Acute Hemodynamic Effects of Pacing in Patients With Fontan Physiology
A Prospective Study

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OBJECTIVES  The purpose of this research was to assess the hemodynamic response to atrial, ventricular, and dual-chamber pacing in patients with Fontan physiology.

BACKGROUND  Bradycardia, due to sinus node dysfunction or atrioventricular (AV) block, with need for pacing, is common after the Fontan operation. The optimal pacing mode for Fontan patients is unknown, but is critical, as hemodynamic aberrancies may cause severe clinical deterioration. We hypothesized that AV synchrony is vital for maximizing Fontan hemodynamics.

METHODS  A cross-over trial was conducted with 21 patients (age 2 to 18 years, median 4 years; male patients /1005 13) in the intensive care unit after a Fontan operation. Hemodynamic parameters, including mean left atrial pressure (LAP, in mm Hg), mean pulmonary artery pressure (PAP, in mm Hg), mean arterial blood pressure (MAP, in mm Hg), and indexed cardiac output via Fick (Qs, in l/min/m²) were measured with atrial, ventricular, and dual-chamber pacing. Measurements were made after pacing for 10 min in each mode, and a 10-min rest was given between each pacing maneuver.

RESULTS  Asynchronous ventricular (VOO) pacing resulted in significantly worse hemodynamics when compared to dual-chamber (DOO) and atrial (AOO) pacing with a higher LAP (9.4 VOO; 6.8 DOO; 5.4 AOO) and PAP (15.2 VOO; 13.5 DOO; 12.7 AOO) and lower Qs (3.0 VOO; 3.5 DOO; 3.9 AOO) and MAP (60.1 VOO; 66.5 DOO; 67.2 AOO).

CONCLUSIONS  Asynchronous ventricular pacing, after the Fontan procedure, has acute, adverse hemodynamic consequences (elevated LAP and PAP and decreased Qs and MAP). (J Am Coll Cardiol 2005;46:1937–42) © 2005 by the American College of Cardiology Foundation

The Fontan operation is currently the surgical approach of choice for patients with single-ventricle physiology. Despite numerous advances and modifications of the original operation described by Fontan (1), bradyarrhythmias associated with sinus node dysfunction and/or atrioventricular (AV) block continue to occur commonly. Studies have estimated that approximately 10% of these patients will require a pacemaker (2–5). Patients with Fontan physiology can be very sensitive to loss of normal rhythm. Arrhythmias in these patients have a high incidence of morbidity and mortality (6). It is therefore assumed that AV synchrony is vital for Fontan patients. However, no standard for pacemaker mode selection exists. Reports in the literature show that various pacing modes are being employed in these patients (5), but there has been no systematic study of the different types of pacing in the Fontan circulation. We therefore performed a prospective study to look at the acute hemodynamic effects of different types of pacing in Fontan patients.

METHODS  

Patients. Twenty-one patients (ages 2 to 18 years, median 4 years, 13 male patients) with complex congenital heart defects of single-ventricle physiology (double-inlet left ventricle, n = 6; tricuspid atresia n = 4; hypoplastic left heart syndrome, n = 6; pulmonary atresia, n = 5) were studied after the Fontan operation. The type of Fontan operation was an extracardiac conduit (n = 12) or an intracardiac lateral tunnel (n = 9). Fenestrations in the Fontan baffle were present in 19 patients.

Temporary pacing leads were placed at the time of surgery after the patient had been weaned from cardiopulmonary bypass. Leads were placed on the surface of the right-sided atrium and the epicardial surface of the anterior ventricle, typically the right ventricular free wall or near the AV groove.

Patients were studied in the pediatric intensive care unit, early postoperatively (postoperative day 1 to 6; mean 2 days). The study was performed after extubation to room air or supplemental oxygen via nasal cannula, when hemody-
ventricular capture. Electrocardiograms were obtained at the patient’s baseline PR interval (70 to 100 ms) to ensure capture. Atrioventricular delay was manipulated in DOO mode to approximately 80% to 90% of baseline, and therefore DOO data was available in 17 of 21 patients. Left atrial pressure (LAP) was measured in 13 of 21 patients. Left atrial pressure was significantly elevated with VOO pacing compared to AOO or DOO pacing. Dual-chamber demand pacing resulted in a significantly higher LAP compared to AOO pacing (Table 1, Fig. 3).

PAP. Pulmonary artery (Fontan circuit) pressure was significantly elevated with VOO pacing compared to AOO or DOO pacing. No significant difference in PAP was noted between AOO and DOO pacing (Table 1, Fig. 2).

LAP. Eight patients did not have a left atrial catheter, and therefore LAP was measured in 13 of 21 patients. Left atrial pressure was significantly elevated with VOO pacing compared to AOO or DOO chamber pacing. No significant difference in LAP was noted between AOO and DOO pacing (Table 1, Fig. 2).

MAP. Mean arterial blood pressure was significantly lower with VOO pacing compared to AOO and DOO pacing. No significant differences in MAP were noted with AOO pacing (Table 1, Fig. 3).

Pacing. Atrial demand pacing and VOO pacing were successful in all patients. In 4 patients consistent ventricular capture was unsuccessful in the DOO mode at an AV delay of 80% to 90% of baseline, and therefore DOO data was only available in 17 of 21 patients.

Pacing protocol. Utilizing temporary, epicardial pacing wires in the atrium and ventricle, patients went through a series of pacing maneuvers. First, baseline hemodynamic values were obtained in the patient’s intrinsic rhythm. Next, the pacer was set to pace the atrium (AOO), ventricle (VOO), or both atrium and ventricle (DOO) at a rate 10 beats/min faster than the intrinsic rhythm. Voltages were adjusted to ensure capture. Atrioventricular delay was manipulated in DOO mode to approximately 80% to 90% of the patient’s baseline PR interval (70 to 100 ms) to ensure ventricular capture. Electrocardiograms were obtained at baseline and with each maneuver to document capture (Fig. 1).

Patients were paced for 10 min, and at the end of the 10-min period pressures were recorded and blood gases obtained for Fick analysis. Next, each patient was “rested” for 10 min off the pacer, and new baseline values were recorded. Patients went through each pacing maneuver in random sequence, and baseline values were obtained after the 10-min rest period before each 10-min pacing maneuver.

Statistical analysis. To account for a correlation within a subject, we used a mixed effects model with a random subject effect. We initially evaluated a comparability of three baseline measures. Once we confirmed that there was no significant difference in the baseline measurements, we performed a pairwise comparison of the treatments: 1) pacing AOO versus DOO; 2) pacing AOO versus VOO; and 3) pacing DOO versus VOO. To maintain the overall type I error of 0.05 for the treatment comparisons, p value <0.0167 (adjusted for three comparisons using the Bonferroni method) was considered statistically significant. All analyses were performed using SAS software (SAS Institute Inc., Cary, North Carolina).

RESULTS

Baseline. There were no significant differences in any of the baseline values before each pacing maneuver. Mean baseline values are shown in Table 1.

Pacing. Atrial demand pacing and VOO pacing were successful in all patients. In 4 patients consistent ventricular capture was unsuccessful in the DOO mode at an AV delay of 80% to 90% of baseline, and therefore DOO data was only available in 17 of 21 patients.

Cardiac output. Systemic blood flow was significantly lower with VOO versus AOO or DOO pacing. Dual-chamber demand pacing resulted in similar mean values to baseline and a lower Qs compared to AOO pacing, although these results did not reach statistical significance in our study (Table 1, Fig. 2).

LAP. Eight patients did not have a left atrial catheter, and therefore LAP was measured in 13 of 21 patients. Left atrial pressure was significantly elevated with VOO pacing compared to AOO or DOO pacing. Dual-chamber demand pacing resulted in a significantly higher LAP compared to AOO pacing (Table 1, Fig. 3).

PAP. Pulmonary artery (Fontan circuit) pressure was significantly elevated with VOO pacing compared to AOO or DOO chamber pacing. No significant difference in PAP was noted between AOO and DOO pacing (Table 1, Fig. 2).

MAP. Mean arterial blood pressure was significantly lower with VOO pacing compared to AOO and DOO pacing. No significant differences in MAP were noted with AOO compared to DOO pacing (Table 1, Fig. 5).

No significant differences were noted when fenestrated Fontan patients were compared to the nonfenestrated group. Similarly, there was no difference between those with a single systemic left ventricle compared to those with a single systemic right ventricle (although only 6 of 21 patients in our study had a systemic right ventricle). Also, no significant differences were observed between the lateral tunnel and extracardiac Fontan groups.

DISCUSSION

Our study showed that asynchronous ventricular pacing results in adverse hemodynamics in patients with Fontan physiology. Atrial pacing with intact AV conduction pro-
duced the most optimal hemodynamics. Synchronous dual-chamber pacing trended towards less optimal hemodynamic results compared to atrial pacing.

Choussat et al. (7) emphasized the importance of sinus rhythm in patient selection in order to have a successful outcome. Others have argued that normal sinus rhythm is not a prerequisite for surviving a Fontan operation (8). The high incidence of bradyarrhythmias, sinus node dysfunction (9), and chronotropic incompetence with exercise (10) in these patients makes this a question of vital importance, which led us to design this study.

We found that asynchronous VOO pacing resulted in elevations in LAP and PAP (systemic venous pressure), and reductions in MAP and Qs. Rychik et al. (11) showed significant pulmonary venous flow reversal via Doppler echocardiography in hemi-Fontan patients in junctional rhythm. Similarly, we noted significant elevations in mean LAP with loss of AV synchrony during VOO pacing, and many patients developed marked cannon waves with VOO pacing (Fig. 5). These cannon waves were likely a result of loss of AV synchrony, although V-A conduction could yield similar findings. It is possible to contend that those with

Figure 1. For each strip the top tracing is the surface lead electrocardiogram and the bottom tracing is left atrial pressure (LAP). Atrial pacing (AOO): note small atrial pacemaker deflections preceding each narrow QRS complex and normal appearing LAP tracing. Dual-chamber pacing (DOO): note atrial deflection, wide QRS, and normal appearing LAP tracing. Ventricular pacing (VOO): note absence of P-wave, wide QRS, abnormal and elevated LAP waves. See Discussion section in the text. NSR = normal sinus rhythm with narrow QRS and normal A and V waves on left atrial tracing.

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retrograde conduction would do worse than those without because, in the former, the atrial contraction would necessarily be against a closed AV valve leading to cannon A waves, whereas in the latter, cannon waves would occur less frequently.

Systemic blood flood decreased with VOO pacing, despite pacing at a rate of 10 beats/min faster than baseline. Therefore, the drop in $Q_s$ reflects a decrease in stroke volume with VOO pacing of a single ventricle with Fontan circulation. Several mechanisms could explain this finding: elevation in LAP and loss of atrial kick would decrease preload to the single ventricle, and increased incoordination of ventricular contraction/relaxation with eccentric ventricular pacing could further reduce stroke volume.

Several studies have examined the clinical consequences of various modes of pacing in Fontan patients. Fishberger et al. (4) found a trend for decreased survival in Fontan patients paced in the ventricle alone (4 of 9) versus dual-chamber pacing (15 of 19). They found no differences in survival in patients with normal sinus rhythm, atrial pacing, or dual-chamber pacing. Pacemaker implantation before the Fontan operation has been shown to be associated with decreased long-term survival (12). Paridon et al. (13) found that Fontan patients were unable to increase their maximum work rate, oxygen consumption, and ventilatory anaerobic threshold despite an increase in heart rate with a rate responsive ventricular pacemaker. Pacing manipulations have been reported to be successful in the treatment of Fontan patients with protein losing enteropathy and plastic bronchitis, presumably secondary to optimized hemodynamics (14–16).

The acute hemodynamic affects of AOO pacing in our study raise interesting possibilities. At least acutely it appears that $Q_s$ can be increased and LAP decreased by AOO pacing. This argues for the use of atrial pacing in the postoperative period in patients with borderline hemodynamics. Whether the same rationale can be used to support the chronic use of atrial pacing in Fontan patients remains to be studied.

There appeared to be a tendency towards worse hemodynamics with DOO pacing compared to AOO pacing. Overall, DOO pacing did not result in a significant increase in $Q_s$ from baseline despite pacing at 10 beats/min higher. There are many potential causes for this finding. During DOO pacing by necessity the AV delay was shorter than the PR interval during atrial pacing. This shortened ventricular

### Figure 2
Indexed cardiac output (l/min/m²) at baseline and with pacing post-Fontan procedure. Values are mean ± SE. $Q_s$ = indexed cardiac output; other abbreviations as in Figure 1.

### Figure 3
Mean left atrial pressure (LAP) at baseline and with pacing post-Fontan procedure. Values are mean ± SE. Abbreviations as in Figure 1.

### Figure 4
Mean pulmonary artery pressure (PAP) at baseline and with pacing post-Fontan procedure. Values are mean ± SE. Abbreviations as in Figure 1.
filling time could adversely affect hemodynamics in susceptible patients. Another possible explanation is that eccentric ventricular activation due to ventricular pacing (in the dual-chamber pacing mode) is responsible for worsened hemodynamics.

There has been much interest recently on the potentially deleterious effects of eccentric ventricular pacing (17). Such deleterious effects of dual-chamber pacing could be exaggerated in the Fontan patients. Penny et al. (18) showed that there is significant asynchrony of ventricular contraction and relaxation even at baseline in Fontan patients. This may be an inherent finding in single-ventricle patients, but it also appears to be worsened in the immediate postoperative period after the Fontan operation. Therefore, asynchronous ventricular pacing may be particularly detrimental in early postoperative Fontan patients.

Extrapolation of our study therefore suggests that atrial pacing may be preferable to dual-chamber pacing in patients with intact AV conduction, but final judgment should await further studies comparing these two techniques. This still leaves the question of patients with complete heart block and Fontan. Clearly, dual-chamber pacing is preferable to ventricular pacing in these patients as shown in our study. Whether novel pacing techniques, such as biventricular (resynchronization) pacing, have any advantages over conventional dual-chamber pacing merits study.

Thus, we believe the implantation of an asynchronous ventricular pacemaker in a patient with Fontan physiology is fraught with adverse consequences including acute deterioration of hemodynamics. The decision to implant an atrial or dual-chamber pacemaker also must take several factors into account: the difficulties of placing leads in Fontan patients with complex venous anatomy that may preclude a transvenous approach, concern over the thromboembolic risk of an endovascular pacing lead in this passive flow system, and the challenging surgical approach of placing epicardial atrial and ventricular leads on these patients who have already undergone multiple surgeries and in whom anatomic landmarks can be difficult. 

Study limitations. Our study was performed on patients in the postoperative setting with inherent variability in patient anatomy and physiologic states. We tried to mitigate this by waiting to perform the study when the patients were breathing spontaneously and hemodynamically relatively stable on minimal inotropic support. Also, the acute and short-term nature of our study may not be translatable to interpretations of long-term effects of pacing on the Fontan circuit.

Our limited sample size may have prevented us from noting a significant difference with atrial versus dual-chamber pacing. Also, it could be argued that the comparison of AOO with DOO pacing is inherently flawed because the AV delay was different in these two modes. However, this problem was unavoidable in this study given the fact our study patients had intact AV nodal conduction. We tried to limit the confounding effect of AV delay difference by making the AV delay as close as possible to the PR interval during AOO, while maintaining ventricular capture in the DOO mode.

Conclusions. Our study demonstrates the acute negative hemodynamic consequences of loss of AV synchrony in Fontan patients. We believe that the results of our study, coupled with other studies showing the detrimental consequences of ventricular pacing in Fontan patients, should lead to the avoidance of asynchronous ventricular pacing in patients with Fontan physiology if at all possible.

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