60 Fontan Pathway From Birth Through Early Childhood

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The "Fontan" Concept

A typical mammalian cardiovascular system consists of two circuits, pulmonary and systemic, connected in series where each circuit is powered by its own pump. In the absence of congenital heart disease, the right ventricle pumps blood through the pulmonary circulation and the left ventricle through the systemic circulation (Fig. 60.1A).

Several complex cardiac malformations are characterized by the existence of only one functional ventricle. This "single" ventricle has to maintain circulation through both the systemic and the pulmonary circulations, which during fetal life and at birth are not connected in series but remain in parallel. Such a circuit has two major disadvantages: diminished oxygen saturation of the systemic arterial blood and chronic volume overload of the single ventricle. The chronic ventricular volume overload leads to progressive ventricular dysfunction and remodeling of the pulmonary vasculature, causing gradual attrition due to congestive heart failure and pulmonary hypertension from the third decade of life, with few survivors beyond the fourth decade.[1]

In 1971 Francis Fontan[2] from Bordeaux, France, reported a new approach to the operative treatment of these malformations, separating the systemic and pulmonary circulations. A "Fontan circulation," after numerous modifications, currently consists of connecting the systemic venous return to the pulmonary arteries without the interposition of a pumping chamber (see Fig. 60.1B and C). In this construction, residual postcapillary transit energy is used to push blood through the lungs in a new portal circulation-like system.[3] Advantages of a Fontan circuit include (near-) normalization of the arterial oxygen saturation and abolishment of the chronic volume overload of the single ventricle. However, because the pulmonary impedance hampers venous return through the pulmonary vasculature, this circulation creates congestion of the systemic veins upstream and downstream decreased output throughout the whole closed circuit (including the heart), both at rest and during exercise[4,5] (see Fig. 60.1C). These two features of the Fontan circulation, elevated systemic venous pressure and chronically low cardiac output, are the root cause of the majority of the physiologic impairments of this circulation.

Is Every Fontan Circuit the Same?

Since its original description, the Fontan circuit has undergone numerous modifications. Early on surgeons used valves (cavoatrial, atrioventricular, or atriopulmonary), and created various connections between the right atrium and the pulmonary artery (anterior atriopulmonary connection, with or without inclusion of a small hypoplastic right ventricle, posterior atriopulmonary connection), with different materials (valved conduits, homografts, patches, direct anastomosis). The high incidence of late reoperations, reaching more than 40% in some series, reflects the poor design of the initial Fontan circuits and the less-than-ideal surgical techniques used in the early series. Most of the older circuits are no longer created and are considered obsolete; however, many patients still survive with such circuits. When assessing a patient with a "Fontan circuit," the clinician needs to know exactly which connection has been made and what material has been used.

During the last decade the total cavopulmonary connection has emerged as being superior.[6] The caval veins are connected to the pulmonary artery, bypassing not only the right ventricle but also the right atrium (see Fig. 60.1B). The superior caval vein is connected to the pulmonary artery (bidirectional Glenn shunt or partial cavopulmonary connection). There are two variants to connect the inferior caval vein: (1) lateral tunnel and (2) extracardiac conduit. Introduced in the mid-80s, the lateral tunnel provides a tubular path between the inferior caval vein and the pulmonary artery, consisting of a prosthetic baffle and a portion of the lateral atrial wall. This circuit has growth potential and can, therefore, be created in children as young as 1 year; it leaves, however, a small amount of atrial tissue exposed to high pressure, which over time may cause atrial arrhythmias. The extracardiac conduit was introduced in 1990 and consists of a tube graft between the transected inferior caval vein and the pulmonary artery. This circuit leaves the entire atrium at low pressure, has no or minimal atrial suture lines, and can be performed without aortic cross-clamping or even cardiopulmonary bypass. This conduit has no growth potential (but can be expanded percutaneously) and, therefore, is only offered to patients large enough to accept a graft of 16 to 20 mm (adequate for an adult's inferior caval vein flow).

How to Build a Fontan Circuit?

At birth, it is impossible to create a Fontan circulation. The pulmonary vascular resistance is still elevated for several weeks, and the vessels (caval veins and pulmonary arteries) are usually too small, making any cavopulmonary shunt impossible during this period. As the pulmonary arteries are

LEARNING OBJECTIVES

After reading this chapter, the learner should be able to:

1. The Fontan operation as performed the last decades (cavopulmonary connection) is extracardiac vascular surgery, which leaves the ventricle essentially untouched, but alters the boundary conditions to the heart enormously (predominantly chronic preload deprivation).
2. The pulmonary circulation is put in series in the closed circuit, thereby creating upstream congestion and overall reduced inertial output, irrespective of the ventricle.
3. The chronic congestion and low output are primary effects of the Fontan circulation and may cause early circulation failure; they will induce secondary and tertiary changes in all organs including the ventricle, which will codetermine late function or failure.
4. The ventricle evolves from large but adapted to overall output at birth, to overgrown and dilated while shunted, to volume deprived and possibly collapse at Fontan with decreasing compliance.

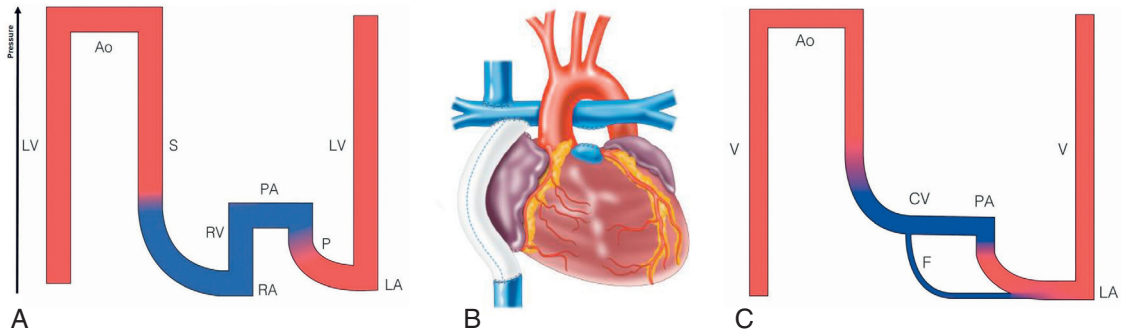


Fig. 60.1 (A–C) Schematic representation of the normal cardiovascular circulation (A) and Fontan circulation (C). (A) Normal circulation: the pulmonary circulation (*P*) is connected in series with the systemic circulation (*S*). The right ventricle (*RV*) maintains a right atrial pressure lower than the left atrial pressure, and provides enough energy for the blood to overcome the pulmonary resistance. (B) Illustration of total cavopulmonary connection Fontan circuit: the superior caval vein has been connected end-to-side to the right pulmonary artery; the inferior caval vein has been connected through a conduit to the caudal end of the right pulmonary artery. (C) Fontan circuit: the systemic veins are connected to the pulmonary artery (*PA*), without a subpulmonary ventricle or systemic atrium: the lungs are thereby converted into a neoportal system that limits flow to the ventricle. In the absence of a fenestration, there is no admixture of systemic and pulmonary venous blood, but the systemic venous pressures are markedly elevated. A fenestration (*F*) allows the systemic venous blood to bypass the Fontan portal system and limits the damming effect, thereby increasing output and decreasing congestion, but also arterial saturation. *Ao*, Aorta; *CV*, caval veins; *F*, fenestration; *LA*, left atrium; *LV*, left ventricle; *RA*, right atrium; *V*, single ventricle. Line thickness reflects output, color reflects oxygen saturation. (Adapted from Gewillig M, Brown SC. The Fontan circulation after 45 years: update in physiology. *Heart*. 2016;102(14):1081–1086.)

frequently hypoplastic, significant catch-up growth of these vessels with eventually low impedance is required during infancy, not only to have an acceptable early result but also the best possible late result. Even when resistance has fallen, a staged approach is preferred, connecting the superior and inferior caval veins on separate occasions. Such a staged approach allows the body to gradually adapt to the different hemodynamic conditions, avoids ventricular damage by limiting volume overload in time, and reduces the overall operative morbidity and mortality. A staged approach also allows better patient selection and preparation of pulmonary vasculature by adding intermediate interventions if required.

Initially, in the neonatal period, management should focus on providing unrestricted flow from the heart to the aorta (if required: coarctectomy, Damus-Kaye-Stansel, Norwood repair); a limited well-balanced flow to the lungs (if required: pulmonary artery banding, modified Blalock-Taussig or central shunts, stent in duct); and unrestricted return of blood to the ventricle (if required: Rashkind balloon septostomy, atrial septectomy). The infant is then allowed to grow for several months. Over this period, the heart is submitted to a chronic volume overload, which is beneficial for the development of the pulmonary vasculature, but if excessive detrimental to ventricular function. The infant will have mild oxygen desaturation, which is inversely related to mild cardiac failure.

At the age of several months (4–12 months old), most centers will introduce a partial cavopulmonary connection or bidirectional Glenn shunt: the superior caval vein is transected and connected end-to-side to the pulmonary artery (bilateral if a left-sided superior caval vein is also present). If no other blood flow is directed to the lungs, the volume load for the heart is significantly decreased to slightly less than normal for the body surface area. When proceeding to a Glenn shunt, the size of the pulmonary arteries and symmetric perfusion should be adequate as pulmonary blood flow is from then on significantly less than normal both in volume and pressure. No further catch-up growth of the pulmonary vessels can be expected, and asymmetric perfusion may be enhanced, both of which can be detrimental for the later Fontan circulation. The patient at this stage will remain slightly cyanosed, as the desaturated blood from the inferior caval vein is still allowed to flow to the aorta.

At the age of several years (1–5 years), depending on the preference of the center, growth of vascular structures, and cyanosis at rest and during exercise, the Fontan circuit is completed by connecting the inferior caval vein to the pulmonary artery (see Fig. 60.1B). Frequently a small fenestration is created between the tunnel conduit and the pulmonary atrium, either routinely or only in "high-risk" patients.[7] Such a fenestration will allow a residual right-to-left shunt, thereby limiting caval pressure and congestion and increasing the preload of the systemic ventricle and cardiac output at the expense of cyanosis. It has also been demonstrated to reduce the operative mortality and morbidity associated with pleural effusions; the fenestration can later be closed percutaneously (weeks to months) after adaptation of the body to the new hemodynamic condition.

Cardiac Output in the Setting of a Fontan Circulation

By creating a total cavopulmonary connection, the surgeon dams off venous return to the ventricle, essentially without touching the ventricle itself; this is, in effect, noncardiac vascular surgery. Like any dam, this will create upstream congestion and downstream decreased blunted inertial flow; the energy stored by the dam will be used for oxygenation. The ventricle, while still the engine of the circuit, cannot compensate for this major flow restriction: the suction required to compensate for the damming-up effect of the Fontan portal system cannot be generated.[8] The heart, therefore, no longer controls cardiac output, nor can it alter the degree of systemic venous congestion. Cardiologists have very little experience with such upstream restriction;

they are more familiar with primary myocardial problems (ischemia, myocarditis, cardiomyopathy) or excessive volume preload of afterload, but not chronic volume deprivation. This chronic volume deprivation combined with venous congestion, however, characterizes completely the Fontan circulation. In this chapter, we will therefore concentrate on the critical components of the circulation: the effect of an upstream flow restrictor on congestion and the overall output, the nature of the band (Fontan portal system), and the early but especially the late effects of chronic volume deprivation on the ventricle. These three components will change and interact continuously throughout life, making the Fontan circulation difficult to characterize at any moment in time since there is an evolution from an initial upstream restriction, later aggravated by impeded runoff and finally ventricular systolic dysfunction.

Effect of an Upstream Flow Restrictor

Cardiologists are rarely confronted with a flow obstruction upstream of the systemic ventricle: examples are critical mitral valve stenosis, divided atrium, pulmonary vein stenosis, any severe right heart failure (extreme pulmonary hypertension, critical pulmonary or tricuspid valve stenosis) or constrictive pericarditis. The basic pathophysiology of the acute Fontan insult is better understood when using a simple model without pulmonary hypertension. Let us assume progressive snaring of both caval veins (Fig. 60.2). Any experienced cardiologist will easily predict the following changes: pressure in caval veins will rise, while all pressures and flow downstream will decrease, both in the right heart, but specifically in the left atrium, left ventricle, and aorta; the left ventricular cavity will decrease with a proportional increase of wall thickness, contractility indices will decrease (Frank-Starling)) and diastolic pressure will (initially) decrease; as aortic pressure decreases, systemic vascular resistance will increase to maintain flow in critical organs. Note that the ventricle at this point has been left untouched, and that all changes are not due to an intrinsic myocardial problem but are due to the markedly different loading conditions. Further snaring of the caval veins will result in excessive congestion, edema and effusions, low overall output with hypotension, and eventually death. When the intensivist is confronted early after the caval banding with this failing circulation, he will aim to decrease the congestion and increase overall flow. He therefore will have to concentrate on the new critical bottleneck (snares at both caval veins). Flow through a bottleneck or dam is determined by the push above, the resistance within, and the suction below the restriction. Thus, in order to improve flow throughout the system, simple hydrodynamics and experience dictate that pushing more above is the easiest, dealing with the resistance is the most effective, and pulling harder from below is the least efficient; decreasing flow resistance much further downstream from the critical dam will be irrelevant. Translated into clinical management, options are:

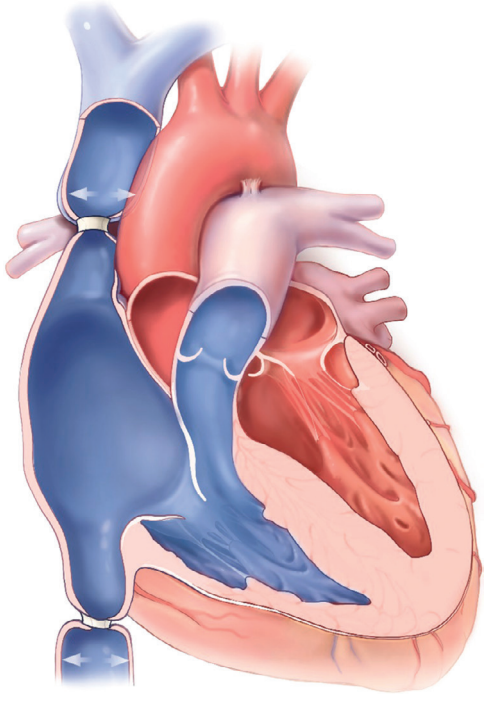


Fig. 60.2 Model to study an upstream flow obstruction without right heart hypertension: banding of the inferior and superior caval vein.

- More push above: filling the subject will increase flow through the bands, but this will be limited by developing edema and effusions.
- The resistance itself: the most efficient way to relieve congestion and low output is releasing the bands; if not possible, a bypass (fenestration) is an option.
- Suction below the obstruction: the ventricle below the obstruction cannot generate the negative pressures required to overcome the upstream flow obstruction; we have no lusitropic drugs with such an effect.
- Downstream: all changes observed well downstream of the bands are secondary or even tertiary changes; altering these downstream changes will have little or no effect on the caval vein congestion nor on the overall output but may attenuate or delay further changes like hypotension or shock. Little will thus be expected in this situation from inotropes, vasoconstrictors, or a left ventricular assist device; pacing and systemic vasodilators can even be detrimental.

This model perfectly describes what happens early after creating a Fontan circulation.

What are the differences between this model and a Fontan circulation? The presence of a pulsatile right heart will attenuate the effects of the banding but is probably not very relevant. Major differences are the nature of the dam (simple caval bands vs. the complex Fontan portal system) and the ventricle (a normal left ventricle vs. a single ventricle with unusual loading conditions and growth during fetal, neonatal, and pre-Fontan life, and hemodynamic insults during previous operations). A single-ventricle patient may already have aortopulmonary collaterals at the time of Fontan surgery. The differences between this simple model and the Fontan circuit will be discussed in the following section as they will influence the Fontan circulation at a later stage.

The Nature of the Band: The Fontan Neoportal System

The "band" or the upstream dam in a Fontan circuit is complex and includes the venoarterial Fontan connection itself (atriopulmonary in older patients), the pulmonary arteries, the pulmonary capillary network, the pulmonary veins, and the veno-atrial connection. We refer to this dam as "the Fontan neoportal system"; a portal system occurs when one capillary bed pools blood into another capillary bed through veins without passing through the heart. Impairment at any level of this portal system will have profound consequences on the output of the Fontan circuit, much more than a comparable dysfunction in a two-ventricle circulation.

The surgical connection: in the current era, the surgical technique used to create a total cavopulmonary connection is usually quite good, with minimal energy loss due to focal stenosis, reduced or absent turbulence, and minimal flow collision; ideally, flow of the hepatic veins blood should be diverted to both lungs to avoid pulmonary arteriovenous fistulae.[6,9]

The pulmonary circulation: Francis Fontan recognized early on that a high PVR was highly predictive of postoperative mortality and morbidity in the immediate and midterm follow-up periods. Pre-Fontan management is therefore pivotal for future Fontan patients and should strive for a large, well-developed and low-impedance pulmonary vascular bed. The impairments that need to be avoided include, but are not limited to, stenosis, hypoplasia, distortion, pulmonary vascular disease, loss or exclusion of large vessels or microvessels, turbulence and flow collision, flow mismatch, and obstruction as a result of external compression. Once created, the Fontan circulation itself may lead to deterioration of the pulmonary vasculature and raise impedance by its chronically decreased flow, mild desaturation, increased collateral flow, suboptimal mixing of inferior and superior caval flows, circulating pulmonary vasoconstrictors, lack of pulmonary vasodilators, absence of pulsatility with endothelial dysfunction, micro- or large thrombi, and absence of episodes of high flow and high pressure as is normally seen during exercise. It is, therefore, no surprise that pulmonary vascular resistance in a patient with a Fontan circulation may increase faster than normal aging would predict.

Effects of Chronic Volume Deprivation on a Ventricle (Normal and Single Ventricle)

In clinical conditions with systemic ventricular deprivation such as large atrial septal defects and mitral stenosis, the left ventricle has been shown to become less compliant with increasing filling pressures.[10,11] Restoration of preload resulted in improved volume-pressure relationships in both diastole and systole.[10,12,13] This should not surprise us. In striated muscles, limiting the range of motion by splinting or disuse leads to increased muscle stiffness, most likely due to reduced or absent stretching from the new baseline; similarly, stretching will reduce stiffness. A sedentary lifestyle with the absence of ventricular muscular stretch from baseline detrimentally affects the elasticity and worsens diastolic compliance. Endurance training with its ventricular stretch has been shown to decrease left atrial pressure (LAP) in normal subjects, in athletes, and in the elderly.[14,15]

In the Fontan state with the upstream dam, chronic volume deprivation of the ventricle will lead to an attenuated to absent ventricular stretch during exercise. The degree of deprivation is determined by many factors such as the flow restriction by the Fontan dam, the degree of ventricular overgrowth, the presence or absence of ventricular remodeling, and resting and exercise heart rates. For the same preload reduction, the effect on a single ventricle will be more pronounced than on a normal left ventricle as the single ventricle is large for body surface area due to previous volume overload during fetal life and initial palliation.[5] During exercise, a normal left ventricle within a biventricular circulation "stretches" from baseline; the augmented venous return during exercise increases stroke volume of the thin-walled right ventricle, consequently elevating stroke volume in the left ventricle (as both ventricles are synchronized). In contrast, the Fontan patient experiences limited and blunted exercise-induced flow augmentation due to the absence of a right ventricle and the damming effect of the Fontan portal system on overall output. During exercise, if the heart rate increases faster than the output, stroke volume will even decrease. With time, Fontan physiology renders an accelerated and amplified rise of filling pressure more likely (Fig. 60.3), especially in so-called "poor" Fontan patients.[16–18] In a failing Fontan circulation, it is not uncommon to witness a rise in left atrial pressure up to 20 mm Hg and higher, even at a young age.

This, however, has an enormous deleterious effect; flow through the critical bottleneck is further hindered by poor runoff into the ventricle, resulting in more retrograde congestion and decreased output, which will even further deprive the single ventricle. Reduced preload will further reduce systolic function (Frank-Starling), and when

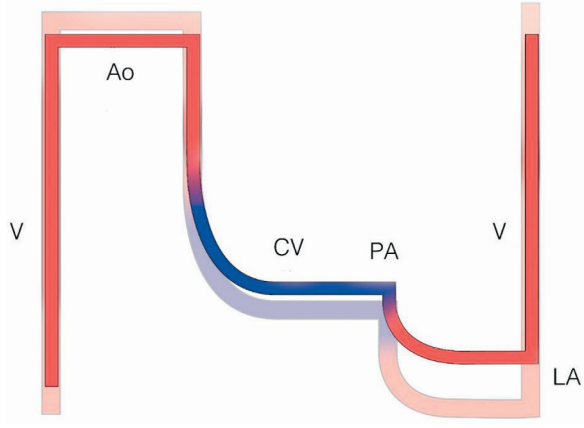


Fig. 60.3 Scheme of a Fontan circuit early and late (superimposed on early Fontan circuit). With time, a negative spiral ensues: ventricular filling pressure increases typically more than caval venous pressure, resulting in less gradient, less flow, and more venous congestion. *Ao*, Aorta; *CV*, caval veins; *LA*, left atrium; *PA*, pulmonary artery; *V*, single ventricle. Line thickness reflects output, color reflects oxygen saturation. (Adapted from Gewillig M, Brown SC. The Fontan circulation after 45 years: update in physiology. *Heart*. 2016:102(14):1081–1086.)

severely deprived reaching the ventricular closing volume, systolic dysfunction disproportionately increases.

While the early circulation failure of a Fontan circuit is predominantly caused by the damming effect of the Fontan portal system, late aggravation of the circulation failure is predominantly caused by the superimposed progressive stiffening of the ventricle, amplified by an increase in PVR and systolic dysfunction.

Functional Impairment After the Fontan Operation

The restriction of the cardiac output and the inability to power the blood through the pulmonary vasculature result in a circulation in which the ability to perform exercise is reduced. Under resting conditions, cardiac output in a patient with a Fontan circulation is approximately 70% to 80% of normal with a range from 30% to 95%. During exercise, the limitations of the Fontan circuit are substantially magnified such that the small difference in cardiac output at rest becomes a large difference during activity (Fig. 60.4). At peak exercise, a well-trained athlete with a normal heart can increase blood flow through the lungs by up to five-fold. This is accomplished through a substantial increase in the right ventricular systolic pressure (up to 70 mm Hg![19]) as well as with pulmonary blood flow acceleration coupled with a decrease in pulmonary vascular resistance. In a patient with Fontan physiology, there is no physiologic mechanism to allow for a similar increase in cardiac output. The maximal mean venous pressure rarely reaches 30 mm Hg, there is no blood acceleration, and the pulmonary vascular reactivity and ability to recruit reserve vessels are attenuated or absent.[20] Together, these limitations result in a diminished ability to augment cardiac output in response to increased metabolic demand and therefore limit the ability of a patient with a Fontan circulation to perform exercise.

Through childhood and until puberty, the mean maximal exercise capacity for patients with a Fontan circulation is in the range of 65% predicted for gender and age.[21] While successful Fontan patients may remain stable for many years, poor Fontan patients suffer an accelerated decline. Longitudinal studies of late adolescents and young adults demonstrate this point well; as patients progress to late adolescence and early adulthood, exercise capacity tends to continue to decline by about 2.6% per year.[22–24]

Evolution of Strategies in Single-Ventricle Patients Heading for a Fontan Circulation

There are several reasons why adults with a Fontan circuit in the current era do not represent the current cohort of pediatric patients. Many of the original candidates for a Fontan operation, the now adult cohort, were suboptimal for this type of surgery from a hemodynamic standpoint, with many significant residual lesions and sequelae related to the original cardiac malformation and palliative procedures. A shunt procedure performed during the period from the 1960s to the 1980s was evaluated based on the goal of the long-term relief of cyanosis: "The pinker, the better." Often, a second aortopulmonary shunt was created to augment pulmonary blood flow after the first shunt was deemed inadequate. The potential that these shunts could induce pulmonary vascular disease, ventricular hypertrophy and dysfunction, or pulmonary artery distortion was not—as it is now—a principal concern of the surgeon. Currently, the success of a shunt is evaluated by obtaining acceptable relief of cyanosis without significant volume overload of the ventricle and by the induction of adequate pulmonary growth

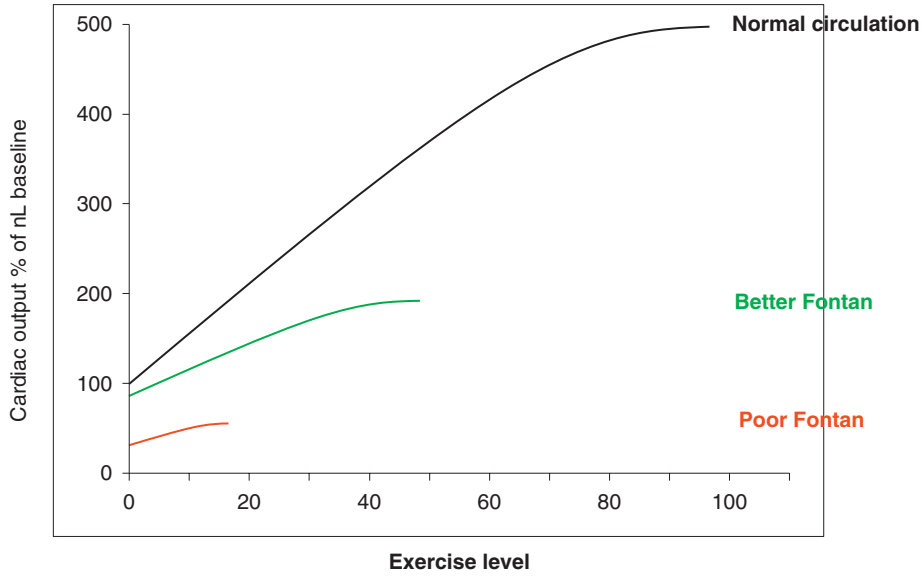


Fig. 60.4 Exercise and output: normal versus Fontan circulation: A normal subject with a biventricular circuit can increase their output by a factor of 5 (*black line*). In Fontan patients, output is significantly impaired both at rest and during exercise; at best (*green line*) the output is mildly decreased at rest, with moderate capacity to increase flow during moderate exercise. At worst (*red line*), the output is severely reduced at rest and barely augments during minimal exercise. (Adapted from Gewillig M, Goldberg DJ. Failure of the Fontan circulation. *Heart Fail Clin*. 2014;10(1):105–116.)

without causing changes in pulmonary vascular resistance. In addition, in the modern era of palliation, the systemic-to-pulmonary shunt is designed to last 4 to 6 months, enough time for the pulmonary vascular resistance to drop to such a level that a partial cavopulmonary connection can safely be created. Fig. 60.5A–C illustrates the different loading conditions of the single ventricle at the various stages of palliation, highlighting the differences in management strategy before the 1990s (typically two aortopulmonary shunts prior to the full Fontan circulation) and after (typically one shunt, then partial and later complete Fontan circulation). However, with the current staged strategy for functionally single ventricles, only a limited period of controlled pulmonary "overflow" is allowed to stimulate pulmonary arterial growth. The only time of significant pulmonary overflow—and catch-up growth if required—is during infancy when a shunt or band is placed. In many situations, the systemic-to-pulmonary shunt is currently made as small as possible to avoid volume overload of the ventricle and potential cardiac damage. However, if flow to the lungs is too low for too short a period, inadequate development of the pulmonary vascular bed, high PVR, and eventually, a poorly functioning Fontan circulation may result (Fig. 60.6). Similarly, hybrid procedures involving neonatal banding of branch pulmonary arteries may cause distortion and inadequate or asymmetric growth or even loss of the distal pulmonary arteries. The loading and boundary conditions change enormously from fetal to Fontan; this is reflected in the changing pressure-volume loops (Fig. 60.7).

Consequences of the Fontan Circulation

Complications after Fontan repair are common and related to the continuously increased venous pressure and congestion and chronic low cardiac output. Complications include early and late mortality, exercise intolerance, ventricular dysfunction, rhythm and conduction disturbances, hepatomegaly with secondary fibrosis, cirrhosis and carcinoma,[25,26] systemic venous thrombi, lymphatic dysfunction with protein-losing enteropathy[27] and bronchial casts,[28,29] ascites, pleural effusions, and peripheral edema.

Therapeutic Strategies to Improve Fontan Output

The circulatory problems in a Fontan circuit are primarily created by the damming effect of the Fontan neoportal system and the subsequent limit on cardiac preload. It has become clear that once created, the Fontan circuit runs on "autopilot" and allows little modulation. Strategies to increase cardiac output should maximize the flow through the critical bottleneck: the Fontan portal system. Like with any critical bottleneck, this can be done by increasing the pressure before the dam (systemic venous pressure), lowering the resistance of the Fontan neoportal system dam, enhancing the runoff after the dam (ventricular suction), or bypassing the dam (fenestration). Strategies aiming at changes further beyond the critical bottleneck (systolic function, systemic afterload, heart rate) will have little effect in the early phase of the Fontan circulation.

Increasing central venous pressure leads to an immediate output increase. This practice is commonly adopted by intensivists shortly after the Fontan procedure, while keeping in mind that high venous pressures may result in edema and effusions. Fontan patients themselves can enhance their output via their muscular pump—employing their major striated leg muscles to elevate venous pressure up to 30 to 35 mm Hg.[8,30,31]

The resistance of the surgical connection obviously carries significance. Over the years, surgeons have refined the procedure to eliminate flow restrictors such as a hypoplastic stiff subpulmonary ventricle, venous valves, a bulky atrium, or flow vortices.[6] Currently, the Fontan operation has been reduced to its essentials: direct and broad connection of the caval veins to the branch pulmonary arteries without pressure loss, with a mild offset, limiting flow collision but allowing flow of the hepatic factor to both lungs. The conduit and pulmonary branches should be nonrestrictive at creation and during growth, not only at rest, but also during exercise. Little improvement is to be expected at this level.

Pulmonary vasodilators have emerged as a therapeutic tool in Fontan patients, but only in those patients where vasoconstrictors, lack of vasodilators, or mild pulmonary vascular disease play a prominent role. Other pulmonary vascular lesions such as stenosis, distortion, kinking, loss or exclusion, hypoplasia, or external compression will not be influenced by pulmonary vasodilators. The role of pulmonary vasodilators to increase output in a Fontan circuit is therefore modest. In clinical series in nonselected patients, pulmonary vasodilators could augment output only by 0% to 8%.[32–34] Intensivists have learned to limit positive pressure ventilation and encourage early spontaneous breathing or negative pressure ventilation.[35,36] Fontan patients can proactively mitigate the gradual rise in PVR by engaging in regular physical activity, which aids in flushing and recruiting lung vessels, and practicing preventive measures (vaccination, vigorous treatment of bronchitis, weight control).[37]

Fenestration: Introducing a fenestration allows for flow to occur parallel to the Fontan portal system. Similar to any bypass, fenestration-mediated flow reduces upstream congestion and, since it operates across the critical bottleneck, augments overall output. However, the augmented flow carries desaturated blood, resulting in arterial desaturation as a trade-off. Fig. 60.8 shows the relationship between output, congestion, and arterial saturation in a successful and a failing Fontan circuit and the effect of partial improvement by a fenestration. In a successful Fontan circuit, the low resistance portal system will cause a mild decrease of output with a modest increase in the systemic venous pressures, making a fenestration unnecessary. In a failing Fontan circuit, the inclusion of a high vascular resistance portal system will decrease the cardiac output and create venous congestion of an unacceptable degree; a fenestration will attenuate these changes, but in patients with an increased PVR, an acceptable compromise may not be possible.

Decreasing ventricular filling pressure: theoretically, the ventricle that is downstream of the dam could improve output by creating negative pressure and "pulling" blood

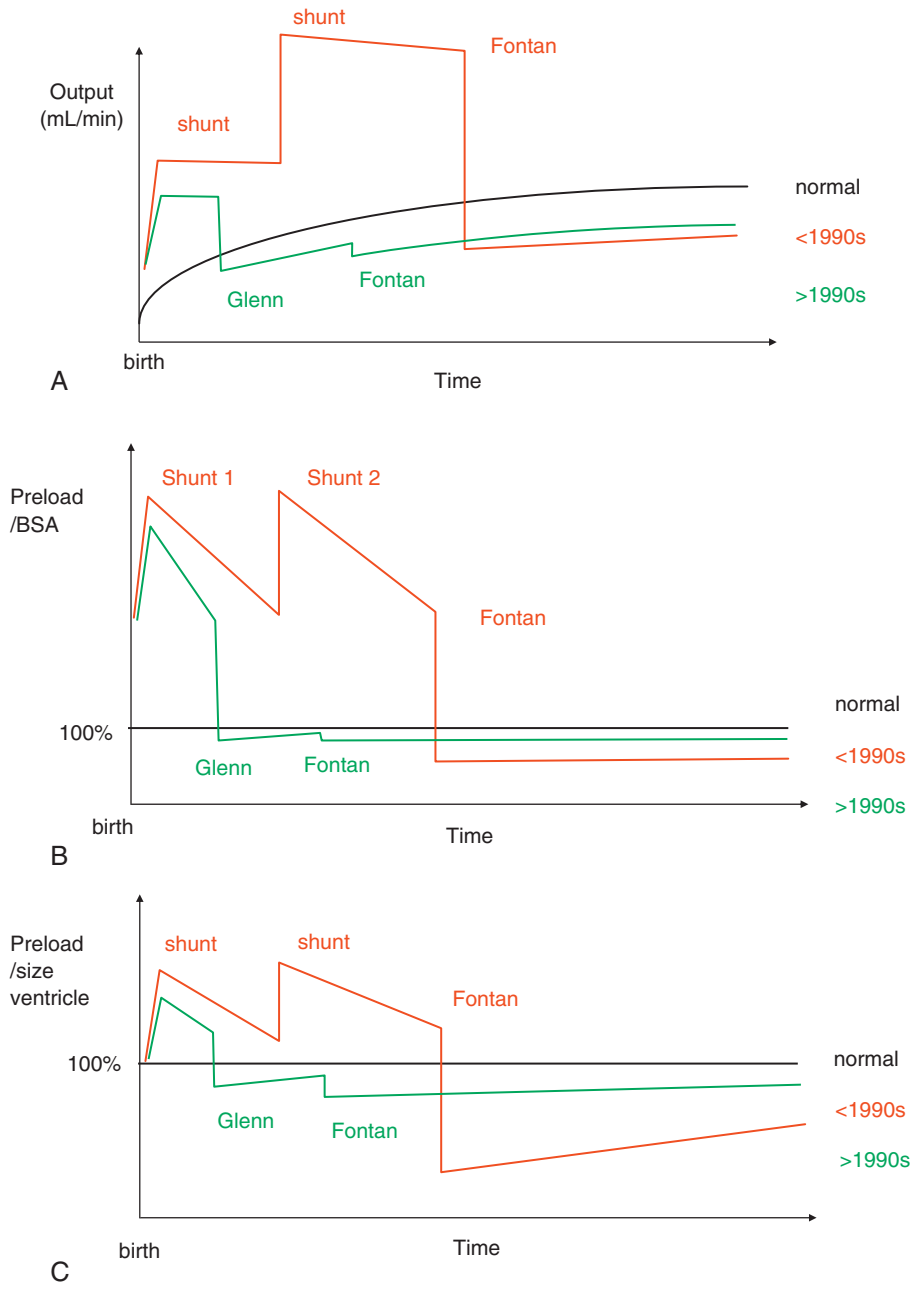


Fig. 60.5 (A–C) Cardiac output versus time in the normal left ventricle and the univentricular heart (UVH) managed before and after the 1990s. The same story but expressed with different reference frame: in absolute value (A), related to body surface area (*BSA*) (B), and to ventricular size (C). (A) **Cardiac output expressed in absolute value:** The *black line* shows output of a normal ventricle, which increases proportional to growth. At birth the volume load to the UVH is about 250%–300% of that of a normal left ventricle. Prior to the 1990s, a neonatal and infant large shunt was created with significant increase in output (*red line*); the shunts were abolished at the time of the Fontan operation, and the Fontan portal dam reduced even further preload. After the 1990s, a small neonatal shunt is created for a short time, and the ventricle is progressively unloaded both at the Glenn and the Fontan operation (*green line*). (B) **Cardiac output related to BSA**. *Black line*: output of normal remains at 100% for BSA. This representation assumes only dilation and stretch without any overgrowth of the ventricle. The patient with a UVH is born with a large ventricle (volume load of 250% of normal for BSA). Prior to the 1990s (*red line*), the preload to the ventricle is augmented shortly after birth by a shunt procedure to ±350% of normal for BSA. The patient slowly outgrows their shunt, thereby gradually reducing the volume overload. A second shunt was created, augmenting the volume overload again. As this patient again outgrows their shunt, a Fontan circuit is made, reducing the volume load to <80%. After the 1990s (C, *green line*), a small neonatal shunt was created for a short time; the patient slowly outgrows their shunt; the ventricle is progressively unloaded both at the Glenn and Fontan operation (C: *green line*). (C) **Cardiac output related to ventricular size in UVH managed before and after the 1990s**. This representation assumes adapted overgrowth of the ventricle at every stage in function of chronic preload. (A) Output of normal remains at 100% for ventricular size. The patient with a UVH is born with an appropriate ventricle for volume load (100% of normal for ventricular size). Prior to the 1990s (B, *red line*), the preload to the ventricle was augmented shortly after birth by a shunt procedure to ±150%. The patient slowly outgrows their shunt and adapts their ventricle, thereby gradually reducing the volume overload to ±100% for its size. A second shunt was created, augmenting the volume overload again to 150%. As this patient again outgrows their shunt, a Fontan circuit is made, reducing the volume load to 25% of its "due" preload. After the 1990s (C, *green line*), a small neonatal shunt was created for a short time; the patient slowly outgrows their shunt; the ventricle is progressively unloaded both at the Glenn and Fontan operation in much milder steps avoiding acute unloading and severe deprivation (C: *green line*). (Adapted from Gewillig M, Goldberg DJ. Failure of the Fontan circulation. *Heart Fail Clin*. 2014;10(1):105–116.)

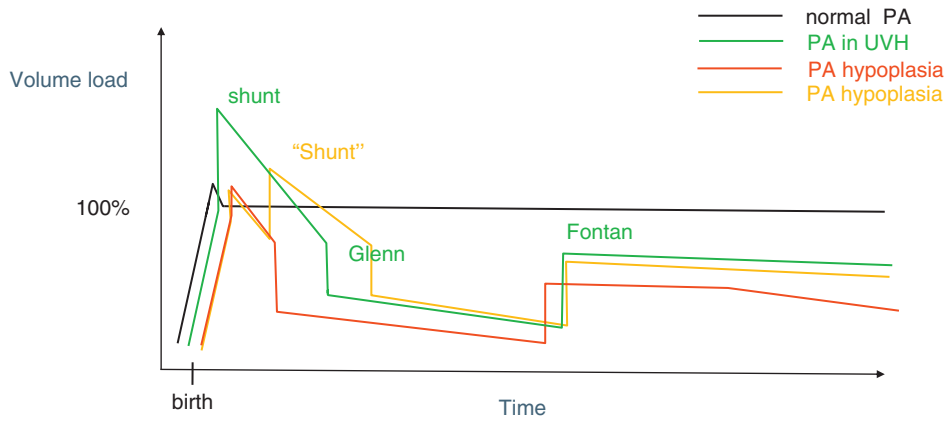


Fig. 60.6 Pulmonary volume load (and outcome) of Fontan since 1990s. In the normal circulation, pulmonary blood flow inc**reases** at birth and remains at 100% of normal for body surface area (*BSA*) (*black line*). In a univentricular heart (*UVH*), a phase of significant pulmonary overflow exists immediately after birth when a shunt or band is placed. After adequate pulmonary growth (*green line*), pulmonary blood flow is reduced to about 50% of normal for BSA after the superior cavopulmonary connection (stage 2 palliation). Pulmonary flow is then increased by completion of the total cavopulmonary connection (the Fontan operation). If flow to the lungs is too low after the initial palliation, inadequate growth may result (*red line*). The cyanosis from low pulmonary blood flow may lead to early referral for superior cavopulmonary connection, which may further reduce flow and growth. When the Fontan circuit is created, the Fontan portal system will have a high impedance, resulting in a poor Fontan circulation irrespective of ventricular function, with low cardiac output and a progressive functional impairment. If such poor evolution is expected, this may be avoided by providing additional flow to the lungs (*orange line*), resulting in catch-up growth, lower impedance, and a better Fontan flow. *PA*, Pulmonary artery. (Adapted from Gewillig M, Goldberg DJ. Failure of the Fontan circulation. *Heart Fail Clin*. 2014;10(1):105–116.)

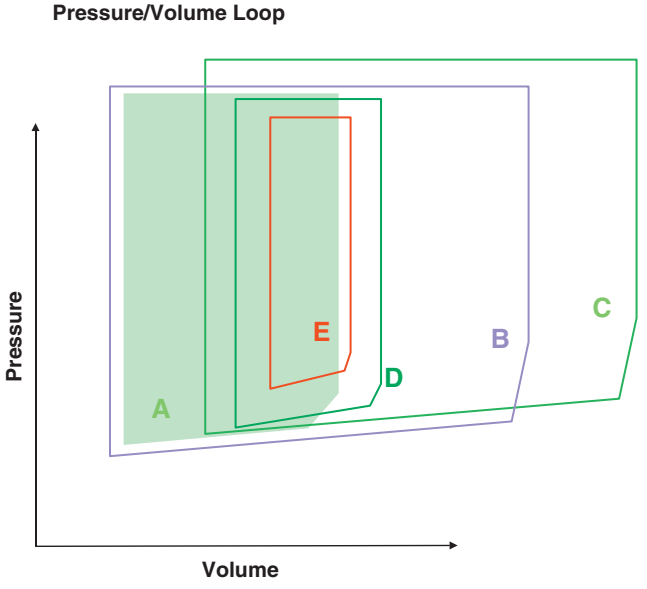


Fig. 60.7 Pressure-volume (*PV*) loops: normal left ventricle (A) versus single ventricle at various stages of palliation (B–E). (A) PV loop of normal left ventricle (*LV*). At birth, the neonatal ventricle (B) of the univentricular heart had an intrauterine volume overload of approximately 250 of normal for body surface area (*BSA*). In the first months a systemic-to-pulmonary shunt is necessary to maintain oxygen saturations of above 85%; the ventricle will now have a volume overload of about 250%–350% of normal for BSA (C: large stroke volume with increasing filling pressures). When a "Fontan" type procedure is performed, all systemic-to-pulmonary shunts are removed, and the volume preload of the ventricle is acutely reduced (D); during the Fontan state, stroke volume decreases and filling pressure rises (E). If the Fontan ventricle is compared to a normal LV it will be called "stretched & dilated" (E vs. A), but when compared to the pre-Fontan state it is "collapsed and deprived" (E vs. C).

through the lungs. However, the human ventricle is unable to generate the negative pressures required for such pull. Clinicians have no lusitropic drugs or maneuvers at their disposal that are of any significant long-term benefit. Diuretics could theoretically be helpful, yet typically lower CVP more than LAP, creating a negative output balance. In the long run, diuretics further deprive the unloaded ventricle, potentially hastening the progressive stiffening of the Fontan ventricle. Exercise might contribute to delaying ventricular stiffening through the mechanism of exercise-induced ventricular stretch. The potential role of negative chronotropic drugs still needs to be determined.

Some measures that in classic cardiology are very useful have only limited value in a Fontan circulation. When a cardiologist is confronted with a patient with venous congestion, low output, and a big hypocontractile heart, the primary reflex will be to launch traditional strategies known to treat heart failure efficiently. However, especially early after the creation of the Fontan circuit, there is no primary heart failure, as the ventricle will pump anything it is offered. There is indeed circulation failure with decreased ventricular systolic indices due to the limited preload (Frank-Starling).

Inotropes may make the ventricle squeeze harder but not pump more volume due to limited preload unless it can lower LAP. It is, therefore, no surprise that studies that investigated the effect of inotropes on cardiac index in Fontan patients showed no or minimal effect.[38–40] Reduced systolic indices after Fontan are frequently observed as obligatory due to the primary preload restriction (Frank-Starling), but may additionally be due to myocardial damage secondary to previous management (volume or pressure overload, cyanosis, ischemia, inflammation). Only the latter component is reactive for inotropes.

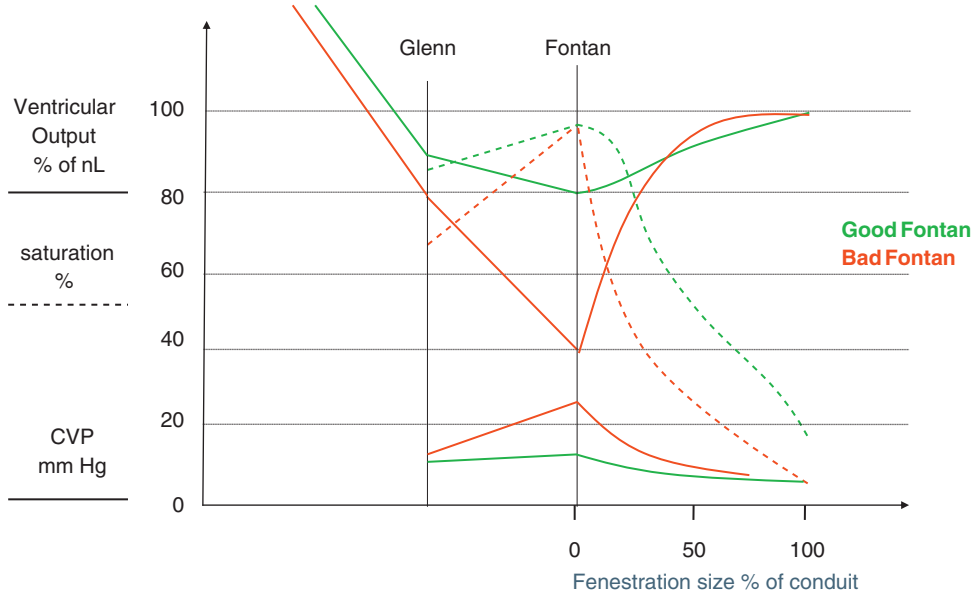


Figure 60.8 Effect of various degrees of pulmonary bypassing in a Fontan circuit on systemic output, saturation, and systemic venous congestion. A "good Fontan" with low neoportal resistance (*green lines*) has an output (*upper solid line*) of about 80% of normal for body surface area, with a high saturation (*dotted line*) and a mildly elevated central venous pressure (*CVP*) (*lower solid line*). The "bad Fontan" with a high portal resistance (*red lines*) has an output with a similar saturation but with a very low to unacceptable output despite a high CVP. Partial bypassing of the Fontan portal system by a fenestration invariably increases systemic output and decreases systemic congestion, but in the "bad Fontan," this occurs at an unacceptable degree of cyanosis. (Adapted from Gewillig M, Goldberg DJ. Failure of the Fontan circulation. *Heart Fail Clin*. 2014;10(1):105–116.)

Afterload: Among numerous studies conducted, not a single one has managed to reveal a significant effect of afterload reducers on output or congestion in Fontan patients. Instead, a multitude of studies either report no impact or indicate a vague nonsignificant effect on secondary or tertiary endpoints.[41,42] Systemic vasodilators can only augment flow in a Fontan circulation by lowering the LAP such as when significant regurgitation of the atrioventricular or semilunar valve(s) is present. However, their short-term efficacy is otherwise very limited, but in the long run, they might prevent accelerated decline. Angiotensin converting enzyme inhibitors might play a role in preserving late ventricular function, slowing age-related changes, or maintaining adequate kidney function, but this needs to be demonstrated.

Conclusion

The Fontan palliation is characterized by the creation of a pulmonary neoportal system, which becomes the new critical bottleneck that leads to upstream systemic venous congestion and downstream chronic low output. The long-term outcomes of the Fontan operation performed in patients with a low-risk profile demonstrate good overall results: arterial hypoxemia is eliminated, volume overload to the ventricle is abolished, the burden of chronic systemic venous hypertension is usually acceptable, and most patients enjoy a reasonable quality of life for several decades. A prematurely functional decline over time is inevitable as ventricular filling pressures and pulmonary vascular resistances increase, which results in increasing venous congestion and decreasing output.

Careful attention to pulmonary blood flow and pulmonary arterial growth during the initial stages of palliation is absolutely crucial, as PVR will become the major determinant for a good long-term result.

Therapeutic options for circulatory failure in a Fontan circuit are limited and unsatisfactory as the Fontan circulation allows little manipulation. Prevention of dysfunction by ensuring a low resistance adequate pulmonary vascular bed while maintaining good ventricular function is therefore of the utmost importance.

The complete reference list for this chapter is available in the eBook at ebooks.health.elsevier.com.

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