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Venous Shunts and the Fontan Circulation in Adult Congenital Heart Disease

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For patients with functionally univentricular hearts, the dramatic refinement in surgical strategies since 1968 has enabled survival for large numbers of adults with truly unique cardiovascular physiology. Due to the complexity of their cardiac anatomy, the insidious nature of disease progression, the high incidence of arrhythmias, and the challenges of assessing the 'Fontan circulation' as opposed to traditional cardiac assessment of ventricular contractility and valve abnormalities, the patient with Fontan palliation poses unique and growing challenges to optimal care.[1,2] The goals of this chapter are to review the evolution of surgical techniques for patients with functionally single-ventricle anatomy, the resulting cardiac physiology, and a review of common cardiac and multiorgan consequences of this circulation. Complications involving the liver assume greater importance over decades and are the subject of the subsequent chapter (see Chapter 13).[3] Particular attention is given to the management of haemodynamic complications and recurrent arrhythmias, with a summary of recent guidelines addressing the management of adults with congenital heart disease, focusing on adult patients with Fontan circulation.[1,2,4–10]

SURGICAL EVOLUTION OF OPERATIVE TECHNIQUES

Venous shunts are surgical reconstructions involving an anastomosis between one or both caval veins to one or both pulmonary arteries (PAs) and were developed to palliate infants and children born without two ventricular chambers (functionally single ventricle).[11–15] *Staging venous shunts* are typically performed during infancy and childhood, and include the older *Glenn shunt*, an end-to-end anastomosis of the superior caval vein to the right PA, and the more recent *bidirectional cavo-pulmonary shunt*, an end-to-side anastomosis of the superior caval vein to the PA, leaving both PAs in continuity. Subsequently *a Fontan-type repair* is performed to anastomose the inferior caval vein flow to the PAs, classically achieved by anastomosing the right atrium to the PAs but more recently achieved by a lateral tunnel or extracardiac connection. The Fontan operation achieves separation of the pulmonary and systemic circulations, resulting in a circulation without a subpulmonic ventricular pumping chamber.

The introduction of venous shunts to the management of patients with univentricular hearts has extended survival for patients with the most complex forms of congenital heart disease to 70% to 90% by age 30 years.[16–20] In general, these procedures are applied to patients with 'functionally univentricular physiology'. As first performed in 1968, the Fontan surgery channelled systemic venous return to the PAs, with the inclusion of inflow and outflow prosthetic valves.[11] The Fontan palliation was initially applied to patients with tricuspid atresia and anatomic single left ventricles (LVs), whose mortality without surgery was more than 90% in the first year of life. The Fontan principle was extended gradually to patients with more complex forms of functionally univentricular anatomy, including unbalanced biventricular anatomy, single right ventricles (RVs), and ultimately hypoplastic left heart syndrome, as shown in Fig. 12.1. In centres seeing adults with congenital heart disease, the Fontan population represents about 5% of patients; of these, the majority currently have single left ventricular anatomy, while patients with single right ventricles (29% of current primary Fontan operations) will account for a growing number of patients.[21–23]

SURGICAL TECHNIQUES FOR PATIENTS WITH FUNCTIONALLY UNIVENTRICULAR PHYSIOLOGY

To survive the neonatal period, infants with univentricular physiology require *adequate pulmonary flow* and *protection from excessive pulmonary flow*, adequate *atrial-level mixing* without restriction at the atrial septal level, and *relief of aortic outflow obstruction* when present. As a *first stage* of surgical interventions, more than 80% of infants undergo surgery for pulmonary flow modification, either augmentation of pulmonary flow with systemic-to-pulmonary shunts in 63% to 80%, or restriction of pulmonary flow with PA banding in 12% to 25%.[21,24] Surgical atrial septectomy to allow adequate atrial mixing without pulmonary venous hypertension was required in up to 14% of patients; repair of the aortic arch was needed in 7% to 10% of patients.[21,24] Subsequent application of Fontan repairs beginning in the 1980s to patients with hypoplastic left heart syndrome required reconstructive surgery of the ascending aorta in all of these patients (Damus–Kaye–Stansel or Norwood procedures).

Once pulmonary blood flow and atrial-level mixing are stabilised, the introduction of the classic Glenn shunt (superior caval vein to right PA) or the bidirectional cavo-pulmonary anastomosis has been used as the *second stage* of surgery prior to the Fontan repair, often with associated PA augmentation performed (Fig. 12.2). In 1958 Glenn reported shunts from the superior caval vein to the right PA, whereby the right PA was divided and anastomosed to the right side of the superior caval vein after ligation and division of the azygos vein.[25] The superior caval vein was then ligated at the cavo-atrial junction. The *Glenn shunt* implies that *the right and left PAs are not in continuity* with each other. The early effects of the unidirectional Glenn shunt showed that it was a relatively simple operation, improved oxygen saturation, and provided excellent palliation for many patients.[26] Unfortunately, late deterioration occurred because of decreased effective pulmonary blood flow, resulting from the development of systemic venous collateral vessels and pulmonary arteriovenous malformations resulting from the absence of hepatic flow to the lungs in addition to lack of pulsatile pulmonary flow.[27]

The development in 1989 of an end-to side anastomosis of the superior caval vein to the main PA without branch PA division took on the name *bidirectional Glenn (or bidirectional cavo-pulmonary) shunt*.[28] The bidirectional Glenn shunt is performed by anastomosing the superior caval vein to the right branch of the PA using fine sutures and then dividing the proximal main PA, leaving the branch PAs in continuity. The introduction of cavo-pulmonary shunt surgery between neonatal

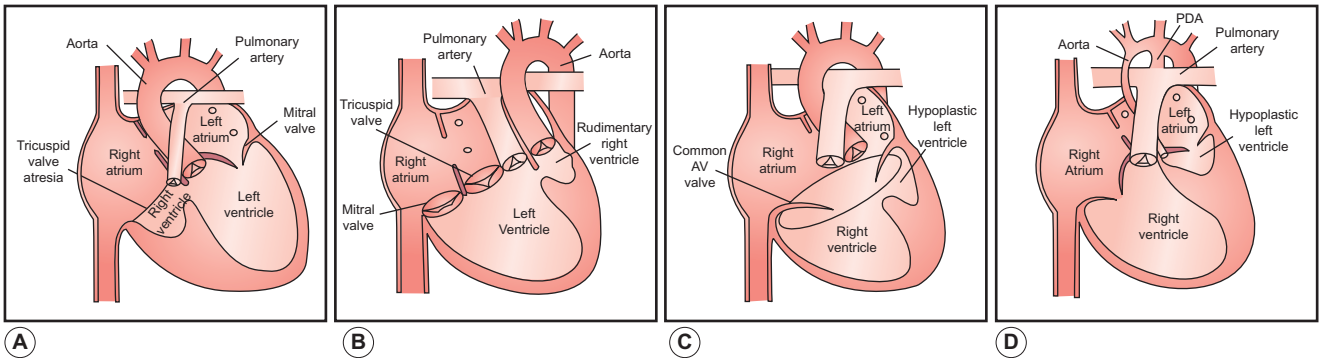


Fig. 12.1 Common types of single ventricles. Functionally univentricular hearts include single left ventricles (*LVs*) including (A) tricuspid atresia and (B) double-inlet LV; (C) unbalanced ventricular anatomy may be seen in heterotaxy syndrome and atrioventricular (*AV*) septal defects; and (D) single right ventricular anatomy as seen in hypoplastic left heart syndrome. *PDA*, Patent ductus arteriosus. (Courtesy Margaret Greco, MD.)

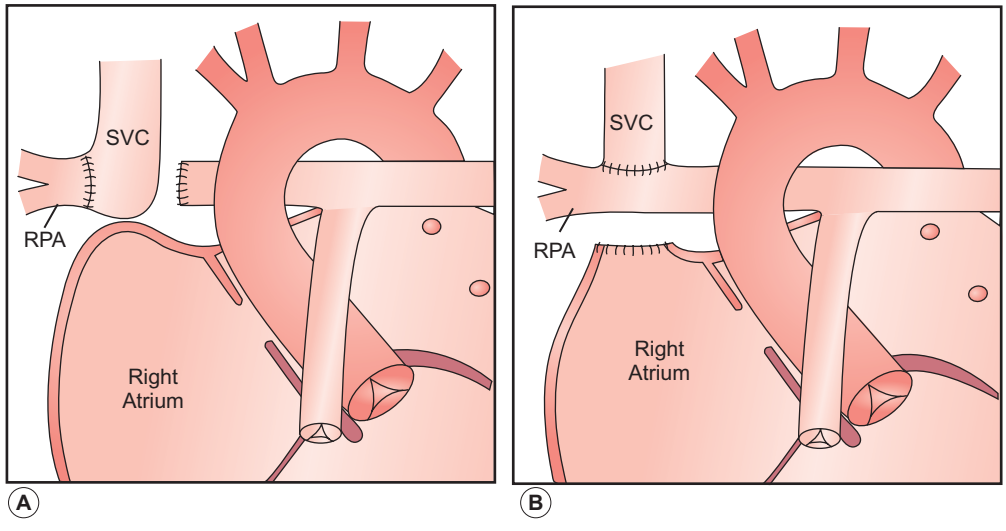


Fig. 12.2 (A) Classic Glenn cavo-pulmonary shunt between the superior caval vein (*SVC*) and the right pulmonary artery (*RPA*), with discontinuity between right and left PAs; (B) bidirectional cavo-pulmonary shunt between the superior caval vein and right PA, leaving PAs in continuity. (Courtesy Margaret Greco, MD.)

surgery and the Fontan repair of childhood coincided with a marked improvement in early survival after the subsequent Fontan surgery, by allowing stepwise diversion of systemic venous return from the upper body directly to the PAs. At the time of later Fontan surgery, acute ventricular volume unloading (which results from the complete separation of pulmonary and systemic flows) is avoided, allowing ventricular function to adapt to the changed loading conditions. The bidirectional cavo-pulmonary anastomosis improves systemic arterial oxygen saturation without increasing pulmonary vascular resistance and maintains continuity of the PAs but may also lead to the development of systemic venous collateral vessels and pulmonary arteriovenous malformations. For these reasons, cavo-pulmonary shunts are usually short-term, palliative procedures performed in young children (usually <2 years) who are being prepared for an eventual Fontan procedure. Simultaneously, the age at which Fontan completion surgery is performed has decreased substantially to limit the period of cyanosis and volume overload and is now generally performed between 2 and 3 years of age, compared with ages 5 to 8 years, which was customary three decades ago.[22]

The *third stage* of surgical intervention is the **Fontan operation** and its many modifications (Fig. 12.3), one of which is the Kreutzer procedure.[11,12,29] The Fontan repairs are characterised by complete separation of the pulmonary and systemic circulations, and depend on high systemic venous pressure and low PA pressure/resistance to propel non-pulsatile blood flow through the pulmonary circulation without the benefit of a pumping chamber. Kreutzer's contribution was the direct atriopulmonary anastomosis, which eliminated the need for interposed venous valves.

Between 1970 and the early 1990s, the **right atrium-to-PA direct connection** (both retro-aortic and antero-aortic) became standard therapy, as did the **Björk modification** in which the right atrial appendage is anastomosed to the right ventricular outflow tract or to the main PA.[30] Due to the compliance and growth potential of atrial tissues, progressive right atrial dilatation, venous stasis and thrombosis, and atrial re-entrant tachycardia developed in patients with atriopulmonary connections, especially those individuals with antero-aortic connections. The gradually enlarging right atrium created a size mismatch to the pulmonary anastomosis, with excessive 'power loss' or turbulence of passive venous flow to the PAs, as well as compression of pulmonary venous return from the right lung (Fig. 12.4). The desire to limit atrial distention and thus avoid obstruction to atrioventricular valve inflow led to the development of the total cavo-pulmonary **lateral tunnel connection**, which was demonstrated to have superior blood flow characteristics and allowed unimpeded pulmonary venous return to a right-sided atrioventricular valve.[14,31] The increased suture load used in the right atrium to construct the lateral tunnel was not initially recognised as a future arrhythmogenic consequence of the procedure.

rt abbreviation:
tricuspid atresia

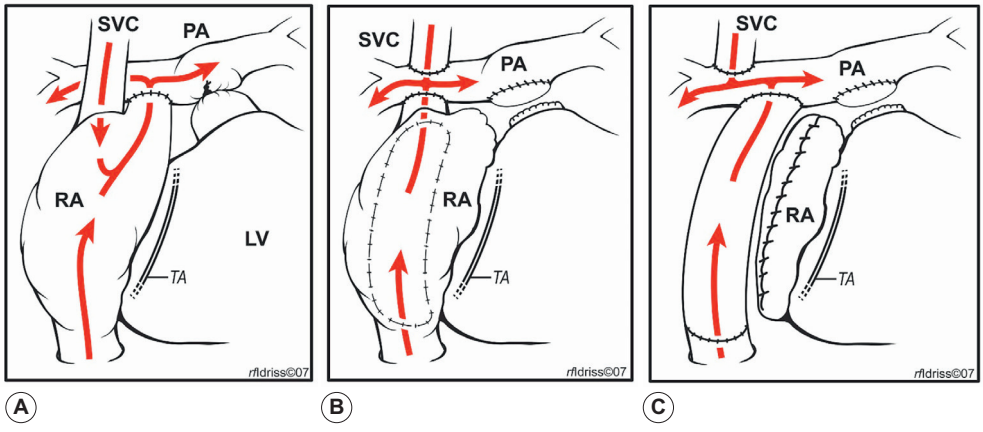


Fig. 12.3 Common modifications of Fontan surgeries: (A) atriopulmonary Fontan; (B) intracardiac lateral tunnel; (C) extracardiac total cavo-pulmonary connection. *LV*, Left ventricle; *PA*, pulmonary artery; RA, right atrium; *SVC*, superior vena cava. (Courtesy Rachid Idriss.)

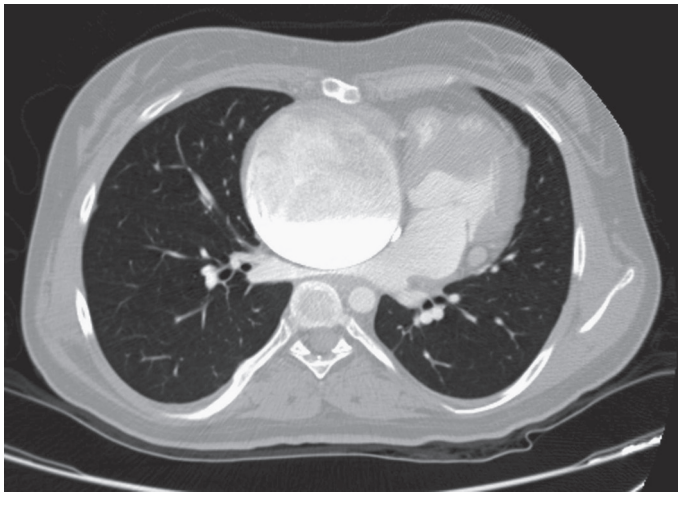


Fig. 12.4 Computed tomography scan of atriopulmonary Fontan showing the markedly enlarged right atrium compressing the right pulmonary veins. (Courtesy Joshua Robinson, MD.)

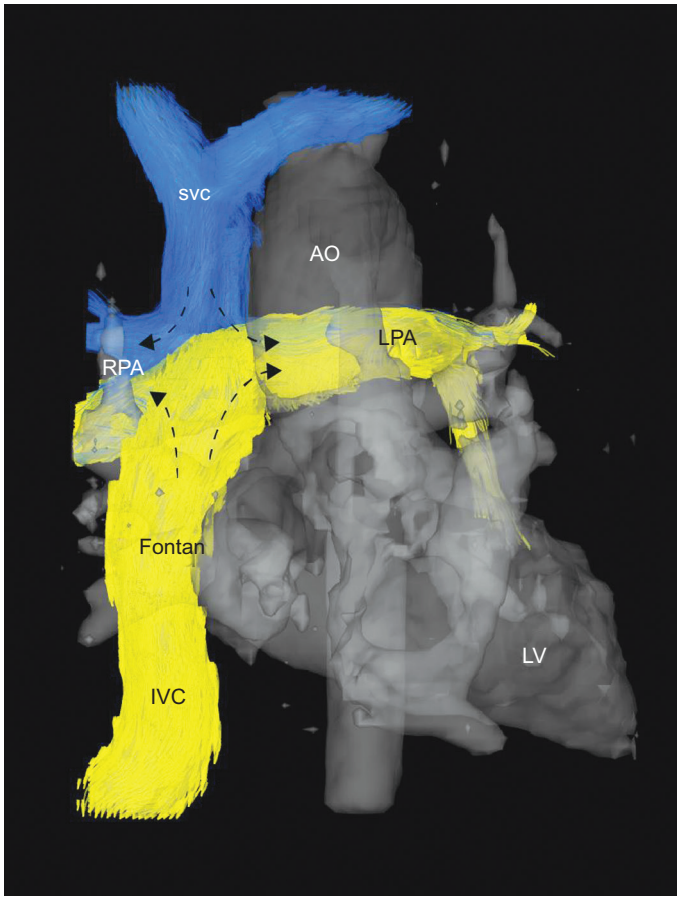


Fig. 12.5 Four-dimensional flow magnetic resonance imaging of inferior caval vein flow from the extracardiac Fontan as it meets the superior caval vein flow. The importance of off-setting of the two flow channels can be appreciated. *AO*, Aorta; *IVC*, inferior caval vein; *LPA*, left pulmonary artery; *LV*, left ventricle; *RPA*, right pulmonary artery. (Courtesy Kelly Jarvis, PhD; Joshua Robinson, MD; and Michael Markl, PhD.)

Further surgical modifications were developed to allow application of the Fontan surgery to patients with hypoplastic left ventricles and to limit the development of atrial arrhythmias.[14,32]

The latest modification of the Fontan operation was the **extracardiac total cavo-pulmonary connection**, which was introduced by Marcelletti et al. in 1988.[15] This surgical concept demonstrated that an extracardiac tube graft could successfully link the inferior caval vein directly to the PA without the obligatory suture load within the right atrium. Given the relative technical ease of the extracardiac operation, often requiring no aortic cross-clamp and sometimes performed without cardiopulmonary bypass, the surgery would ideally be associated with a decreased incidence of atrial arrhythmias and limit the potential for size mismatch between the enlarging right atrium and PAs. To achieve optimal flow dynamics, the anastomosis of the tube graft to the inferior aspect of the PA needs to be *offset* from the superior bidirectional Glenn anastomosis, avoiding collision of blood streams (Fig. 12.5); reconstruction of the left PA is often needed. By doing so, the Fontan operation has been reduced to its essence: it has become a non-cardiac vascular operation, connecting caval veins to the pulmonary arteries. The implications of this concept are enormous: the ventricle is technically left untouched, and all changes observed at the ventricular level are therefore secondary changes; control of the circulation has shifted away from the heart and to the pulmonary circulation.

Attention to each of these technical details is crucial to the long-term flow dynamics. The material that was used for the extracardiac connection has changed over time: aortic homografts were initially used but were prone to calcification and induced pre-formed

antibodies, a concern for a population that would potentially require later heart transplantation. As a result, the 16- to 20-mm polytetrafluoroethylene (Gore-Tex) tube became the graft of choice for initial extracardiac connections.

The extracardiac connection has the advantage of improved flow dynamics but *does not have growth potential* commensurate with body growth and is *noncompliant*. As the body surface area of the patient increases and flow increases, the extracardiac connection becomes a potential source of increased pathway resistance and haemodynamic inefficiency, which has been demonstrated by magnetic resonance imaging (MRI) studies.[33,34] Recently, early progressive conduit stenosis has been identified, correlating with reduced exercise capacity.[35] With resultant increase in hepatic congestion, one can expect to see an increased incidence of ascites and protein-losing enteropathy (PLE) at a younger age compared with older atriopulmonary Fontan patients.

SURGICAL AND CATHETER REINTERVENTIONS

Lifetime cardiac reinterventions following the Fontan procedure occur in almost two-thirds of patients, predominantly occurring during late follow-up.[18,36,37] By 30 years post-Fontan surgery, 55% to 69% of patients require reinterventions, the majority performed late after surgery.[18,37] Fenestration closure, pulmonary artery augmentation, and pacemaker-related procedures were most common, followed by catheter ablation of arrhythmia, coiling of collaterals, and augmentation of pulmonary arteries or distal aortic arch.[18,37] Surgical Fontan revision or conversion was performed in 3% to 11% of patients, with surgical atrioventricular valve repair/replacement, and pulmonary artery reconstruction or systemic ventricular outflow obstruction surgeries more commonly performed. Non-pacemaker-related cardiac surgeries, excluding Fontan conversion or transplantation, were associated with 6% mortality.[18] Survival and freedom from late Fontan failure were significantly worse in patients requiring late re-interventions.[18]

Following Fontan surgeries, **systemic venous pathway obstruction** can result from stenotic atriopulmonary connections; lateral tunnel or extracardiac graft stenosis or calcification, graft size restriction, and peripheral PA stenosis. Any obstruction to the passive venous flow to the lungs leads to hepatic congestion, atrial enlargement, venous stasis with thrombus formation, decreased pulmonary flow, and decreased cardiac output. In particular, atriopulmonary obstructions can be subtle, often showing only 2- to 3-mm Hg gradients by catheterisation, which are nonetheless quite important haemodynamically due to the requirement of *passive venous flow*. Although these stenotic lesions can occur in any Fontan patient, they are more likely to develop in patients with certain types of anastomoses: patients with a Glenn shunt to the right PA and atriopulmonary anastomosis to only the left PA; an antero-aortic connection from the right atrium to the PA; a valved or non-valved conduit from the right atrium to the RV or PA (Bjork anastomosis); or an aortic homograft extracardiac anastomosis.

Pulmonary venous obstruction in Fontan patients usually occurs as a consequence of severe right atrial dilation causing compression of the right pulmonary veins, or marked coronary sinus dilation causing left pulmonary vein obstruction. **Left ventricular outflow tract obstruction** occurs most commonly in patients with a double-inlet LV and transposition of the great arteries with a closing bulbo-ventricular foramen producing subaortic stenosis, or following staged correction of hypoplastic left heart syndrome resulting in recurrent coarctation or increased aortic stiffness from the use of prosthetic or homograft material.

Cardiac catheterisation should carefully assess sites of Fontan narrowing and may identify 1- to 2-mm Hg gradients, which in this passive flow state are haemodynamically significant. The total cavo-pulmonary connection, with uniform non-distensible diameter and the potential for colliding flows from the lower body and superior caval vein, in addition to the frequently encountered PA narrowing, provides important areas of resistance that become magnified with exertion. The resistance provided by the total cavo-pulmonary connection is magnified under conditions of exercise or volume loading. Extracardiac conduit size of 12.5 mm/m^2 was associated with optimal exercise capacity in one study; conduits may be catheter-expanded to 20 mm diameter.[38,39] Acute fluid challenge may unmask increased gradients as well as diastolic dysfunction, particularly in patients with mildly elevated end-diastolic pressures at rest.[40,41] Accordingly, transcatheter intervention with angioplasty or stenting may effectively reduce the physiologic load imposed by pathway narrowing or small size (Fig. 12.6) and should be considered even when the mean pressure

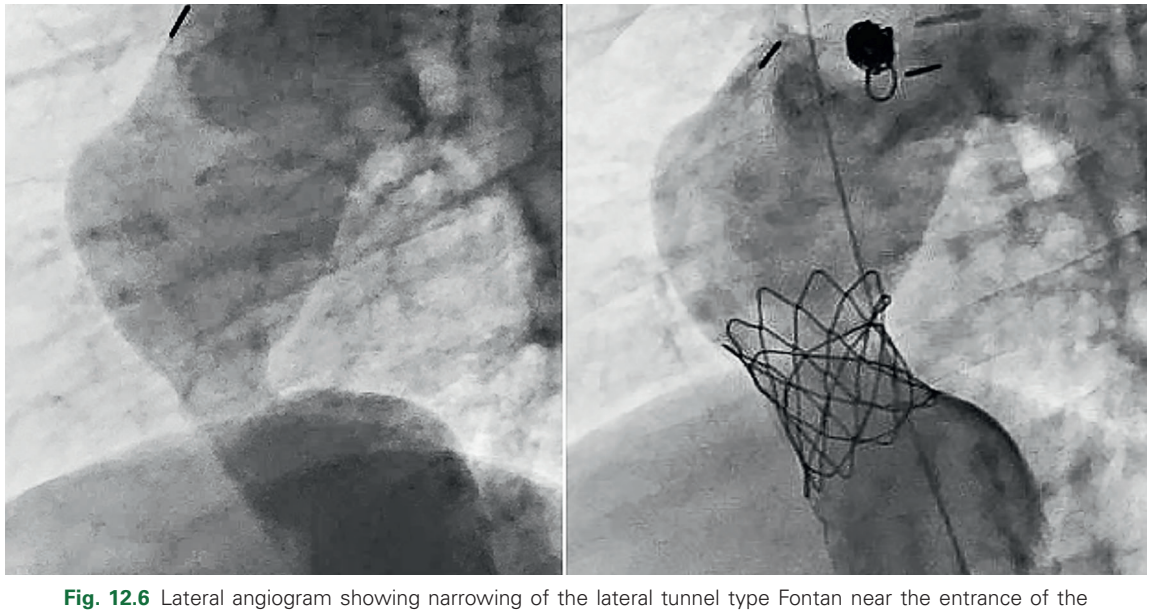


Fig. 12.6 Lateral angiogram showing narrowing of the lateral tunnel type Fontan near the entrance of the inferior caval vein, with stent implantation to relieve stenosis. (Courtesy Doff McElhinney, MD.)

gradient is very low or even absent in the setting of angiographic narrowing.[42] Similarly, treatment of branch PA narrowing or stenosis, if feasible, may lower the total cavo-pulmonary pathway resistance and minimise exercise-related power loss and hydrodynamic inefficiency.[43] Occlusion of major collaterals or veno-venous collaterals may reduce volume overload or increase oxygen saturation, thus improving cardiac output, but occlusion of veno-venous collaterals may result in elevation of central venous pressures while decreasing preload. Creation of an atrial-level defect is sometimes used for palliation of PLE, accepting cyanosis to achieve increased cardiac output.

Fontan revision refers to a surgical intracardiac intervention to rectify significant haemodynamic issues such as atrioventricular valve regurgitation, subaortic resection, revision of venous to pulmonary artery connections or repair of aortic aneurysms but maintaining the integrity of the original Fontan anastomosis.[44] The cumulative incidence of late atrioventricular valve failure was 56% by 25 years of age, highest among common atrioventricular valves.[45] By raising left atrial pressure and pulmonary venous pressure, moderate or greater atrioventricular valve regurgitation results in further decline of cardiac output; valve repair poses the risk of worsening ventricular function by removing the afterload reduction provided by valvar regurgitation.[46–48] Valve repair is associated with valve failure in as many as 40% of patients, based on specifics of valve morphology.[45] The need for atrioventricular valve replacement is associated with high mortality/need for transplantation.[45]

'**Fontan conversion**' refers to the replacement of an atriopulmonary anastomosis or lateral tunnel with an extracardiac total cavo-pulmonary connection; this surgery is usually performed in association with focused arrhythmia surgery, and placement of an epicardial dual chamber pacemaker.[49–57] The indication for such surgery most commonly includes recurrent atrial tachycardia or fibrillation in the setting of other haemodynamic issues, such as marked atrial dilation or atriopulmonary narrowing. The **Fontan conversion operative technique** consists of three components: takedown of the existing atriopulmonary communication and repair of associated haemodynamic lesions, arrhythmia surgery, and epicardial pacemaker implantation (Fig. 12.7). The enlarged right atrial anterolateral wall is widely resected, followed by takedown of the existing atriopulmonary connection. An extracardiac polytetrafluoroethylene (Gore-Tex) tube graft (usually 24 mm in diameter) replaces the atriopulmonary connection, anastomosed inferiorly to the inferior caval vein and superiorly to the underside of the PA. The superior caval vein is anastomosed to the superior position of the right pulmonary artery. The atrial septum is widely resected to form a single atrium to receive pulmonary venous inflow. Additional right and/or left pulmonary arterioplasty may be necessary, or pulmonary reconnection in cases with a right Glenn shunt and an atrio-left PA connection. The coronary sinus may require unroofing in patients with left pulmonary vein compression from massive coronary sinus dilatation.

Right atrial macro-re-entry tachycardia is predominantly present in patients undergoing Fontan conversion surgery and is addressed using a modified right-sided maze procedure (Fig. 12.8A).[58,59] In some patients, the atrial re-entry tachycardia is present in the left atrium, and increasing numbers of adult patients with Fontan circulations develop atrial fibrillation in addition to right atrial tachycardia. In the presence of atrial fibrillation or left atrial re-entry tachycardia, or in patients with significant left-sided atrioventricular valve regurgitation, the left atrial Cox-maze IV procedure is performed in addition to the modified right atrial maze (see Fig. 12.8B).[59] Implantation of an epicardial dual chamber antitachycardia pacing system is performed to achieve atrial pacing with intact atrioventricular conduction and avoid ventricular pacing. Insertion of ventricular leads has been performed to enable

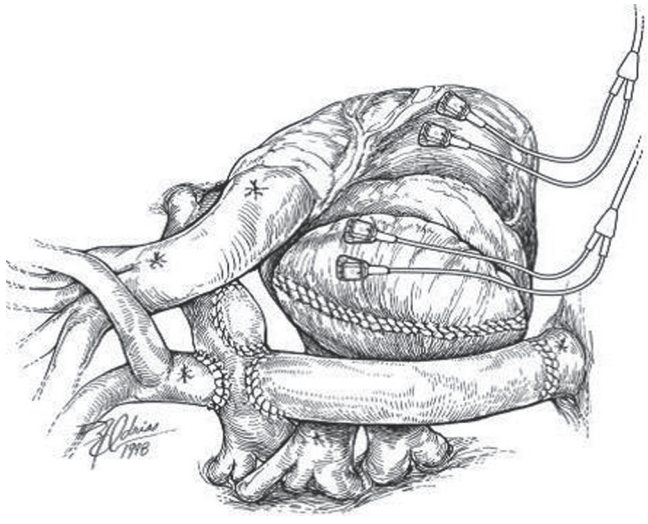


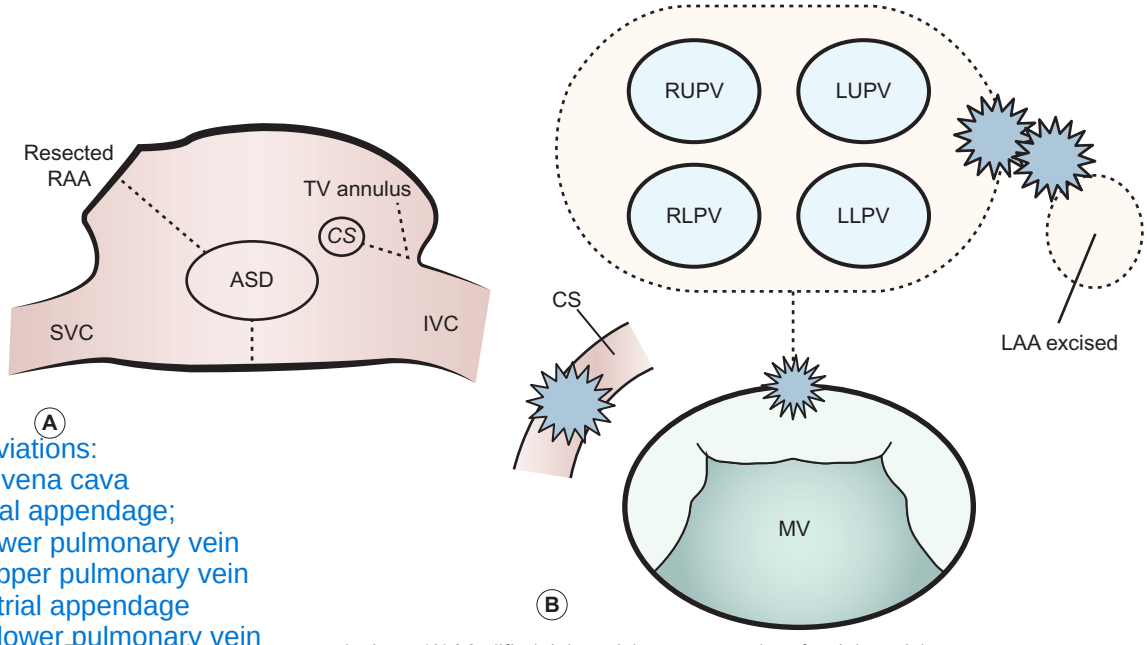
Fig. 12.7 Fontan conversion surgery. The atriopulmonary anastomosis is replaced with an extracardiac tube graft between the inferior caval vein and the underside of the pulmonary artery (PA) confluence. The superior caval vein is anastomosed to the PA confluence, which may have undergone patch arterioplasty. Epicardial atrial and ventricular pacing wires are placed. (From Mavroudis C, Deal BJ, Backer CL, Johnsrude CL. The favourable impact of arrhythmia surgery on total cavo-pulmonary artery Fontan conversion. Semin Thorac Cardiovasc Surg Pediatr Card Surg Annu. 1999;2:43–156.)

atrial tachycardia detection algorithms, and to avoid reoperation in the setting of later development of atrioventricular block, although it is preferable to avoid ventricular pacing whenever feasible in this population. Multisite ventricular leads (resynchronisation) or epicardial ventricular defibrillator leads may also be required.[60]

In our series of 140 patients, early operative mortality was 1.4%, freedom from arrhythmia was 77% at 10 years, and freedom from death or transplant was 84% at 10 years, which serves as a comparison for 10-year survival of 71% with heart transplantation in Fontan patients.[59,61] Proper patient selection is key to successful Fontan conversion surgery, with early conversion prior to the development of end-stage complications such as PLE or severe ventricular dysfunction associated with decreased surgical mortality.[57,59,62–64] Since 1994 over 1100 such surgeries have been performed in centres around the world with mean perioperative mortality of 5% to 6%, with optimal results at highly experienced centres.[59,62,63]

During the last two decades, the primary Fontan surgical techniques shifted to total cavo-pulmonary connections, either intracardiac or extracardiac, so that the population of adults with atriopulmonary anastomoses who would benefit from Fontan conversion has declined, and represent about 10% of current adult congenital heart disease cardiac surgeries.[16,65–67] The distensibility, compliance, and energy loss of the right atrium in the atriopulmonary connection has been traded for improved flow dynamics and a potentially restrictive extracardiac graft: the long-term outcome of this strategy is presently evolving. Patients with small or calcified extracardiac conduits, particularly aortic homograft connections, may become candidates for Fontan conversion in the future, as conduit size has been shown to progressively decrease over time.[35]

The survival to adulthood of patients with single-ventricle physiology has resulted in an increased population referred for **cardiac transplantation**, currently performed in about 4% of patients with prior Fontan surgery, and sometimes referred to as the *fourth stage* of Fontan surgery.[68,69] Among a series of adults with congenital heart



Insert abbreviations:
IVC, inferior vena cava
LAA, left atrial appendage;
LLPV, left lower pulmonary vein
LUPV, left upper pulmonary vein
RAA, right atrial appendage
RLPV, right lower pulmonary vein
RUPV, right upper pulmonary vein
AUG

Fig. 12.8 Arrhythmia surgery lesions. (A) Modified right atrial maze procedure for right atrial macro-re-entrant tachycardia. The anterior right atrial wall is resected, with a linear incision from the superior caval vein to inferior caval vein. Cryoablation lesions are delivered between the base of the resected atrial appendage to the superior rim of the atrial septal defect (ASD), from the posterior rim of the ASD to the resected lateral wall, and from the inferior rim of the ASD to the posterior rim of the coronary sinus; from the coronary sinus (CS) to the inferior caval vein (IVC), and from the right-sided atrioventricular annulus (if present) to the IVC. (B) Modified left atrial Cox-Maze IV: The pulmonary veins are encircled with a malleable cryoablation probe, and linear lesions are placed between the pulmonary veins and the os of the left atrial appendage, and from the inferior rim of the encircling lesion to the P2 leaflet of the mitral valve. The left atrial appendage is either resected, or a circular cryoablation lesion is placed at the os. An epicardial lesion is placed on the coronary sinus, in alignment with the endocardial lesion at the mitral valve leaflet. SVC, Superior vena cava. (From Deal BJ, Mavroudis C, Backer CL, Johnsrude CL. New directions in surgical therapy of arrhythmias. Pediatr Cardiol. 2000;21:576–583.)

disease undergoing heart transplantation, about 44% carry a diagnosis of single ventricle, with or without prior Fontan surgery.[70] The particular challenges of these fragile patients relative to physiology, technical considerations and perioperative care resulting in improvements in survival have been summarised recently.[71,72] Acute graft failure, intractable bleeding, multiorgan system failure, and infection are important causes of early transplant failure.[61,73,74]

FONTAN CARDIAC PHYSIOLOGY

The systemic venous circulation in the Fontan circulation is comprised of three distinct channels: superior caval vein flow, inferior caval vein flow, and splanchnic flow. Elevated pressures in the superior caval vein impairs lymphatic resorption, which may contribute to increased pulmonary vascular resistance, development of collateral flow, and uncommonly, plastic bronchitis (fibrinous rubber casts in the tracheobronchial tree producing cough and wheezing).[75] Elevated pressure in the inferior caval vein results in chronic hepatic congestion. Splanchnic flow channels venous blood from the intestine and spleen to the portal vein, and has venous pressure that is up to three times higher than that present in the inferior caval vein flow draining the kidneys, pelvis, and lower extremities. The elevated splanchnic pressure results in lymphatic hypertension and the loss of protein including immunoglobulins via the intestines, which may result in PLE or gastrointestinal tumours.[76,77]

In a 'Fontan circulation', the systemic venous return is connected to the PAs without a sub-pulmonary pump (Fig. 12.9). The residual postcapillary energy is not allowed to run off to the systemic venous atrium but is used to push blood through the lungs. Advantages of a Fontan circulation on single-ventricle physiology include near-normalisation of the arterial oxygen saturation and abolishment of the chronic volume overload on the single ventricle due to systemic arterial to pulmonary artery shunts. However, because pulmonary impedance hampers venous return through the pulmonary vasculature, this connection creates, like any dam, upstream congestion and downstream decreased flow.[78] These two features of the Fontan circulation, upstream venous congestion and downstream decreased output, are the basic cause of the majority of the physiologic impairments of this circulation. De Leval has termed this state the 'paradox of the Fontan circulation': the imposition of caval hypertension and pulmonary arterial hypotension as conditions of success.[79]

Flow through the Fontan circulation will depend on the resistance of a series of locations: the surgical connection, central and peripheral PAs, pulmonary vascular resistance (precapillary sphincters, pulmonary capillaries, and veins), and the pressure gradient across the bottleneck (systemic venous pressure–ventricular filling pressure). The Glenn and Fontan connections themselves create abnormal pulmonary flow conditions characterised by chronically decreased flow, flow differential to the branch PAs, absence of episodes of high flow or high pressure, increased collateral flow, suboptimal mixing of inferior and superior caval flow, and resultant endothelial dysfunction. Any increase in the pulmonary venous atrial pressure, such as from arrhythmia, atrioventricular valve regurgitation, or elevated end-diastolic pressure, will further decrease transpulmonary flow, resulting in a continuously declining cardiac output. The body tolerates only a

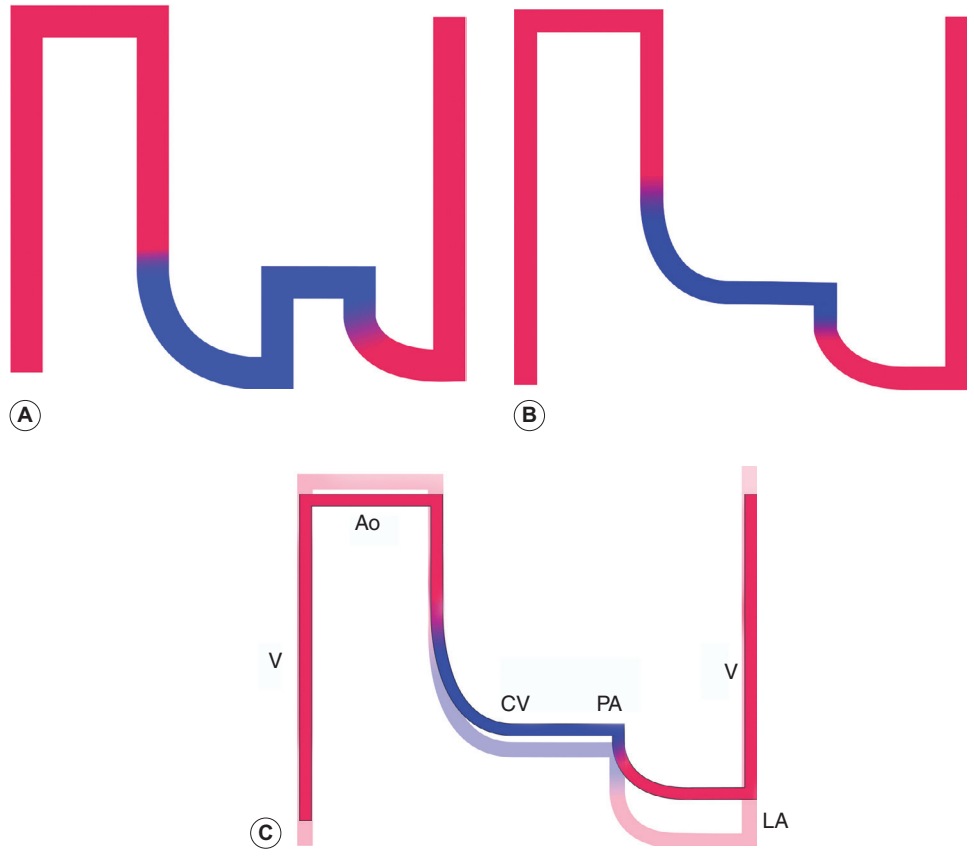


Fig. 12.9 (A–C) Scheme of the normal cardiovascular circulation (A) and the Fontan circulation at different stages (B and C). (A) **Normal biventricular circulation**: The pulmonary circulation (P) is connected in series with the systemic circulation (S). The compliance of the RV ensures that the right atrial pressure remains lower than the left atrial pressure and delivers the driving force for the blood to overcome pulmonary impedance. (B) **Fontan TCPC circuit**: The CVs are directly connected to the PA; systemic venous pressures are markedly elevated compared to a normal biventricular circulation. (C) **Fontan circuit late** (superimposed on early Fontan circuit): with time, pulmonary resistance increases resulting in further increase in CV congestion but more in decreased flow, which in turn increases ventricular filling pressure as a result of chronic disuse remodelling. Ao, Aorta; CV, caval vein; F, fenestration; LA, left atrium; LV, left ventricle; P, pulmonary circulation; PA, pulmonary artery; RV, right ventricle; S, systemic circulation; V, single ventricle. Line thickness reflects output, colour reflects oxygen saturation. (From Gewillig M, Brown SC. The Fontan circulation after 45 years: update in physiology. Heart. 2016;102:1081–1016.)

small range of increased pressures in the systemic veins (between 12 and 20 mm Hg) and a small range of ventricular filling pressures; this leaves the impedance of the neo-portal system as the major determinant of output.

The functionally single ventricle has endured variable years of cyanosis and hypertrophy from volume overload prior to Fontan surgery and has developed increased mass and fibrosis, which may be ongoing in the setting of aortic stiffness or obstruction. The ventricle, which is the typical bottleneck in a biventricular circulation, no longer controls cardiac output and cannot decrease the degree of systemic congestion. However, the functionally single ventricle can make the circulation worse: any increase in filling pressure will result in more systemic venous congestion and less cardiac output.

Ventricular *systolic* function has been shown to remain relatively stable in many adults in the single-ventricle population, in the absence of the development of atrial tachycardia or significant atrioventricular valve pathology.[80,81] However, ventricular *diastolic* dysfunction progresses with age, with gradual increase in filling pressures.[41,82,83] Hypertension or ventricular outflow tract obstruction results in increased ventricular afterload, ventricular hypertrophy, decreased compliance, and ventricular hypertension. Decreased ventricular compliance is associated with increased end-diastolic pressure and diastolic dysfunction, which have a negative back-pressure effect on the Fontan dam, leading to the cascade of progressive Fontan circulatory dysfunction. Obesity contributes significantly to decreased pulmonary compliance, increased systemic resistance, and ventricular hypertrophy, [84] which are directly detrimental to Fontan haemodynamics. Finally, the gradual increase in pulmonary resistance with normal aging contributes to compromised Fontan circulation.[85,86]

Pharmacologic manipulation of systemic and pulmonary haemodynamics has demonstrated limited efficacy in patients with Fontan circulation, using extrapolated efficacy data from patients with two-ventricle circulations. Use of angiotensin-converting enzyme inhibitors, prescribed in 35% to 57% of patients, has not been shown to significantly improve ventricular systolic function or remodelling in patients with Fontan circulation; angiotensin- receptor blockers have not shown improvement in exercise capacity.[87–90] As the Fontan ventricle is chronically volume depleted, systemic afterload reduction may result in hypotension and decrease cardiac output, and may increase right-to-left shunting.

Elevated pulmonary vascular resistance may be related to endothelial dysfunction, micro-pulmonary emboli, and absence of pulsatile pulmonary flow. *Pulmonary vasodilators* can decrease the vasoconstrictive component of the pulmonary vascular resistance, but many lesions in the lung vessels are not amenable to such therapy: hypoplasia, stenosis, distortion, embolisation, loss or exclusion of large and micro vessels, pulmonary vascular disease, turbulence and flow collision, collateral flow, flow mismatch, and obstruction by external compression. Few studies are available to assess the efficacy of pulmonary vasodilator therapy in Fontan patients, with small numbers of patients, surgical substrate variability, and limited follow-up data. Treatment with the endothelin-receptor antagonist bosentan showed improvement in exercise capacity and functional class in two small studies.[91,92] Ambrisentan treatment in adult Fontan patients showed a modest improvement in peak oxygen consumption, without changing physical function score.[93] Sildenafil, a phosphodiesterase type 5 inhibitor, has shown some improvement in exercise capacity in small studies.[94,95] Based on the importance of the pulmonary vascular circulation on outcomes, these studies emphasise the need for larger studies on vasoactive medications with longer-term follow-up in Fontan patients.[96,97]

Aldosterone antagonism using spironolactone or eplerenone may limit scarring and myocardial fibrosis, identified in 28% of Fontan patients using late gadolinium enhancement on MRI and associated with lower ejection fraction and increased ventricular mass.[98,99] Venous insufficiency worsens with age and diuretic use; resistance training, compression stockings, and walking programmes may augment venous flow. A review of exercise training studies in Fontan patients demonstrated safety and improvements in exercise capacity as well as quality of life.[100] The patient with Fontan circulation cannot rapidly augment cardiac output: walking on a flat surface is ideal physical therapy, with lower leg exercise generating pulsatile flow into the pulmonary vascular bed.[101]

To mitigate these competing negative circulatory interactions, the future mechanical support of Fontan patients would lower caval vein pressure and produce increased pulmonary arterial pressure with pulsatile flow. Clinical trials using advanced circulatory assist devices peculiar to the failing Fontan circulation are ongoing and may significantly impact the survival course of these patients. The goal is to improve the circulation, improve liver function, resolve PLE and eventually make the patient healthier for cardiac transplantation.[102] In the meantime, the clinician is challenged to monitor the potential effects of this circulation and improve flow dynamics as feasible, with particular attention to each component of the circuit.

EXERCISE CAPACITY

Exercise in the Fontan patient is characterised by non-pulsatile pulmonary flow due to the lack of a pumping sub-pulmonary chamber, which contributes to attenuated pulmonary arterial growth and endothelial dysfunction.[103,104] Increases in cardiac output for the Fontan patient during exercise rely on increases in heart rate, elevated systemic venous pressure, or adequate preload, and skeletal muscle mass/strength.[105–107] Skeletal muscle contraction contributes to augmented venous return and improvement in cardiac output; many patients with Fontan circulation have relatively under-developed skeletal muscle contributing to reduced peak oxygen consumption.[108–110] High-intensity exercise in Fontan patients is associated with systemic venous hypertension and renal and cerebral deoxygenation.[111]

By adulthood, exercise tolerance is reduced to approximately 60% of predicted, with average peak oxygen consumption in the range of 22 to 25 mL/kg/min, declining by about 1.25% to 2.6% per year.[112–116] Reduced exercise capacity is related to the inability to adequately increase preload, and by restrictive ventilatory physiology identified in 50% to 65% of patients.[117,118] Serial cardiopulmonary exercise testing may identify changes in cardiac output and identify patients at increased risk of major adverse events; specifically, peak oxygen consumption less than 16.6 mL/kg/min or decline of ≥3 percentage points/year has been associated with increased risk of adverse events.[115,116]

Despite these findings, between 74% and 91% of adult patients with Fontan circulation consider themselves in New York Heart Association (NYHA) class I or II.[21,119,120] A subgroup patients with Fontan circulation demonstrate superior exercise performance, dubbed 'Super-Fontan' or 'high-capacity', and accounting for 11% to 19% of patients.[121,122] These patients were characterised by favourable cardiac anatomy (systemic left ventricles), participation in regular sporting activities, and mean body mass index (BMI) <25 kg/m^2; of note, ventricular systolic function was not significant.[121,122] Resistance training focusing on lower legs has been shown to improve muscle mass and strength, and improved cardiac output among patients with Fontan circulation.[123–125] The negative impact of obesity on cardiovascular status is characterised by increased pulmonary and systemic vascular resistance, ventricular hypertrophy and diastolic dysfunction, as well as increased risk for hepatocellular carcinoma.[126] Elevated BMI is present in over 40% of older patients with Fontan circulation, and obesity is associated with increased risk of heart failure and mortality in this population.[127–129] These findings identify attention to nutrition, body weight, and regular physical activity participation as targets for improvement in functional status.

CLINICAL STATUS AND MONITORING OF THE ADULT PATIENT WITH FONTAN CIRCULATION

The care of adult patients with prior Fontan surgeries has as its goal the optimisation of the circulation to prolong the satisfactory longevity of the unique Fontan physiology, with careful attention to the multiorgan manifestations of the circulation, including neuro-psychological outcomes.[130–134] Early anatomic and surgical characteristics, such as *ventricular morphology*, *heterotaxy*, *prior PA or aortic arch reconstruction*, *older age at primary Fontan*, *atrioventricular valve regurgitation or repair*, and *prolonged postoperative pleural effusions* are important predictors of late Fontan adverse outcomes, but obviously these variables cannot be modified for the adult.[24,135,136] Recent publications have described the type and frequency of diagnostic testing recommended for this population of adults.[1–4,8,137]

Unique among patients with repaired congenital heart disease has been the recognition that the Fontan circulation impacts the function of multiple non-cardiac organs, with evaluation of the heart constituting only part of the patient's assessment. Early childhood status and types of interventions influence pulmonary arterial growth, somatic growth, and neurologic development, particularly executive functioning. Unlike patients with other forms of heart disease, these patients have no basis of comparison for completely normal cardiac output, and a slow decline in functional capacity with age may go un-noticed. Such patients may present without complaints of exercise intolerance but may evidence resting cyanosis, abdominal fullness, upper extremity muscular atrophy, and lower extremity brawny oedematous changes. The care of adult patients with Fontan circulations requires a stepwise systematic approach by clinicians familiar with these non-cardiac manifestations, and integrated care among cardiac, hepatic, and imaging specialists among others, to improve quality of life and intervene when feasible to avoid 'Fontan failure'.[2,5,138,139] Modification of lifestyle issues as recommended for cardiovascular health is particularly important in the Fontan patient.[140,141]

Compared to adults without heart disease, adults with Fontan circulation report lower **quality of life** scores in physical functioning, body pain, and general health.[134,142] In studies of perception of quality of life among adolescents and adults with Fontan circulation, the development of arrhythmia, asthma, PLE, or changing functional status, as well as uncertainty regarding their future, contribute to declines in quality of life, with associated increase in sexual dysfunction and mood and anxiety disorders.[143–146] Antenatal and preoperative physiology, cerebral anatomic abnormalities, genetic differences, and perioperative exposures contribute to impaired cognitive function, and mood and anxiety disorders, which are increasingly recognised in as many as 50% of adults with congenital heart disease.[147–149] One cross-sectional study of adults with various types of congenital heart disease identified 41% of patients with impaired cognitive function in the areas of divided attention, motor function, and executive function.[150] Neurocognitive impairment is identified in adults with Fontan circulation associated with decreased white matter.[151] Regular physical activity such as walking to work, education, and occupation correlate with greater quality of life in several studies.[119,134,152,153] Improved referrals for targeted psycho-educational-physical interventions are warranted; recognition of these anxiety and neurocognitive hurdles may also inform the empathy needed for chronic care of this population.[148]

Physical findings commonly seen in adult patients with prior Fontan surgeries are summarised in Table 12.1. Recent data suggest increased morbidity and mortality in Fontan patients with elevated BMI,[154] likely related to decreased pulmonary compliance, ventricular hypertrophy, diastolic dysfunction, and elevated systemic vascular resistance associated with obesity.[84] Conversely, low BMI may indicate progressive bone and muscle mass related to cardiac cachexia and chronic very low cardiac output. Lower extremity venous insufficiency is present in as many as 60% of Fontan adults, manifests as discoloration, brawny induration, or significant varicosities, and may be related to prior catheterisations and deep venous thrombosis, or low cardiac output.[155] The resting heart rate is usually lower than other patients with congenital heart disease, typically less than 75 beats per minute; elevated resting heart rate above 90 beats per minute should raises suspicion for atrial tachycardia. *The findings of obesity or cachexia, resting desaturation, elevated heart rate, ascites, or advanced lower extremity venous changes are of significant concern* and should prompt efforts to improve cardiovascular status.

Sequelae of the Fontan circulation over decades are summarised in Table 12.2. Identifying biomarkers that may be helpful in assessing haemodynamic status is an area undergoing investigation presently.[197–200] Downward trending of albumin levels below 3.6 mg/dL may herald worsening clinical status; in our series of Fontan conversion patients, albumin levels below 3.5 mg/dL were associated with worse outcomes,[59] emphasising the importance of efforts to augment cardiac status before hypoalbuminaemia becomes clinically evident. Elevated B-type natriuretic peptide levels have correlated with longer existence of the Fontan circulation and functional classification, but not necessarily ventricular dysfunction, and serve as a marker of functional status.[199]

Specific health issues impacting survival and quality of life in patients with Fontan surgeries focus on arrhythmia, exercise intolerance, congestive heart failure, liver disease, and PLE.[201–203] One of the most significant long-term concerns for Fontan patients is the effect of chronic venous congestion and elevated systemic venous pressure on the liver and is reviewed in the following chapter (see Chapter 13).[3]

Arrhythmias increase significantly over time in patients with Fontan repairs, occurring with highest frequency among patients with atriopulmonary repairs and older age, summarised in Table 12.3.[159,205] Freedom from arrhythmia at *20 years* post-Fontan surgery was 66% in a study of 1034 patients across Australia and New Zealand,[201] declining to 24% at 30 years in a 40-year follow-up study of 1052 patients at the Mayo Clinic.[156] The development of any arrhythmia is a consistent risk factor for increased hospitalisations, thromboembolic/neurologic events, need for a pacemaker, and late Fontan failure.[112,201,202,206–208]

Atrial tachycardia occurs in over 40% of *atriopulmonary* Fontan patients by 20 years postoperatively; the comparable incidence among patients with *lateral tunnel or extracardiac conduits* is approximately 20% at 15 years postoperatively and is likely to increase with longer durations of follow-up (Fig. 12.10).[159] Risk factors for the development of atrial tachycardia include atrial isomerism, heterotaxy syndrome, atriopulmonary Fontan, sinus bradycardia, advanced age at Fontan surgery, and years since surgery.[20,156,159,160] The mechanism of atrial tachycardia is macro-re-entrant (atrial flutter or atrial re-entrant tachycardia) in about 75% of patients often involving the cavo-tricuspid isthmus, with focal atrial tachycardia present in 3% to 19%, particularly in patients with lateral tunnel or extracardiac repairs; the incidence of atrial fibrillation is at least 19% and is steadily increasing.[156,159,160,209,210]

Recent guidelines and consensus statements for the management of supraventricular arrhythmias including adults with congenital heart disease have been published by the European Society of Cardiology and the American Heart Association/American College of Cardiology/Heart Rhythm Society including Class of Recommendation (COR) for therapies; these recommendations are summarised in Table 12.3.[5,6,9] The haemodynamic consequences of elevated heart rates greater than 90 bpm escalate rapidly, resulting in elevated atrial pressure and decreased ventricular contractility within 24 hours, emphasising the limited functional reserve of Fontan patients. Thus the threshold for suspecting the

TABLE 12.1 Physical Findings in Adults With Prior Fontan Surgeries

Body habitus	Short stature Overweight/obesity Thin extremities	Present in ~18% of adults Overweight: similar to adult population Musculoskeletal wasting of arms prior to advanced cachexia
Head	Facial plethora Jugular venous distention, marked in supine position	Resting oxygen saturations usually >94%
Chest	Sternal concavity; sternotomy scars	Restrictive lung physiology common
Cardiac	Bradycardia or premature beats Increased ventricular impulse Single first and second heart sounds common	Presence of a murmur is *abnormal* and suggests atrioventricular valve insufficiency, outflow tract obstruction, aortic or pulmonic insufficiency
Abdomen	Hepatomegaly typically present Central adiposity Ascites	Lack of hepatomegaly may indicate advanced liver disease/atrophy
Extremities	Mild clubbing common; Venous stasis/brawny discoloration/ varicosities of legs	Leg oedema is an advanced finding of heart failure Advanced stasis changes associated with poor outcomes

TABLE 12.2 Sequelae Reported in Adult Patients With Functionally Univentricular Circulation

Sequelae	Incidence	Considerations
Arrhythmia		
Sinus bradycardia[156–158]	18%–62%	Almost uniformly present; junctional rhythm and escape–capture bigeminy frequently noted; chronotropic incompetence with exercise
SVT [159,160]	30%–80%	Increases with time and among atriopulmonary/lateral tunnel repairs Atrial re-entry/flutter 75%, focal atrial 10%–15%
Atrial fibrillation[159,161]	40%	Increases with age; often associated with atrial re-entry tachycardia or prior ablations
VT[156,157]	2%–10%	Non-sustained VT noted with Holter or pacemaker monitoring; sustained VT is uncommon
Pacemakers[162–165]	11%–23%	Sinus node dysfunction common; atrial pacing preferred to single-chamber ventricular pacing Atrioventricular block more common in double-inlet left ventricle or L-looped ventricle Transvenous pacing approach limited, associated with atrial lead thrombosis; epicardial implantation usually required
Defibrillators[166]	2%	Epicardial or subcutaneous approach usually required; threshold testing not well tolerated
Sudden death[156,167–169]	9%–19%	Potential causes: arrhythmia, pulmonary embolus, stroke, vessel rupture
Systemic		
Somatic[110,127,129,170]		Decreased bone mineral density; decreased skeletal muscle mass Overweight or obesity, 38%–50%, exacerbated by exercise limitations Progressive cyanosis due to right-to-left shunting: intrapulmonary or atrial level/fenestration; veno-venous collaterals to pulmonary veins; coronary sinus drainage to left atrium; hepatopulmonary syndrome
Neurologic[21,171,172]		Stroke, transient ischaemic attacks (4%–12%), related to prior pulmonary artery banding, intra-atrial shunting, atrial arrhythmias, thrombosis
Psychological[59,143,146]	33%–65%	Mood disorder, anxiety, attention-deficit disorder Impaired executive functioning, visuo-spatial and social cognition skills
Haematologic[173,174]	15%–48%	Anaemia 15%–48%, associated with diuretic and warfarin usage, decreased renal function, hyponatremia, and increased mortality risk Thrombocytopenia 30%–36%; splenic sequestration of platelets Circuit thrombosis
Endocrine[175,176]		Hypothyroidism Hyper-parathyroidism, secondary to altered calcium absorption or renal dysfunction Low levels of vitamin D in insert "25%" insert "25%"
Reproductive[177–181]		Delayed menarche; reduced fertility Increased incidence of spontaneous miscarriages (27%–55%), premature deliveries (72%), small-for-gestational age infants (12%–56%) SVT during pregnancy (10%) Acute heart failure in third trimester and post-partum (14%) Increased risk of congenital heart disease among offspring Increased risk for post-partum thromboembolism Volume overload of pregnancy may advance cardiac dysfunction Preconception counselling strongly recommended
Renal[182,183]	10%–40%	Progressive with time: cumulative exposure to cardiopulmonary bypass, nephrotoxic medications, and low cardiac output Albuminuria (33%) Hyperuricemia (33%)
Protein-losing enteropathy[76,184–187]	2%–9%	Endothelial protein-losing disorder related to elevated splanchnic pressure and decreased cardiac output. Manifests as hypoalbuminaemia, ascites, elevated faecal alpha-1 antitrypsin; increased susceptibility to proinflammatory cytokines. Usually resolves following heart transplantation.
Plastic bronchitis[186,188,189]	1%–3%	Lymphatic hypertension; decreased lymphatic resorption
Liver disease[3,190,191]	Late liver failure <10%	Common findings: hepatomegaly, mild elevation of bilirubin and gamma glutamyl transferase Increased risk of hepatocellular carcinoma; requires surveillance with imaging and alpha fetoprotein levels
Carcinoma[192–195]	3%	Cumulative exposure to radiation during interventions; altered splanchnic flow
Endocarditis[196]	2%	Uncommon compared with other forms of congenital heart disease
Sepsis [166,167,172]	<5%	Sepsis reported as cause of death in 3%–18%, related to intestinal immunoglobin loss

SVT, Supraventricular tachycardia; *VT*, ventricular tachycardia.

TABLE 12.3 Guidelines for Management of Supraventricular Tachycardia (SVT) in Adult Patients With Fontan Circulation

COR	Recommendations
Acute management of SVT	
I	Acute antithrombotic therapy is recommended in ACHD patients who have AT or atrial flutter to align with recommended antithrombotic therapy for patients with AF.[6,9]
I	Synchronised cardioversion is recommended for acute treatment in ACHD patients and SVT who are haemodynamically unstable.[6,9]
I	Synchronised direct-current cardioversion is recommended if drug therapy fails to convert or control the tachycardia.[9]
I	Intravenous adenosine is recommended for acute treatment in ACHD patients and SVT.[6,9]
I	Intravenous diltiazem or esmolol (with extra caution used for either agent, observing for the development of hypotension) is recommended for acute treatment in ACHD patients and SVT who are haemodynamically stable.[6]
IIa	Intravenous beta-blockers (esmolol or metoprolol) should be considered if vagal manoeuvres and adenosine fail.[9]
IIA	Intravenous ibutilide or procainamide can be effective for acute treatment in ACHD patients and atrial flutter who are haemodynamically stable.[6]
IIa	Atrial pacing can be effective for acute treatment in ACHD patients and SVT who are haemodynamically stable and anticoagulated as per current guidelines for antithrombotic therapy in patients with AF.[6]
IIa	Elective synchronised cardioversion can be useful for acute termination of AT or atrial flutter in ACHD patients when acute pharmacological therapy is ineffective or contraindicated.[6]
IIb	Oral dofetilide or sotalol may be reasonable for acute treatment in ACHD patients and AT and/or atrial flutter who are haemodynamically stable.[6]
III	Propafenone and flecainide are not recommended for conversion to sinus rhythm.[9]
Prevention of recurrent SVT	
1	New onset or worsening atrial tachyarrhythmias in adults with single ventricle after Fontan palliation should prompt a search for potential haemodynamic abnormalities, which may necessitate imaging and/or cardiac catheterisation.[8]
I	Ongoing management with antithrombotic therapy is recommended in ACHD patients and AT or atrial flutter to align with recommended antithrombotic therapy for patients with AF.[6]
I	Assessment of associated haemodynamic abnormalities for potential repair of structural defects is recommended in ACHD patients as part of therapy for SVT.[6]
IIa	Oral beta-blockers or sotalol therapy can be useful for prevention of recurrent AT or atrial flutter in ACHD patients.[6]
IIa	Beta-blockers should be considered for recurrent focal AT or atrial flutter, if ablation is not possible or successful.[9]
IIa	Catheter ablation is reasonable for treatment of recurrent symptomatic SVT in ACHD patients.[6,8,9]
IIa	Surgical ablation of AT or atrial flutter can be effective in ACHD patients undergoing planned surgical repair.[6]
IIb	Oral dofetilide may be reasonable for prevention of recurrent AT or atrial flutter in ACHD patients.[6]
IIb	Atrial pacing may be reasonable to decrease recurrences of AT or atrial flutter in ACHD patients and sinus node dysfunction.[6]
IIb	Amiodarone may be reasonable for prevention of recurrent AT or atrial flutter in ACHD patients for whom other medications and catheter ablation are ineffective or contraindicated.[6,9]
III	Sotalol is not recommended as a first-line antiarrhythmic drug as it is related to an increased risk of pro-arrhythmias and mortality.[9]
III	Flecainide should not be administered for treatment of SVT in ACHD patients and significant ventricular dysfunction.[6]
III	Flecainide and propafenone are not recommended as first-line antiarrhythmic drugs in patients with ventricular dysfunction and severe fibrosis.[9]
Arrhythmia Surgery	
I	Surgical ablation of AF is recommended in patients undergoing concomitant intracardiac surgery with symptomatic AF refractory or intolerant to at least one Class I or III antiarrhythmic medication.[204]
IIa	Surgical ablation of AT or atrial flutter can be effective in ACHD patients undergoing planned surgical repair.[6]
IIa	In patients with SVT planned for surgical repair of a congenital heart disease anomaly, preoperative catheter ablation or intraoperative surgical ablation should be considered.[6,9]
IIb	Reoperation or intervention for structural/anatomic abnormalities in a Fontan palliated patient with symptoms or with failure of the Fontan circulation may be considered.[8]

ACHD, Adult congenital heart disease; *AF*, atrial fibrillation; AT, atrial tachycardia; *COR*, Class of Recommendation; usage as follows: *COR I*, is recommended/indicated/useful/effective/beneficial; COR IIa, is reasonable/can be useful/effective/beneficial; *COR IIb*, might be reasonable/might be considered; *COR III*, is not recommended; no benefit or potentially harmful; *SVT*, supraventricular tachycardia.

Standardize use of capital

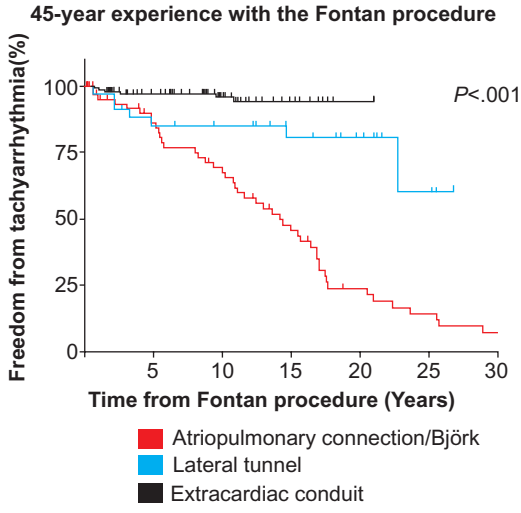


Fig. 12.10 Long-term freedom from tachyarrhythmia versus type of Fontan surgery. Freedom from tachyarrhythmia at 20 years was 24% for patients with atriopulmonary Fontan surgery, 81% for patients with lateral tunnel repairs, and at 15 years was 94% for patients with extracardiac Fontan repairs. (From Rijnberg FM, Blom NA, Sojak V, Bruggemans EF, Kuipers IM, Rammeloo LAJ, Jongbloed MRM, Bouma BJ, Hazekamp MG. A 45-year experience with the Fontan procedure: tachyarrhythmia, an important sign for adverse outcome. *Interact Cardiovasc Thorac Surg.* 2019;29(3):461–468.)

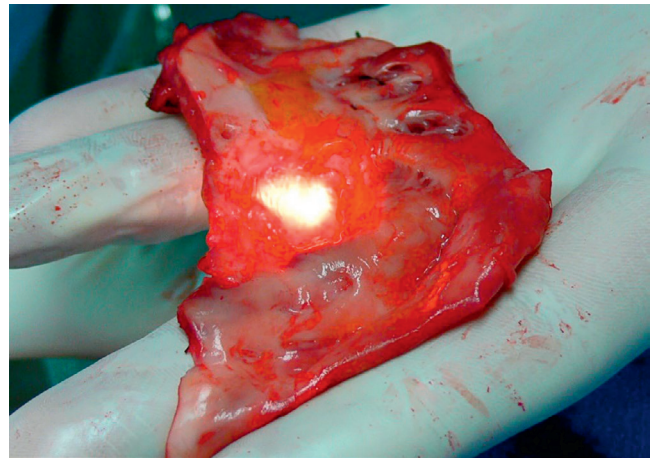


Fig. 12.11 Resected right atrial anterior wall during Fontan conversion. Note atrial hypertrophy; transillumination at site of prior ablation shows marked atrial wall thinning and area for potential thrombus formation.

presence of atrial tachycardia in Fontan patients should be high, and a sense of urgency for achieving a normal heart rate should prevail, in contrast to adult patients with two-ventricle anatomy. Because the absence of a regular atrial rhythm may increase the likelihood of developing atrial tachycardia, either re-entrant or focal in nature, vigorous efforts to maintain sinus rhythm as opposed to rate-control strategies are recommended in Fontan patients. Acute therapy for SVT in Fontan patients includes intravenous adenosine, diltiazem, or esmolol for termination or rate control, with synchronised cardioversion often necessary without lengthy delay after assessment for atrial thrombus.[5,6] Urgent assessment for haemodynamic abnormalities as well as the presence of intracardiac thrombus is recommended to guide initial management of SVT.[5,6]

Catheter ablation for atrial tachycardia in Fontan patients has significantly lower acute success rates (60%–80%) and higher recurrence rates (30%–50%) than ablation in other forms of congenital heart disease.[209,211–214] Ablation is challenged by the hypertrophied atrial tissue and multiple re-entrant circuits, with the risk of thrombogenicity from extensive ablation lesions (Fig. 12.11). Ablation in experienced centres is recommended for patients with recurrent symptomatic atrial tachycardia.[6,9] Predictors of ablation failure include non-cavo-tricuspid isthmus circuits, multiple re-entrant circuits, atrial fibrillation, and elevated BMI.[215] More importantly, focusing on arrhythmia ablation without addressing underlying haemodynamic abnormalities may allow progression to multiorgan system dysfunction, missing a window of suitability for surgery or transplantation.[216] In patients with Fontan circulation and atrial tachycardia undergoing planned surgical repair, the performance of concomitant arrhythmia surgery is recommended.[5,6,204]

Recent guidelines for device implantation in patients with functionally univentricular circulation are summarised in Table 12.4. *Atrial* pacing as technically feasible to minimise recurrences of tachycardia is a therapeutic option; technical considerations for implantation are important in decision making. **Fontan conversion with arrhythmia surgery** and pacemaker implantation has been shown to improve functional status and markedly reduce the incidence of tachycardia, and it has been most frequently applied to patients with prior atriopulmonary Fontan repairs.[59,63,64,216,218,219] The Fontan conversion surgery has been largely applied to patients with atriopulmonary anastomoses who developed refractory atrial arrhythmias, usually with associated exercise intolerance, decreased functional classification, ascites, and sometimes cyanosis.[62,64] Intermediate-term outcomes of our first 140 Fontan conversion surgeries, performed at median age of 23 years, 10-year freedom from arrhythmia recurrence was 77%, with no recurrence of atrial fibrillation in patients undergoing bi-atrial arrhythmia surgery.[59]

Ventricular tachycardia, usually non-sustained, is recognised in about 5% to 12% of patients, and is often detected during pacemaker interrogation or ambulatory monitoring.[156,220] Ventricular fibrillation/resuscitated cardiac arrest have been reported in 4% to 9% of patients.[135,156,167] In contrast to patients with repaired tetralogy of Fallot, it is highly unusual for a Fontan patient to present with sustained ventricular tachycardia, unless prior ventriculotomy has been performed. However, sudden death is increasingly reported in 2% to 19% of adult Fontan patients, which may be arrhythmic, thromboembolic, or due to vessel rupture.[112,156,167–169,221]

Undetected atrial tachycardia with rapid atrioventricular conduction and marked hypokalaemia associated with chronic diuretic use may contribute to ventricular arrhythmias. Minimisation of ventricular ectopy includes optimisation of potassium and magnesium levels depleted by diuretic usage. In patients with implanted pacemakers, atrial pacing at slightly higher minimal heart rates (70–80 beats per minute) or rate optimisation with activity may be beneficial. Implantation of an automatic defibrillator, reported in 2% of patients,[222] requires an epicardial or subcutaneous approach and poses significant surgical risk in the setting of multiple prior sternotomies, which may outweigh the anticipated benefit. The precarious single-ventricle circulation may not tolerate defibrillation threshold testing. These factors are critical in the decision to implant a defibrillator, and are of significant enough impact that the alternative referral for transplantation is an important discussion.

Pacemakers are present in 13% to 38% of adult Fontan patients.[162,166,223] The presence of a pacemaker has been identified as a negative risk factor for survival.[163] Atrial pacing is associated with improved outcomes compared with ventricular pacing, which contributes to ventricular dysfunction and atrioventricular valve regurgitation and should be avoided in favour of atrial pacing whenever feasible; managed ventricular pacing programming in the setting

Consider using abbreviation for "adult congenital heart disease" as ACHD, as used in Table12.3

TABLE 12.4 Device Management for Patients With Fontan Circulation

COR	Recommendations
Pacemaker implantation	
I	Permanent pacing is recommended in adults with CHD and symptomatic bradycardia in conjunction with any degree of AV block or with ventricular arrhythmias presumed to be due to AV block.[5]
I	Permanent pacing is recommended for adults with CHD and symptomatic sinus node dysfunction, including documented sinus bradycardia or chronotropic incompetence that is intrinsic or secondary to required drug therapy. Devices that minimise ventricular pacing are preferred.[5]
IIA	Permanent pacing is reasonable for adults with CHD and impaired haemodynamics, as assessed by non-invasive or invasive means, due to sinus bradycardia or loss of AV synchrony.[5]
IIA	Permanent pacemaker implantation is reasonable for patients with congenital heart disease and impaired haemodynamics due to sinus bradycardia or loss of AV synchrony. [217]
IIa	Permanent pacemaker implantation is reasonable for sinus bradycardia with complex congenital heart disease with a resting heart rate less than 40 bpm or pauses in ventricular rate longer than 3 seconds.[217]
IIa	Permanent pacemaker implantation is reasonable for patients with congenital heart disease and sinus bradycardia for the prevention of recurrent episodes of intra-atrial re-entrant tachycardia; SND may be intrinsic or secondary to antiarrhythmic treatment.[217]
IIb	Atrial pacing may be reasonable to decrease recurrences of AT or atrial flutter in ACHD patients and sinus node dysfunction.[6]
IIb	Permanent pacing may be reasonable in adults with CHD of *moderate complexity* and an awake resting heart rate (sinus or junctional) of 40 bpm or ventricular pauses >3 seconds. A device with antitachycardia pacing properties may be considered if the underlying anatomic substrate carries a high likelihood of developing IART.[5]
III	Endocardial leads are generally avoided in adults with CHD and intracardiac shunts. Risk assessment regarding haemodynamic circumstances, concomitant anticoagulation, shunt closure prior to endocardial lead placement, or alternative approaches for lead access should be individualised.[5]
III	Pacing is not indicated in asymptomatic adults with CHD and bifascicular block with or without first-degree AV block in the absence of a history of transient complete AV block.[5]
Defibrillator implantation	
I	In patients with adult congenital heart disease and complex or sustained VA in the presence of important residual haemodynamic lesions, treatment of haemodynamic abnormalities with catheter or surgical intervention as feasible is indicated prior to consideration of ablation or an ICD.[10]
I	In patients with adult congenital heart disease and haemodynamically unstable VT, an ICD is recommended after evaluation and appropriate treatment for residual lesions/ventricular dysfunction if meaningful survival of greater than 1 year is expected.[10]
I	ICD implantation is indicated for patients with symptomatic sustained VT in association with congenital heart disease who have undergone haemodynamic and electrophysiological evaluation. Catheter ablation or surgical repair may offer possible alternatives in carefully selected patients.[217]
I	In patients with adult congenital heart disease with sudden cardiac arrest due to VT or VF in the absence of reversible causes, an ICD is recommended if meaningful survival of greater than 1 year is expected.[10]
IIa	In patients with repaired moderate or severe complexity adult congenital heart disease with unexplained syncope and at least moderate ventricular dysfunction or marked hypertrophy, either ICD implantation or an electrophysiological study with ICD implantation for inducible sustained ventricular arrhythmia is reasonable if meaningful survival of greater than 1 year is expected.[10]
IIa	ICD implantation is reasonable for patients with congenital heart disease with recurrent syncope of undetermined origin in the presence of either ventricular dysfunction or inducible ventricular arrhythmia at electrophysiological study.[217]
IIb	In patients with adult congenital heart disease and severe ventricular dysfunction (LVEF <35%) and symptoms of heart failure despite GDMT or additional risk factors, ICD implantation may be considered if meaningful survival of greater than 1 year is expected.[10]
IIb	ICD implantation may be considered for patients with recurrent syncope associated with complex congenital heart disease and advanced systemic ventricular dysfunction when thorough invasive and non-invasive investigations have failed to define a cause.[217]
III	ICD therapy is not indicated for patients who do not have a reasonable expectation of survival with an acceptable functional status for at least 1 year, even if they meet ICD implantation criteria specified in the Class I, IIa, and IIb recommendations above.[217]

AV, Atrioventricular; *CHD*, congenital heart disease; *COR*, Class of Recommendation; usage as follows: *COR I*, is recommended/indicated/useful/effective/beneficial; COR IIa, is reasonable/can be useful/effective/beneficial; *COR IIb*, might be reasonable/might be considered; *COR III*, is not recommended; no benefit or potentially harmful; *GDMT*, guideline-directed medical therapy; *ICD*, implantable cardiac defibrillator; *LVEF*, left ventricular ejection fraction; *SCD*, sudden cardiac death; *SND*, sinus node dysfunction; *VF*, ventricular fibrillation; VT, ventricular tachycardia.

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ert abbreviation for: IART, intra-atrial reentry tachycardia

of dual chamber pacemakers is preferred.[224] Optimisation of rate-responsive pacing using pacemaker reprogramming during exercise testing is an important modality to optimise cardiac output because the Fontan patient relies heavily on increases in heart rate to increase cardiac output.[60] Marked exacerbation of ascites following abdominal pacemaker generator change or other abdominal surgery may occur in patients with Fontan circulation, often requiring in-patient management and weeks to resolve.

Protein-losing enteropathy (PLE) is reported in 2% to 10% of adults with Fontan circulation;[166,171,225] plastic bronchitis is unusual in adult patients. The loss of protein from the intestines is diagnosed by low serum albumin less than 3.0 mg/dL, and elevated faecal alpha-1 antitrypsin, and occurs in the setting of decreased cardiac output. Survival following the diagnosis of PLE was 81% to 88% at 5 years, 66% to 71% at 10 years, and 19% at 20 years, consistent with the correlation with low cardiac output.[166,184,225] Aggressive therapy to improve cardiac output includes maintenance of atrial rhythm, relief of anatomic obstruction, and creation of an atrial-level fenestration to improve cardiac output at the cost of cyanosis; these measures should be taken during routine Fontan surveillance prior to the development of PLE. Improved knowledge of the lymphatic system has resulted in direct targeting of the lymphatic system with percutaneous obliteration of hepato-duodenal lymphatic fistulae.[226,227] or decompression of the thoracic duct.[228]

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LONG-TERM OUTCOMES

Recent studies of long-term outcomes following Fontan surgery have been published by several groups.[16,17,19,20,166,171,203] Estimated survival following Fontan surgery is 91% at 10 years and 82% at 20 years, with 30-year survival at 48%.[166,202] *Freedom from Fontan failure*, defined as death, transplant, surgical Fontan takedown or conversion, NYHA class III/IV, or PLE at 25 years post-Fontan was 56% in the large series from Australia and New Zealand.[20] Inclusion of SVT, thromboembolism, or pacemaker implantation was associated with overall freedom from late adverse events of 29% at 25 years following surgery among 1428 patients.[18,20]

Among adults with Fontan circulation surviving to adulthood, the median survival was 49 years in the Dutch national registry.[196] The presence of medical co-morbidities, such as PLE or arrhythmia, is associated with a marked increase in risk for transplantation and death.[202,203] Causes of late mortality are usually multifactorial, and are reported as related to heart failure in 35% to 52%, perioperative issues 37% to 68% (reoperation or transplantation), sudden or arrhythmic events 9% to 19%, thromboembolic issues 8%, liver failure 3% to 10%, and cancer 3%.[167,169,172] *Carcinoma* is becoming recognised with increasing frequency among adults with congenital heart disease. patients are exposed to low-dose ionising radiation throughout their lifetime during diagnostic and therapeutic interventions, including computerised tomography and nuclear stress tests.[192,193,229] Breast, colon, prostate, and blood cancers were the most frequently identified cancers identified in one large study, while hepatocellular carcinoma among patients with Fontan circulation is most common.[192,194]

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CONCLUSION

Refinements in surgical and catheter treatments for patients with Fontan circulation has improved survival into the sixth decade of life for many. Recognition of systemic consequences of the Fontan circulation requires regular and active multiorgan surveillance, with its goal the prolongation and optimisation of the unique Fontan circulation. Attention to neuro-psychological status and physical activity are important components of improving the quality of life among these unique patients.

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THE PATIENT AND NON-EXPERT ACHD GUIDE: FONTAN AND VENOUS SHUNTS

- Unique among patients with congenital heart disease, the Fontan circulation is a multisystem circulatory system, involving the heart as well as the lungs, liver, and gastrointestinal tract among other organs, emphasising the need for regular lifelong follow-up with caregivers with expertise in these areas.
- Currently, survival into the fifth decade of life and beyond is possible for many patients with this condition.
- Non-specific symptoms (such as fatigue, leg/ abdominal swelling, or palpitations) or changes in blood biomarkers (particularly albumin and B-type natriuretic peptide) indicate the need for in-depth evaluation of the circulation.
- Atrial arrhythmias develop with increasing frequency over time, which may manifest as palpitations or fatigue, and require urgent evaluation: many treatment options are available.
- Daily physical activity involving walking or lower extremity strength training, as well as maintaining a healthy body weight, is important to optimize the functional status of patients with this circulation.