TOTAL CAVOPULMONARY CONNECTION WITHOUT THE USE OF PROSTHETIC MATERIAL: TECHNICAL CONSIDERATIONS AND HEMODYNAMIC CONSEQUENCES

Total cavopulmonary connection with use of an autogenous intraatrial tunnel to create a straight tube between the inferior vena cava and the pulmonary artery was attempted in several types of cardiac anomaly in eight consecutive candidates for the Fontan operation. A small right atrium with an extraordinary location of the inferior vena cava and a short superior vena cava prevented the use of this procedure in two cases. By preserving the crista terminalis and the sinus node and its arteries we prevented the development of postoperative atrial arrhythmias in the short follow-up period, and the P trigger-signal averaged P waves were not different from those of other cardiac anomalies. The proximal stump of the superior vena cava was not incised in any case to enlarge the anastomosis, even when size mismatch between the superior and inferior venae cavae existed, as in a case of bilateral superior venae cavae. Stretching the vessels by approximately 150% was possible and permitted an adequate anastomosis. Cavopulmonary connections via the intraatrial tunnel ensured smooth, nonturbulent, somewhat pulsatile flow without a pressure gradient. We concluded that the creation of an autogenous intraatrial tunnel was possible in many cases without serious complications and that this procedure has potential benefit for the pulmonary circulation in the aspect of pulsatility. (*J THORAC CARDIOVASC SURG* 1995;110:625-32)

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The advantages of total cavopulmonary connection (TCPC) over Fontan's operation to treat nonventricular assisted pulmonary circulation have been reported by de Leval and associates.¹ In summary, turbulence is prevented by the use of straight connections, but a polytetrafluoroethylene tube graft or some other type of synthetic material was thought to be essential.^{1,2} Recently, however, surgeons have become aware of the size mismatch that develops when prosthetic material is implanted in pediatric patients. Therefore techniques to create an autogenous intraatrial tunnel from the inferior vena cava (IVC) to the superior vena cava (SVC) have been developed.³⁻⁶ We have extended this approach to the management of several types of cardiac

anomalies: tricuspid atresia, univentricular heart with or without isomerism, and imbalanced atrio-ventricular septal defect.

This paper describes the surgical techniques, problems, and hemodynamic characteristics as assessed by echocardiography and cardiac catheterization of TCPC without the use of prosthetic material. Atrial arrhythmic events and atrial electrical activities were evaluated by Holter electrocardiograms and P trigger-signal averaged electrocardiograms after operation.

Patients and methods

Patients. Eight consecutive patients who were candidates for a Fontan-type operation between September 1992 and September 1993 were included in this study (Table I). Preoperative data are listed in Table II. We attempted (1) to create TCPC, (2) to avoid the use of prosthetic materials, and (3) to avoid surgically induced atrial arrhythmias as much as possible. All patients received an antiplatelet agent for 3 months after the operation. At about 3 months after operation, all survivors were evaluated by echocardiography and catheterization. Angiographic evaluation was done with a Kontron Cardio-500 analyzer (Kontron Instruments, Inc., Everett, Mass.). A Holter electrocardiogram was obtained at that time, and atrial electrical activity was assessed by a P

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Table I

Case	Age (yr)	Diagnosis	Status
1	19	Tricuspid atresia (1B)	Alive
2	12	DIRV with small LV, DORV, intact IAS, post PAB	Alive
3	6	Asplenia, dextrocardia, common atrium, two AV valves, bilateral SVCs, isolated hepatic drainage	Alive
4*	4	DIRV with small LV, DORV, left PA distortion	Alive
5	27	AV discordance, MA, small LV, VSD, ASD, PS	Alive
6	6	AVSD (RV dominant), DORV, post PAB	Dead
7	4	Tricuspid atresia (1A), coronary AV fistula	Alive
8	19	Asplenia (RV type), CAVV	Alive

DIRV, Double inlet right ventricle; LV, left ventricle; DORV, double outlet right ventricle; IAS, intact atrial septum; PAB, pulmonary arterial banding; AV, atrioventricular; MA, mitral atresia; VSD, ventricular septal defect; ASD, atrial septal defect; PS, pulmonary stenosis; AVSD, atrioventricular septal defect; RV, right ventricle; CAVV, common atrioventricular valve.

*Fenestrated.

trigger-signal averaged electrocardiogram (250 beats) and compared with findings in other patients after operation for congenital cardiac disease.

Surgical techniques. A cavopulmonary connection was created with the use of cardiopulmonary bypass. In cases in which a Blalock-Taussig shunt had been placed in the planned location for the cavopulmonary connection, we always used the site of the Blalock-Taussig anastomosis for the connection. This technique eliminated even minimal stenosis or distortion from a previous Blalock-Taussig shunt. Even when size mismatch between the SVC and IVC existed, especially as in a case of bilateral SVCs (Fig. 1, case 3), the proximal stump of the SVC was not incised nor was a patch used in any case to enlarge the anastomosis. The anastomosis between the main pulmonary artery (PA) and the proximal stump of the SVC was enlarged by extending the stump of main PA toward the left PA. However, the SVC was stretched to 150% of its native size, which created a bell-bottom anastomosis. In the case noted (case 3, Fig. 1), the anastomosis was curved anteriorly to avoid compression of the common pulmonary vein, which ran beneath the left PA-SVC anastomosis.

After cardioplegic arrest, the right atrium (RA) was opened by a longitudinal incision along the sulcus terminalis in most cases, as in the Senning operation applied for transposition of the great arteries. The intact fossa ovalis was incised anteriorly and longitudinally, creating a large atrial septal defect. The superior edge of the septal flap was turned over and then sutured toward the SVC orifice, which was subsequently incorporated into the intraatrial tunnel (Fig. 2). In patients with a common atrium or atrioventricular septal defect, the superior or inferior septal ridges, when they existed, were incised and turned toward the venous chamber side and sutured to the posterior wall of the RA; consequently, they were incor-

Table II. Preoperative cardiac catheterization data

Case	RAP (mm Hg)	LAP (mm Hg)	PAP (mm Hg)	PAR (mm Hg)	PA index ²⁰
1	6/3	8/2	10/4 (8)	1.9	252
2	8/0	9/0	15/8 (11)	1.8	243
3	9/6	10/8	13/8 (10)	—	230
4	8/1	9/2	14/11 (12)	—	204
5	11/7	10/8	22/10 (16)	2.2	602
6	7/1	7/1	13/2 (7)	2.0	390
7	17/8	12/8	21/11 (16)	1.3	430
8	14/12	15/13	19/15 (17)	1.9	299

RAP, RA pressure; LAP, left atrial pressure; PAP, PA pressure; PAR, PA resistance; PA index, cross-sectional area (mm²) of both the right and left PA/body surface area (m²).

porated into the intraatrial tunnel (Fig. 3). The intraatrial tunnel was constructed by suturing the atrial posterior flap around the orifice of the IVC, through the base of the coronary sinus, and then to the incised septal ridges, creating a passage from the IVC to the SVC in all cases (Figs. 2 and 3).

In case 3 (Fig. 1), the left-sided RA was incised in a trapezoid fashion along the atrial crest to prepare the RA free wall flap. The intraatrial tunnel was constructed by suturing the atrial flap around the orifice of the IVC, to the posterior septal ridge, and to the right side of the ridge of the hepatic vein orifice. Thus the hepatic vein blood flow was diverted into the intraatrial tunnel. As a final step, the anterior flap of the RA was brought down and sutured on the outer wall of the intraatrial tunnel to create a pulmonary venous chamber in all cases (Figs. 1 through 3). In case 4, a 4 mm hole was created on the posterior RA flap. In case 4, the right Blalock-Taussig shunt had produced severe right PA distortion. The anterior wall of the transected main PA was incised, and the incision was extended distally into the right main basal branch. The main PA was turned toward the right as a flap and sutured widely along the right PA incision, enlarging the stenotic and distorted right PA. An incision was made in the right PA flap superiorly to create a wide anastomosis with the SVC (Fig. 4).

In two patients, this technique was not used. In one case, the SVC was too short to create a cavopulmonary connection. However, a straight intraatrial tunnel from the IVC to an atriopulmonary anastomosis was created using the RA wall, as in the other cases (case 5). In another patient (case 8), because the RA was small and the IVC drained more or less into the center of the common atrium, creation of an autogenous intraatrial tunnel was too difficult, and a polytetrafluoroethylene graft patch* was used.

Results

Among the eight candidates for inclusion in the study, autogenous intraatrial tunnel was not created in two. The patient in case 6 died 10 days after the

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Fig. 1. Surgical technique in asplenic syndrome. Intraatrial tunnel was constructed by suturing atrial flap around orifice of IVC, to posterior septal ridge, and to right side of hepatic vein (HV) orifice, and suturing was continued toward left SVC. Then anterior flap of RA was brought down and sutured on outer wall of intraatrial tunnel to create pulmonary venous (PV) chamber. BT, Blalock-Taussig shunt.

operation of ventricular failure with a left atrial pressure of 21 mm Hg. The intraatrial venous channel in this patient was noted to be widely patent without thrombi by echocardiography. The postoperative course was uneventful in the other patients. No patients had evidence of any thromboembolic episode.

Cardiac catheterization. Cardiac catheterization was done 3 ± 1 months (mean plus or minus standard deviation) after operation and demonstrated unobstructed flow (no pressure gradient) from both the SVC and the IVC to the PA (Fig. 5, A). In the one unique case (case 3), blood from both the isolated hepatic vein and the IVC flowed smoothly into the PA (Fig. 5, B). The pressures in the autogenous atrial tunnel and the PAs are listed in Table III with pulse pressures of 4.4 ± 1.1 and

4.2 ± 1.0 mm Hg, respectively. The pulse pressure in case 4, with a fenestrated TCPC, was the minimum. Flow in the autogenous atrial tunnel was pulsatile, and the ejection fraction in the intraatrial channel ranged from 31% to 40% (Tables III and IV). Because the RA wall was used for the creation of the intraatrial tunnel, the pulmonary venous chamber (the remaining atrial space) was not abnormally large (Table IV).

Echocardiographic and electrophysiologic assessments. Transthoracic echocardiography demonstrated widely patent atrial tunnels without intramural thrombi in all cases.

All patients had sinus rhythm after the operation (12 ± 4 months after the operation) without supraventricular arrhythmias on Holter electrocardiogram. The duration, area, and root mean square of

Fig. 2. Surgical technique in intact atrial septum. Intact fossa ovalis was incised, creating large atrial septal defect. Right atrial posterior flap was sutured along posterior edge of atrial septal defect.

Fig. 3. Surgical technique in atrioventricular septal defect. In patients with atrioventricular septal defect, superior or inferior septal ridges were incised and turned toward venous chamber side and sutured to posterior wall of RA; consequently, they were incorporated into intraatrial tunnel.

the P trigger-signal averaged P waves were not different from those of other patients with congenital heart disease after cardiac repair (Table V).

Discussion

The creation of an autogenous intraatrial tunnel by diverting IVC blood to the PA via a TCPC has been advocated by several groups.³⁻⁶ This technique is an alternative to the use of prosthetic material (polytetrafluoroethylene graft patch).^{1,2} An intraatrial tunnel can be used with different types of atrial

morphologic conditions and in complex cardiac anomalies. A small RA with an extraordinary location of the IVC and a short SVC was the only prohibiting factor encountered in this series.

Although our technique is adaptable in most anomalies, it is well suited to the correction of univentricular heart, in which a common atrioventricular valve or two atrioventricular valves are preserved unrestricted without jeopardizing venous chamber inflow.^{1,2} Even in the patient with isolated hepatic vein drainage, an atrial flap produced

Fig. 4. Repair of pulmonary arterial distortion. Main pulmonary artery was turned toward right as flap and sutured widely along right PA incision, enlarging stenotic and distorted right PA.

smooth and nonturbulent flow from both the IVC and the hepatic vein to the PA. The morphologic features of the atrium and the existence of an atrial septum were not problematic in creating the intra-atrial tunnel. The atrial septal flap remained after the creation of an atrial septal defect and alternatively the superior-inferior septal ridge of the common atrium can be used as the side of the intraatrial tunnel. Because the intraatrial tunnel is created with autogenous tissue, the remaining atrial space, namely the pulmonary venous chamber, is kept at the proper size. In the cases of original TCPC the pulmonary venous chamber results in a larger size.

de Leval and associates¹ have recommended that the proximal end of the transected SVC be incised anteriorly and medially to enlarge it to the diameter of the IVC; a small triangular pericardial patch was used for this purpose. The incision did not reach the caval-atrial junction in their cases. Puga⁷ has commented on this paper and advised that the enlargement be extended farther, down to the caval-atrial junction, to eliminate a size mismatch between the SVC and the IVC completely. However, both procedures increase the risk of injury to the sinus node artery.⁸ Our results show that enlargement of the SVC stump is not necessary. An expanded anastomosis, forming a bell-bottom shape, is able to han-

dle the increased blood flow by expansion. Because we did not enlarge the proximal SVC stump and incised the atrium carefully, avoiding the crista terminalis, the sinus node, and the sinus node artery when we created the atrial flap, postoperative atrial arrhythmias were not a problem in this series. However, we think that unobstructive flow is much more important at caval connections. Thus, in some cases, enlargement of the SVC orifice might be necessary. Atrioventricular block also was avoidable in all types of atrioventricular connections. A modification of the Fontan operation with use of a pedicled flap of RA wall has been reported by Puga, Chiavarelli, and Hagler.⁹ This maneuver excluded systemic venous drainage from the atrioventricular valve while maintaining a generous communication between the pulmonary venous orifices and the ventricular inlet. All four patients who underwent this procedure had recurrent atrial arrhythmias. Parallel incisions were made in the body of the RA, extending from the atrioventricular groove anteriorly to the interatrial sulcus posteriorly. These long transverse (longitudinal in our technique) incisions reached the crista terminalis, and high central venous pressures (14 to 20 mm Hg) were believed to be the cause of the arrhythmias, rather than the atrial flap itself. A new modification recently re-

Case 2 Lateral view

Case 3 Frontal view

Fig. 5. Angiographic appearance of autogenous intraatrial tunnel. Flow in straight atrial tunnel was nonturbulent and nonobstructive.

ported by von de Wal, Tanke, and Roef¹⁰ creates an autogenous intraatrial tunnel by using both anterior and posterior RA flaps instead of using only a posterior flap as in our technique. This technique is probably more widely applicable to creation of the autogenous tunnel in any situation. However, the atrial incision has to cross the crista terminalis and the cavopulmonary connection has the potential for injuring the sinus node artery.

The prevalence of early arrhythmia was reported to be less in patients with TCPC than in patients with an atriopulmonary connection.¹¹ The solution to this was to exclude the atrial wall from high

Table III. Cardiac catheterization data

Case	Pressure (mm Hg)		
	LAT(a/x)	LPA(a/x)	PVC(a/x)
1	14/10	14/10	8/4
2	15/10	15/10	8/3
3	15/10	12/6	4/2
4*	8/6	8/6	6/4
7	11/5	12/8	4/2
Pulse	4.4 ± 1.1	4.2 ± 1.0	3.0 ± 1.2

LAT, Intraatrial tunnel; LPA, left pulmonary artery; PVC, pulmonary venous chamber, (a/x), a and x waves.

*Fenestrated.

Table IV. Cardiac catheterization data

Case	LAT (ml)	LAT EF (%)	PVC (ml)	SV (ml)	SV EF (%)
1	50	31	34	152	59
2	11	39	12	95	55
3	33	40	22	77	66
4*	19	36	13	93	68
7	22	40	25	102	59

LAT, Intraatrial tunnel; EF, ejection fraction; PVC, pulmonary venous chamber; SV, systemic ventricle.

*Fenestrated.

Table V. Postoperative atrial electrical activity

	Autogenous TCPC (n = 7)	Other anomalies (n = 12)
Duration (msec)	129.8 ± 20.8	116.6 ± 17.8
Area (μVolt · msec)	1026.9 ± 287.1	1041.6 ± 271.4
RMS (μVolt)	9.8 ± 3.0	11.4 ± 3.2
Area (20, μVolt · msec)	83.0 ± 44.5	95.1 ± 32.2
RMS (20, μVolt)	4.6 ± 2.4	5.3 ± 1.4

No significance between the two groups. Area, Area of P wave; RMS, root mean square of P wave; Area (20, μVolt · msec), area of P wave at last 20 msec; RMS (20, Volt), root mean square of P wave at last 20 msec.

pressure to the greatest extent possible. An autogenous intraatrial tunnel contains much more atrial tissue than the usual TCPC; however, no early supraarrhythmic episodes were observed in this series. According to Laplace's law, it is likely that the straight tunnel provides minimum wall tension with minimum autologous tract diameter, resulting in a less arrhythmogenic configuration. The duration, area, and root mean square of averaged P waves were not different from those of other anomalies after the operation, which indicates that the chance of supraventricular arrhythmia was the same; it was not particularly high in this series.¹² However, the long-term effect of chronically elevated systemic venous pressure in supraventricular arrhythmia is still unknown even in this maneuver.

An autogenous intraatrial tunnel offers a number of potential advantages over the use of prosthetic material: a straight tunnel is created from the IVC to the PA, the tunnel will enlarge as the patient grows, anticoagulation is not needed, and left atrial cavity size is preserved properly. Although long-term follow-up on the growth of autogenous tunnels has not been obtained, we are forecasting a positive result, similar to that found in the Senning operation. Our apprehension, which necessitates long-term observation, is that there is the potential for the intraatrial tunnel to dilate and for pulmonary venous obstruction to develop, inasmuch as the pressure within the intraatrial tunnel is higher than that of the pulmonary venous chamber. In the Fontan-type operation, although infrequently, some have reported that thrombi formation occurred in about 10% of patients. This complication resulted from protein C (a natural anticoagulant) deficiency in patients having the Fontan operation.¹³ We think that the application of the autogenous tunnel may be a possible solution in the circumstance of hypercoagulability and may be recommended, because this complication is important and is to be solved with intensive effort. Straight cavopulmonary connection has, of course, certain hemodynamic advantages over the Fontan operation. However, the use of prosthetic material to partition the venous root results in a rather large pulmonary venous chamber, which we believe is a disadvantage, not only in hemodynamics but also as an arrhythmogenic configuration.

Formation of an arteriovenous fistula after a Glenn anastomosis has been reported,^{14, 15} and this problem recently has been reported in TCPC.^{16, 17} Although possible causes of arteriovenous malformations have been discussed by Jonas¹⁸ and a time factor (aging) and a hepatic factor were identified, nonpulsatile flow was considered as a major cause. Moore and associates¹⁶ and Puga¹⁷ have reported that pulmonary arteriovenous malformations developed only in patients in whom direct cavopulmonary anastomosis was done.¹⁷ A difference in the pressure tracing between TCPC and atriopulmonary connection has been demonstrated by de Leval¹ and Ishikawa¹⁹ and their colleagues. Atriopulmonary connections have tall waves in the RA and the PA flow is relatively more pulsatile than that with TCPC. Because TCPC with greater pulsatile flow than usual was created by an autogenous intraatrial tunnel in this series, TCPC with autogenous intraatrial tunnels may prevent the formation of pulmo-

nary arteriovenous malformations. The minimal backflow into the IVC observed during atrial systole did not produce hemodynamic problems or hepatic dysfunction in any patient. Although Stark and Kostelka¹⁴ did not mention the characteristic of pulsatility in their series, they found no significant difference in the amount of postoperative chest drainage, the incidence of arrhythmia, or the length of the hospital stay compared with these findings in usual TCPC.

We conclude that the creation of an autogenous intraatrial tunnel was possible in many cases without the development of atrial arrhythmias. In addition, the pulmonary venous chamber was proper in size and pulsatility may prevent delayed onset of pulmonary arteriovenous malformation.

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