

# Clinical research to optimize the Fontan concept: a long, difficult, but rewarding, journey

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In this issue of the Journal, Iwai *et al.* [1] report on their experience in preserving maximal ventricular function after Fontan type repair for complex congenital heart disease. They show evidence that avoiding intraventricular outflow resistance by maximally incorporating every usable semilunar valve into the circuit is beneficial for long-term ventricular and atrio-ventricular valve function. Incorporating the pulmonary outflow tract in the Fontan circuit by performing a Damus–Kaye–Stansal manoeuvre is essential in patients with a proven or expected subaortic stenosis (all patients with coarctation, small aortic valve, subaortic stenosis), but also appears to be beneficial in patients without an apparent or expected gradient. Their report is another step in the process of optimising the Fontan circuit.

We have come a long way since the first Fontan circulation was reported in 1971 [2]. Surgeons have learned how to avoid the cardiac factors that are deleterious to the Fontan circuit: avoid ventricular overgrowth, hypertrophy, dilation and dysfunction, excessive unloading at the time of the cavopulmonary connection and energy loss at the cavopulmonary anastomosis [3]. Some improvement is still possible, but with adequate management, it has now become rare that failure of the Fontan circuit is attributable to the surgical connection or primary cardiac dysfunction.

The circulatory output—the most important determinant of a good Fontan circuit—now largely depends on the pulmonary vasculature: by connecting the pulmonary and systemic vasculature in series, the surgeon dams off the flow to the ventricle, thereby enormously limiting the preload to the ventricle to levels of ~60–80% of the normal for body surface area (and even less when normalized for ventricular size in the overgrown – overstretched ventricle) [4]. Control of the circulatory output thereby shifts from the ventricle to the transpulmonary flow, which has quite different rules and kinetics! Most frequently the ventricle becomes ‘the innocent bystander’: the ventricle can squeeze no more blood than is allowed to flow through the lungs [5]. Interventions to significantly improve the Fontan circuit now need to target the pulmonary vasculature. After completion of the Fontan circuit, the pulmonary vasculature allows little modulation with low response to medication [6]; only a fenestration is efficient to augment the circulatory output by bypassing the pulmonary vasculature at the expense of arterial

desaturation. Therefore, we now should focus on the growth and optimal development of the pulmonary vasculature before the Fontan surgery: the initial palliation is crucial, allowing adequate volume load for sufficient time to obtain the optimal catch-up growth and development of the pulmonary vasculature before the Glenn shunt [7]. However, these considerations should not keep us from further improving the heart itself.

Assessing cardiac parameters has become increasingly difficult as we have learned that many variables depend on and interfere with each other. A ventricle in a Fontan circuit has a history: at birth it is usually well adapted, but the initial palliative state nearly always imposes a volume overload for a few months (pulmonary flow), and sometimes also an excessive pressure overload (outflow tract obstruction, residual coarctation, arterial hypertension). By the time the Glenn state removes this volume load, the ventricle has developed overgrowth, dilation and remodelling, with variable degrees of eccentric and concentric hypertrophy; many of these residua persist by the time the Fontan circuit is completed and beyond. When a ventricle is large in a Fontan circuit, our management will differ depending on whether we consider this a stretched small ventricle, or rather a collapsed underloaded but overgrown pump. Similarly, when a Fontan ventricle is hypocontractile, our management will differ depending on whether we attribute this dysfunction to a damaged burned-out ventricle, or rather to the underfilling of an overgrown chronically deprived pump. Assessing the contributions of ventricular overgrowth, dilation, hypertrophy, dysfunction due to intrinsic myopathy or due to relative underfilling (controlled by pulmonary vasculature) is extremely difficult and still beyond our comprehension. By necessity any analyses today will work with simplified and incomplete models.

Iwai *et al.* divided their study patients into three groups [Damus–Kaye–Stansal (DKS), mild pulmonary stenosis and pulmonary atresia]; these groups are not completely comparable, which may introduce a selection bias. Patients with pulmonary valve atresia typically will have hypoplastic pulmonary arteries at birth; an aortic-pulmonary shunt will be created, causing a sudden large volume load on the ventricle; catch-up growth of the pulmonary arteries can be significant, but overall, some degree of hypoplasia or subnormal compliance will persist. In contrast, patients requiring a banding procedure typically will

have large pulmonary arteries, the volume overload to the ventricle augments progressively over weeks (allowing adaptation) and decreases by the banding procedure. An ideal banding management results more frequently in an optimal growth of the pulmonary arteries with low resistance and good ventricular function. These patients therefore frequently will end up at the better end of the Fontan spectrum: the low pulmonary vascular resistance will allow the highest output after the cavopulmonary connection, resulting in a lower arterial vasoconstriction and thus lower ventricular afterload. Patients with moderate pulmonary stenosis are frequently allowed to evolve 'spontaneously', with a suboptimal balance of systemic or pulmonary flow, resulting in a suboptimal growth of the pulmonary arteries and ventricle. Considering all these factors, the patients with banding are predisposed to perform better; as they are overrepresented in the DKS group, it is not surprising that this group had the better ventricular performance with lower ventricular afterload and higher output. Although the conclusions of this study might be biased, they seem logical and acceptable; we need, however, to see this confirmed by other investigators, taking into account all confounding variables.

We have come a long way on the Fontan journey: the procedure has evolved from a poorly understood operation with high early and late mortality, high morbidity and frequent reinterventions, to a nearly 'routine' surgery on a beating heart with minimal mortality and morbidity. We do understand more than before, but we are still far from 'full control'. The final result is still suboptimal, requiring us to stay focused and to look for further improvement.

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