Abnormal patterns of intraventricular flow and diastolic filling after the Fontan operation: evidence for incoordinate ventricular wall motion

D J Penny, M L Rigby, A N Redington

Abstract

Objective—To assess whether regional abnormalities of ventricular function are present in patients after the Fontan operation and to explore the implications of any such abnormalities for ventricular filling.

Design and patients—Prospective study in which 25 patients after the Fontan operation were compared with 25 healthy controls and 12 patients with a univentricular atrioventricular connection, before the Fontan operation.

Interventions—Doppler echocardiography, with simultaneous electrocardiogram, phonocardiogram, and respirometer.

Results—Isovolumic relaxation time was significantly longer in patients after the Fontan operation than in normal children ($p < 0.001$) or the preoperative patients ($p = 0.001$). Systolic intraventricular flow was detected in 60% of patients after the Fontan operation and in 42% of preoperative patients. After the Fontan operation 80% of patients showed intraventricular flow during isovolumic relaxation compared with 8% of normal children and none of the preoperative patients.

Conclusions—Incoordinate ventricular relaxation is common after the Fontan operation. This may have important implications for ventricular diastolic filling, pulmonary blood flow, and cardiac output in these patients.

The Fontan operation¹ (atriopulmonary anastomosis), in which a pulmonary circulation devoid of a ventricular pumping chamber is created, has been developed as the definitive method for the palliation of various complex congenital heart lesions. By separating the pulmonary and systemic circulations, arterial oxygenation is improved and systemic ventricular preload is reduced. This operation is palliative rather than curative, however, with a significant late decline in survival and functional state as follow up is extended.² The principal cause of this deterioration is circulatory decompensation, but as yet the precise mechanism for this is unclear.

This study of systemic ventricular function in patients after the Fontan operation has principally considered the analysis of ventricular systolic pump function. Many patients display normal or near normal ejec-

tion fractions at rest.³ One longitudinal study showed an improvement in so-called load independent indices of contractility during a seven year follow up.⁴ It thus appears unlikely that the late decline in functional state of survivors after the Fontan operation is related to a primary deterioration in ventricular systolic function. It is clear that the study of ventricular function in patients after the Fontan operation must extend beyond the study of systolic pump activity only.

Doppler echocardiography has facilitated the identification of dynamic blood flow patterns in the ventricular cavity during systole⁵ and diastole,⁶ reflecting the development of transient intraventricular pressure changes secondary to incoordinate ventricular wall motion during ventricular contraction and relaxation. The presence of this intraventricular flow correlates closely with abnormalities of regional wall motion, identified by cineangiography in patients with left ventricular disease.^{5,6}

When present during early systole, abnormalities of wall motion may have important implications for overall ventricular efficiency and rate of pressure development,⁷ whereas non-uniformity of ventricular wall motion during isovolumic relaxation may slow ventricular pressure decline, resulting in a prolongation of isovolumic relaxation time⁸ and a reduction in the rate of ventricular filling during early diastole.⁹ So far, regional ventricular wall motion or ventricular diastolic function have not been formally studied in patients after the Fontan operation.

In this study, Doppler echocardiography was used to examine atrioventricular and intraventricular flow patterns in patients before and after the Fontan operation and in healthy controls, so that possible regional abnormalities of ventricular function might be explored.

Methods

PATIENTS

Twenty-five patients (14 male and 11 female) with a median age of 94 (range 12–221 months) were studied at a median interval of 28 (0.03–105) months after the Fontan operation. Fifteen patients had tricuspid atresia (with the ventriculoarterial connection concordant in 13, discordant in one, and double outlet in one). Eight patients had double inlet left ventricle (with the ventriculoarterial connection discordant in six and double outlet in two). One patient had pulmonary atresia with

Department of
Paediatric Cardiology,
Royal Brompton
National Heart and
Lung Hospital, London
D J Penny
M L Rigby
A N Redington

Correspondence to
Dr A N Redington,
Department of Paediatric
Cardiology, Royal Brompton
National Heart and Lung
Hospital, Sydney Street,
London SW3 6NP.

Accepted for publication
23 May 1991

intact interventricular septum and one had double outlet right ventricle with anomalous insertion of the tricuspid valve tensor apparatus precluding a biventricular repair. Fifteen patients had previously undergone insertion of one or more systemic to pulmonary artery shunts, four had undergone pulmonary artery banding alone, two had undergone pulmonary artery banding before insertion of systemic to pulmonary artery shunts, and four had undergone the Fontan operation as a primary operation. Atriopulmonary anastomosis was performed in 22 patients. In two patients the rudimentary ventricle was incorporated into the anastomosis and in one patient a total cavopulmonary anastomosis with an intra-atrial baffle was performed.¹⁰ Indices were compared with 25 age and sex matched controls and 12 patients with a median age of 59 (0.06–258) months and a univentricular atrioventricular connection (eight with absent tricuspid atresia and four with double inlet ventricle) before the Fontan operation. Of these, five had undergone insertion of one or more systemic pulmonary artery shunts and two had undergone pulmonary artery banding.

MEASUREMENTS

Patients were studied at rest, lying in a supine position. Colour flow Doppler echocardiograms were recorded from an apical position, using a 5 MHz or 3.5 MHz transducer interfaced with a Toshiba SSH-160A or Hewlett Packard Sonos 1000 ultrasound machine. The transducer was angled until optimal flow signals were recorded and a pulsed wave, range gated sample volume was positioned at the centre of the colour signal in the inlet of the ventricle, at the level of the tips of the atrioventricular valve leaflets. Simultaneous electrocardiograms, phonocardiograms, and respirometer were recorded. The coincidence of the first and second heart sounds on phonocardiogram, with mitral and aortic valve closure, was verified by M mode echocardiography before measurements were made. All recordings were made at a paper speed of 100 mm/s.

Total electromechanical systole was recorded as time interval between the onset of the QRS complex on the electrocardiogram and the first high frequency component of the second heart sound ($Q-A_2$). Isovolumic relaxation time was measured as the interval between the first high frequency component of the second heart sound and the onset of early rapid ventricular filling (A_2-E). Peak atrioventricular flow velocity during early diastole (E wave) and during atrial systole (A wave) was measured and the E:A ratio and the E:E + A ratio were measured in each patient.^{11 12}

ANALYSIS

Measurements were averaged over three cardiac cycles for all indices. All data are expressed as mean (SD) and the statistical significance of differences between group means was assessed by Student's *t* tests. The null hypothesis was rejected when $p < 0.05$.

Results

TIME INTERVALS

The RR interval was similar in patients after the Fontan operation (708 (141) ms), normal children (704 (139) ms), and in patients with a univentricular atrioventricular connection before the Fontan operation (629 (90) ms). The isovolumic relaxation time, however, was significantly longer in patients after the Fontan operation (93.8 (14.5) ms) than in controls (55.2 (8.6) ms) ($p < 0.0001$) and the preoperative patients (66.4 (22.4) ms) ($p = 0.001$).

ATRIOVENTRICULAR FLOW

Atrioventricular Doppler flow showed early rapid E wave and atrial systolic A wave filling in all patients and controls, except in one patient with a univentricular atrioventricular connection before the Fontan operation, who had summation flow, so that E and A wave filling could not be separated for the purposes of analysis.

The E:A and the E:E + A velocity ratios were similar in patients before and after the Fontan operation (table). The E:A and the E:E + A ratios were higher in the normal children, than in both patient groups, however. The E wave velocity was significantly lower in patients after the Fontan operation than in either the controls or the preoperative patients. In patients after the Fontan operation an inverse relation was observed between isovolumic relaxation time and E wave velocity ($p = 0.007$). Whereas A wave velocity was similar in the control and post operative groups, A wave velocity was significantly higher in patients with a univentricular atrioventricular connection before the Fontan operation.

INTRAVENTRICULAR FLOW

Fifteen of the 25 patients after the Fontan operation (60%) showed the presence of intraventricular Doppler flow during early systole. Twenty patients had diastolic flow during isovolumic relaxation (80%), and 12 displayed both. Intraventricular flow was not detected in two patients after the Fontan operation.

SYSTOLIC INTRAVENTRICULAR FLOW

Systolic intracavitary flow (fig 1), as found in the patients after the Fontan operation, was directed from base to apex and had a mean velocity of 23.7 (5.26) cm/s. This flow began in early systole and persisted for 241.5 (59) ms after the onset of the QRS complex on the electrocardiogram—that is, 71 (11.2)% of total electromechanical systole. The intraventricular flow during systole was distinct from the atrioventricular flow signal and persisted after atrioventricular valve closure.

A similar pattern was detected during early systole in five of the 12 patients (42%) with a univentricular atrioventricular connection before the Fontan operation. This flow had a mean velocity of 23 (3.46) cm/s and lasted for 237 (65.7) ms after the onset of the QRS complex and was not significantly different from that detected in patients after operation. A lower velocity (15 cm/s) systolic flow, which

Table Atrioventricular velocity profiles and velocity ratios in the three groups of subjects studied. All indices are expressed as mean (SD). The statistical significance of differences between groups was analysed by Student's t test

	Controls	Pre-Fontan	Post-Fontan	Control v Pre-Fontan	Control v Post-Fontan	Pre- v Post-Fontan
No	25	12	25	—	—	—
RR interval (ms)	704 (141)	629 (90)	708 (141)	NS	NS	NS
E wave velocity (cm/s)	69.9 (18)	65.2 (36.7)	44.8 (17.1)	NS	p < 0.001	p = 0.028
A wave velocity (cm/s)	29.08 (11.67)	47.8 (23.6)	33.76 (12.6)	p = 0.003	NS	p = 0.025
E:A ratio	2.6 (0.9)	1.4 (0.4)	1.4 (0.5)	p < 0.001	p < 0.001	NS
E:E + A ratio	0.71 (0.07)	0.58 (0.07)	0.57 (0.08)	p < 0.001	p < 0.001	NS
Isovolumic relaxation time (ms)	55.2(8.6)	66.4 (22.4)	93.8 (14.5)	NS	p < 0.001	p = 0.001

Figure 1 Pulsed wave Doppler velocity tracing with simultaneous electrocardiogram (ECG), phonocardiogram (PCG), and respirometer (RESP) in a patient after the Fontan operation. Base to apex Systolic flow (S) is shown, which begins around the time of the first heart sound on the phonocardiogram (S₁). There is continued atrioventricular flow during mid-diastole (diastasis flow) in this patient.

Figure 2 Pulsed wave Doppler velocity tracing in a patient after Fontan operation. Isovolumic relaxation flow (R) peaks at the time of the second heart sound on the phonocardiogram (S₂) and persists until the development of early rapid ventricular filling. ECG, electrocardiogram; PCG, phonocardiogram; Resp, respirometer.

lasted for only 145 ms after the onset of the QRS complex (42% of total electromechanical systole), was detected in two of the 25 normal children.

INTRAVENTRICULAR FLOW DURING ISOVOLUMIC RELAXATION

An early diastolic intraventricular base to apex flow signal was detected in 20 patients after the

Fontan operation (80%) (fig 2). This peaked at or just after the time of aortic valve closure, had a mean velocity of 21.4 (6.7) cm/s, and ended with the development of atrioventricular flow. Intraventricular flow with a velocity of 10 cm/s was detected in two normal children (8%), but was not seen in any of the patients with a univentricular atrioventricular connection before the Fontan operation.

There was no relation between the duration of follow up and the presence of abnormal intraventricular flow. Respiration had no significant effect on intraventricular flow.

Discussion

This study shows the presence of two distinct patterns of intraventricular flow in patients after the Fontan operation; the first occurred during early systole and the second during isovolumic relaxation.

SYSTOLIC INTRAVENTRICULAR FLOW

In 15 of 25 patients (60%) an intraventricular Doppler signal, reflecting blood flow towards the apex, occurred in early systole. This was distinct from the atrioventricular flow, and persisted for about 70% of electromechanical systole. A similar signal was seen in five of 12 patients (42%) with a univentricular atrioventricular connection before the Fontan operation, but in only two of 25 normal children. Although the precise mechanism for this flow remains uncertain we postulate that as in other groups of patients with left ventricular disease,⁵ it occurs as a result of incoordinate ventricular contraction during early systole.

This hypothesis is supported by the angiographic data of Gibson and coworkers, which showed the presence of delayed onset of ventricular contraction and areas of regional hypokinesis in 11 of 20 patients with a univentricular atrioventricular connection.¹³ There was evidence of incoordinate relaxation in only four patients, although this study did not include patients after the Fontan operation.

The aetiology of this systolic incoordination may be related to an alteration in the arrangement of muscle fibres and ventricular geometry resulting from the underlying congenital heart lesion,¹⁴ or from chronic volume overload,¹⁵ or which may be secondary to myocardial necrosis or fibrosis manifest in the myocardium of some patients with congenital heart disease from an early age.¹⁴ It is not surprising that the incidence of systolic intraventricular flow is not increased by the Fontan operation, as neither afterload nor global ventricular systolic function seems to be significantly worsened.

INTRAVENTRICULAR FLOW DURING ISOVOLUMIC RELAXATION

By contrast with systolic flow, the incidence of intraventricular flow during isovolumic relaxation was much higher in patients after the Fontan operation (80%) than in the healthy children (89%) and in the children with a univentricular atrioventricular connection before the Fontan operation (0%). Again, the exact mechanism for this phenomenon is unclear, but incoordinate ventricular relaxation may be an explanation. M mode echocardiography studies showed that an acute reduction in ventricular preload precipitated the development of incoordinate left ventricular relaxation in patients with ischaemic heart disease.⁸ Furthermore, in patients with left ventricular hypertrophy a similar pattern of base to apex intraventricular flow during isovolumic relaxation was attributed to incoordinate relaxation demonstrated by angiography.⁶ By separating the pulmonary and systemic circulations, the Fontan operation imposes an acute and dramatic preload reduction on a previously volume loaded ventricle. Furthermore, our own findings suggest that considerable systemic ventricular "hypertrophy" may develop at the time of the Fontan operation.¹⁶ Presumably this is related to an acute reduction in preload in a ventricle in which shortening fraction and muscle mass remain constant. Indeed in patients studied two months after this operation posterior wall thickness was increased.⁴ It thus seems reasonable to postulate that the diastolic flow in patients after the Fontan operation reflects the development of incoordinate ventricular relaxation resulting from an acute preload reduction and the development of a "hypertrophic" left ventricle at the time of operation.

VENTRICULAR RELAXATION AND ATRIOVENTRICULAR FLOW

Incoordinate ventricular relaxation results in an impairment of overall ventricular relaxation with prolonged isovolumic relaxation time,⁸ which may cause a reduction in atrioventricular flow velocity during early diastole.⁹ In our patients after Fontan operation, the isovolumic relaxation time was prolonged and early atrioventricular filling was lower than in healthy children and patients before operation.

Both E and A wave atrioventricular velocities were proportionately lower in post-operative patients, however, than in patients before the Fontan operation, so that E:A and E:E + A ratios were similar in the two groups. Thus the lower rate of ventricular filling in the patients after operation may merely reflect a reduction in total stroke volume consequent on separation of the systemic and pulmonary circulations. It would be premature to assume that these data provide evidence for changes in ventricular compliance characteristics resulting from the Fontan operation. The inverse relation between isovolumic relaxation time

and early filling velocity in these patients suggests that impaired ventricular relaxation may be the primary cause of altered filling after this operation.

This study does provide evidence for the development of incoordinate ventricular relaxation in patients after the Fontan operation. We postulate that the underlying mechanism for these abnormalities is related to a combination of preload reduction and acquired ventricular hypertrophy. The presence of incoordinate ventricular relaxation may alter ventricular diastolic function, which in turn may influence pulmonary blood flow after the Fontan operation. The possible influence of abnormal ventricular relaxation on diastolic filling and cardiac output after the Fontan operation warrant further study.

DJP is supported by the British Heart Foundation.

- Fontan F, Baudet E. Surgical repair of tricuspid atresia. *Thorax* 1971;26:240-8.
- Fontan F, Kirklin JW, Fernandez G, et al. Outcome after a "perfect" Fontan operation. *Circulation* 1990;81:1520-36.
- Hagler DJ, Seward JB, Tajik AJ, Ritter DG. Functional assessment of the Fontan operation: combined two-dimensional and Doppler echocardiographic studies. *J Am Coll Cardiol* 1984;4:756-64.
- Gewillig MH, Lundstrom UR, Deanfield JE, et al. Impact of the Fontan operation on left ventricular size and contractility in tricuspid atresia. *Circulation* 1990;81:118-27.
- Garrahy PJ, Kwan OL, Both DC, DeMaria AN. Assessment of abnormal systolic intraventricular flow patterns by Doppler imaging in patients with left ventricular dysrhythmia. *Circulation* 1990;82:95-104.
- Sasson Z, Hatle L, Appleton CP, Jewett M, Alderman EL, Popp RL. Intraventricular flow during isovolumic relaxation: description and characterization by Doppler echocardiography. *J Am Coll Cardiol* 1987;10:539-46.
- Gibson DG. Ventricular function. In: Anderson RH, Macartney FJ, Shinebourne EA, Tynan M, eds. *Paediatric cardiology*. Edinburgh: Churchill Livingstone, 1987:159-82.
- Hall RJC, Doran J, Pusey C, McHaffie D, Gibson DG. The effect of nitroglycerine, beta-blockade with acebutolol and isometric stress on incoordinate left ventricular function. *Eur Heart J* 1982;3:23-8.
- Appleton CP, Hatle LK, Popp RL. Relation of transmitral flow velocity patterns to left ventricular diastolic function: new insights from a combined hemodynamic and Doppler echocardiographic study. *J Am Coll Cardiol* 1988;12:426-40.
- de Leval MR, Kilner P, Gewillig M, Bull C. Total cavopulmonary connection: a logical alternative to atrioventricular connection for complex Fontan operations. *J Thorac Cardiovasc Surg* 1988;96:682-95.
- Mirsky I. Assessment of diastolic function: suggested methods and future considerations. *Circulation* 1984;69:836-41.
- Little WC, Downes TR. Clinical evaluation of left ventricular diastolic performance. *Prog Cardiovasc Dis* 1990;32:273-90.
- Gibson DG, Traill TA, Brown DJ. Abnormal ventricular function in patients with univentricular heart. *Herz* 1979;4:226-31.
- Becker AE, Caruso G. Congenital heart disease—a morphologist's view on myocardial dysfunction. In: Becker AE, Losekoot TG, Marcelletti C, Anderson RH, eds. *Paediatric cardiology vol. 3*. London: Churchill Livingstone, 1981:307-23.
- Di Donato M, Barletta G, Mori F, Fantini F. Regional left ventricular wall motion abnormalities in chronic volume overload. *Cathet Cardiovasc Diagn* 1983;9:453-62.
- Penny DJ, Lincoln C, Xiao H, Rigby ML, Redington AN. Acute effects of transition to a Fontan circulation. *Br Heart J* 1991;66:66.