Fontan-type procedures. Pacing Clin Electrophysiol 2005; **28**: 140–148
25) Shah MJ, Nehgme R, Carboni M, et al: Endocardial atrial pacing lead implantation and midterm follow-up in young patients with sinus node dysfunction after the Fontan procedure. Pacing Clin Electrophysiol 2004; **27**: 949–954
26) Khairy P, Landzberg MJ, Gatzoulis MA, et al: Transvenous pacing leads and systemic thromboemboli in patients with intracardiac shunts: multicenter study. Circulation 2006; **113**: 2391–2397
27) Triedman JK, Bergau DM, Saul JP, et al: Efficacy of radiofrequency ablation for control of intraatrial reentrant tachycardia in patients with congenital heart disease. J Am Coll Cardiol 1997; **20**: 1032–1038
28) Kannankeril PJ, Anderson ME, Rottman JN, et al: Frequency of late recurrence of intra-atrial reentry tachycardia after radiofrequency catheter ablation in patients with congenital heart disease. Am J Cardiol 2003; **92**: 879–881
29) Blaufox AD, Numan MT, Laohakunakorn P, et al: Catheter tip cooling during radiofrequency ablation of intra-atrial reentry: effects on power, temperature, and impedance. J Cardiovasc Electrophysiol 2002; **13**: 783–787
30) Tanner H, Lukac P, Schwick N, et al: Irrigated-tip catheter ablation of intraatrial reentrant tachycardia in patients late after surgery of congenital heart disease. Heart Rhythm 2004; **1**: 268–275
31) Triedman JK, DeLucca JM, Alexander ME, et al: Prospective trial of electroanatomically guided, irrigated catheter ablation of atrial tachycardia in patients with congenital heart disease. Heart Rhythm 2005; **2**: 700–705
32) Tai CT, Chen SA: Noncontact mapping of the heart: how and when to use. J Cardiovasc Electrophysiol 2009; **20**: 123–126
33) Markowitz SM, Lerman BB: How to interpret electroanatomic maps. Heart Rhythm 2006; **3**: 240–246
34) Packer DL: Evolution of mapping and anatomic imaging of cardiac arrhythmias. Heart Rhythm 2004; **1** (Suppl 1): 153C–176C
35) Paul T, Windhagen-Mahnert B, Kriebel T, et al: Atrial reentrant tachycardia after surgery for congenital heart disease: endocardial mapping and radiofrequency catheter ablation using a novel, noncontact mapping system. Circulation 2001; **103**: 2266–2271
36) Betts TR, Roberts PR, Allen SA, et al: Electrophysiological mapping and ablation of intra-atrial reentry tachycardia after Fontan surgery with the use of a noncontact mapping system. Circulation 2000; **102**: 419–425
37) Triedman JK, Jenkins KJ, Colan SD, et al: Intra-atrial reentrant tachycardia after palliation of congenital heart disease:

characterization of multiple macroreentrant circuits using fluoroscopically based three-dimensional endocardial mapping. J Cardiovasc Electrophysiol 1997; 8: 259–270
38) Abrams DJ, Earley MJ, Sporton SC, et al: Comparison of noncontact and electroanatomic mapping to identify scar and arrhythmia late after the Fontan procedure. Circulation 2007; 115: 1738–1746
39) Lukac P, Pedersen AK, Mortensen PT, et al: Ablation of atrial tachycardia after surgery for congenital and acquired heart disease using an electroanatomic mapping system: Which circuits to expect in which substrate? Heart Rhythm 2005; 2: 64–72
40) Collins KK, Love BA, Walsh EP, et al: Location of acutely successful radiofrequency catheter ablation of intraatrial reentrant tachycardia in patients with congenital heart disease. Am J Cardiol 2000; 86: 969–974
41) Mandapati R, Walsh EP, Triedman JK: Pericaval and periannular intra-atrial reentrant tachycardias in patients with congenital heart disease. J Cardiovasc Electrophysiol 2003; 14: 119–125
42) Love BA, Collins KK, Walsh EP, et al: Electroanatomic characterization of conduction barriers in sinus/ atrially paced rhythm and association with intra-atrial reentrant tachycardia circuits following congenital heart disease surgery. J Cardiovasc Electrophysiol 2001; 12: 17–25
43) Deal BJ, Mavroudis C, Backer CL: The role of concomitant arrhythmia surgery in patients undergoing repair of congenital heart disease. Pacing Clin Electrophysiol 2008; 31 (Suppl 1): S13–S16
44) Collins KK, Rhee EK, Delucca JM, et al: Modification to the Fontan procedure for the prophylaxis of intra-atrial reentrant tachycardia: short-term results of a prospective randomized blinded trial. J Thorac Cardiovasc Surg 2004; 127: 721–729
45) Deal BJ, Mavroudis C, Backer CL: Arrhythmia management in the Fontan patient. Pediatr Cardiol 2007; 28: 448–456
46) Mavroudis C, Deal BJ, Backer CL, et al: Arrhythmia surgery in patients with and without congenital heart disease. Ann Thorac Surg 2008; 86: 857–868
47) Mavroudis C, Deal BJ, Backer CL, et al: J. Maxwell Chamberlain Memorial Paper for congenital heart surgery. 111 Fontan conversions with arrhythmia surgery: surgical lessons and outcomes. Ann Thorac Surg 2007; 84: 1457–1465; discussion 1465–1466