Commentary: Will the fourth dimension guide us toward the “perfect” Norwood arch reconstruction?

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Although rapid strides have been made in the short- and medium-term survivals after stage 1 Norwood palliation for single-ventricle disease, long-term survival is limited by the failing Fontan circulation.¹ Residual coarctation and aortic arch obstruction is common and has been associated with poor long-term single-ventricular function and survival.²

Even despite normal 2-dimensional aortic-arch specific parameters on standard echocardiography and cardiac catheterization, studies have demonstrated that abnormal shape, size mismatch, and contour can lead to maladaptive ventriculoaortic interaction and systemic ventricular dysfunction.³ Three-dimensional (3D) magnetic resonance imaging (MRI) studies with computational fluid dynamic modeling have shown that even after a successful coarctation repair in patients with 2-ventricle physiology, those who had abnormal arch shapes and contours (ie, a gothic arch) had worse ventricular function than those who had a natural (“Romanesque”) shape.⁴ In patients with single-ventricle physiology, altered arch morphology was associated with higher Glenn shunt pressures and longer intensive care unit and hospital stays.⁵ According to these previous 3D MRI computational fluid dynamic modeling studies, there is evidence that reconstructed aortic arch morphology is independently associated with ventricular function and late outcomes.^{4,5}

Although 3D flow models have clear advantages relative to standard 2-dimensional imaging, they are based on theoretic modeling and geometric-flow assumptions. In contrast, 4D flow MRI directly measures actual flow patterns, thus quantifying viscous or abnormal kinetic energy dissipation as a result of frictional forces.

In their article in this issue of the *Journal*, Schäfer and colleagues⁶ evaluated 4-dimensional flow MRI characteristics to calculate viscous energy losses at the ascending aorta, aortic arch, and descending aorta in 4 patients who had undergone Norwood arch reconstruction, 2 at the pre-Fontan stage and 2 at the post-Fontan stage.⁶ They found

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Central Message

Four-dimensional flow magnetic resonance imaging can identify inefficient flow patterns, which may increase single-ventricle workload and performance after Norwood arch reconstruction.

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that ascending aortas that were bulky demonstrated diastolic blood pooling and recirculation, with increased viscous energy loss at all 3 levels. A significantly dilated arch with increased size mismatch, where the arch transitions to the descending aorta, was also associated with a high energy loss throughout the aorta. They demonstrated that despite normal aortic arch hemodynamics according to cardiac catheterization and echocardiography, abnormal aortic arch shape and morphology is associated with abnormal flow patterns and energy loss.

Multiple factors determine optimal Norwood arch reconstruction, including the technique, the final shape, and the prosthetic material used, which can result in varying degrees of compliance mismatch with the native aortic tissue. Long-term survival after a Fontan procedure is dependent on good ventricular function, for which an unobstructed systemic ventricular outflow tract is a prerequisite.¹ To achieve the “ideal” Norwood arch reconstruction, we will need to tailor the arch to patient-specific anatomic variations and dimensions. Use of 4-dimensional flow MRI, which complements 3D MRI with computational fluid dynamic modeling, may help determine preoperatively the size and shape of an ideal aortic arch reconstruction for a specific patient subtype. Along with the growing interest and experience with 3D-printed models for congenital heart defects, advanced imaging techniques may soon be able to

provide reproducible templates for Norwood arch reconstructions and minimize the incidence of recurrent arch obstruction, late ventricular dysfunction, and Fontan failure.

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