PEDIATRIC CARDIAC

Computational Analysis of Hybrid Norwood Circulation With Distal Aortic Arch Obstruction and Reverse Blalock-Taussig Shunt

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Background. **The hemodynamics characteristics of the hybrid Norwood (HN) procedure differ from those of the conventional Norwood and are not fully understood. We present a multiscale model of HN circulation to understand local hemodynamics and effects of aortic arch stenosis and a reverse Blalock-Taussig shunt (RBTS) on coronary and carotid perfusion.**

Methods. **Four 3-dimensional models of four HN anatomic variants were developed, with and without 90% distal preductal arch stenosis and with and without a 4-mm RBTS. A lumped parameter model of the circulation was coupled to a local 3-dimensional computational fluid dynamics model. Outputs from the lumped parameter model provided waveform boundary conditions for the computational fluid dynamics model.**

Results. **A 90% distal arch stenosis reduced pressure and net flow-rate through the coronary and carotid arteries by 30%. Addition of the RBTS completely restored pressure and flow rate to baseline in these vessels. Zones of flow stagnation, flow reversal, and recirculation in the presence of stenosis were rendered more orderly by addition of the RBTS. In the absence of stenosis, presence of the shunt resulted in extensive zones of disturbed flow within the RBTS and arch.**

Conclusions. **We found that a 4-mm × 21-mm RBTS completely compensated for the effects of a 90% discrete stenosis of the distal aortic arch in the HN. Placed preventatively, the RBTS and arch displayed zones with thrombogenic potential showing recirculation and stagnation that persist for a substantial fraction of the cardiac cycle, indicating that anticoagulation should be considered with a prophylactic RBTS.**

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The hybrid Norwood (HN) management of hypoplastic left heart syndrome (HLHS) has emerged as a promising strategy. The procedure avoids cardiopulmonary bypass and consists of branch pulmonary artery banding, stenting of the ductus arteriosus, and balloon atrial septostomy [1]. The less invasive nature of the HN and deferment of the risk of a major open heart operation to an older age are considered to help improve survival, neurologic, and cardiac functional outcomes [2]. Most recent reports of survival after the HN are comparable with those obtained with the traditional surgical Norwood, and at some institutions, HN has become the preferred first intervention for HLHS palliation [3–5].

An important concern after the HN is the possibility of obstruction in the aortic isthmus after stent deployment. This is because during the interstage period, the coronary and cerebral circulations depend mainly on retrograde flow through the aortic arch. In patients with aortic atresia, this flow is entirely dependent on retrograde perfusion. Obstruction can occur immediately as a result of stent maldeployment, within a few hours from ductal remodeling after discontinuation of prostaglandins, or late as a result of fibrosis in the distal stent [6]. Clinically important obstruction of the distal aortic arch has been reported in 24% of patients after hybrid procedures for HLHS [7]. It has been suggested that placement of a reverse Blalock-Taussig shunt (RBTS), a main pulmonary artery-to-innominate artery shunt, in patients with distal aortic arch obstruction could prevent myocardial and cerebral ischemia [6]. The RBTS is a straightforward surgical addition to the HN, and although benefits of implementing this step remain unproven, some groups have adopted the policy of placing this shunt as a prophylactic measure in patients with limited or absent antegrade aortic flow or in those at high risk of developing aortic arch obstruction [2, 6].

Computational fluid dynamics (CFD) is being successfully used to elucidate the optimal approach to staged reconstruction of HLHS [8–12]. We extend these investiga-

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Abbreviations and Acronyms

BPA	=	branched pulmonary arteries
CFD	=	computational fluid dynamics
CO	=	cardiac output
DA	=	descending aorta
HLHS	=	hypoplastic left heart syndrome
HN	=	hybrid Norwood
IA	=	innominate artery
LCA	=	left carotid artery
LcorA	=	left coronary artery
LPA	=	left pulmonary artery
LPM	=	lumped parameter model
LSA	=	left subclavian artery
MPA	=	main pulmonary artery
Nom	=	nominal anatomy
Nom-RBTS	=	nominal with reverse Blalock-Taussig shunt anatomy
PDA	=	patent ductus arteriosus
RBTS	=	reverse Blalock-Taussig shunt
RCA	=	right carotid artery
RcorA	=	right coronary artery
RPA	=	right pulmonary artery
RSA	=	right subclavian artery
Sten	=	stenosis anatomy
Sten-RBTS	=	Stenosis with reverse Blalock-Taussig shunt

tions by using a multiscale CFD model of the HN to characterize the effects of stenosis of the distal arch and of the RBTS on cerebral and coronary perfusion as well as the local flow patterns through the aortic arch and the RBTS graft.

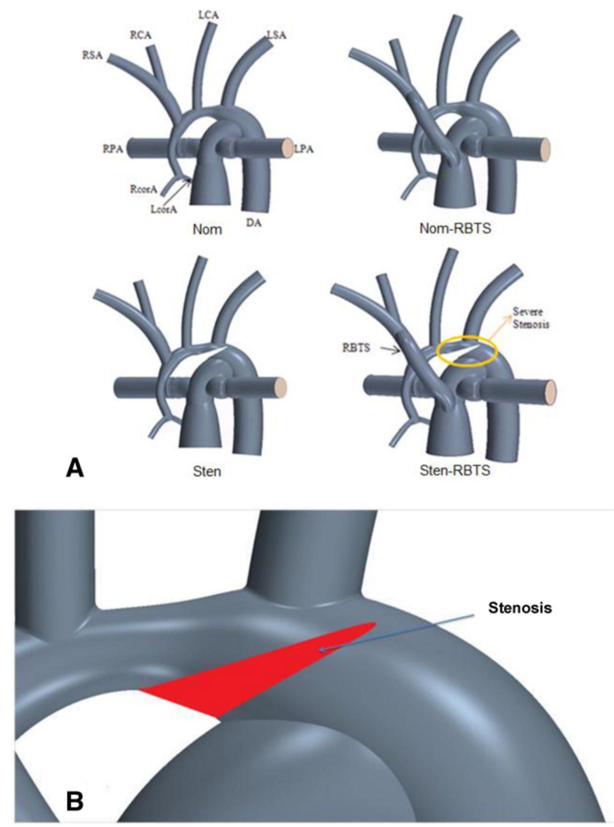

Fig 1. (A) Three-dimensional models are shown of the hybrid Norwood. (B) Detailed view of the transverse aortic arch with stenosis highlighted in red. (DA = descending aorta; LCA = left carotid artery; LcorA = left coronary artery; LPA = left pulmonary artery; LSA = left subclavian artery; Nom = nominal anatomy; RCA = right carotid artery; RBTS = reverse Blalock-Taussig shunt; RcorA = right coronary artery; RSA = right subclavian artery; RPA = right pulmonary artery; Sten = stenosis anatomy.)

Materials and Methods

We examined complex hemodynamics after HN by using a multiscale model, comprising a lumped parameter model (LPM) of the peripheral circulation coupled with a localized 3-dimensional (3D)-CFD model.

Anatomic Model

Synthetic rigid-walled 3D models representative of an infant with HLHS after the HN procedure were constructed using SolidWorks software (Dassault Systemes, Concord, MA), assuming atresia of the aortic valve and including the ascending aorta, transverse arch, innominate artery (IA), right and left subclavian arteries (LSA), right and left carotid arteries, main pulmonary artery (MPA), branched pulmonary arteries (BPA), patent ductus arteriosus (PDA), descending aorta, and right and left coronary arteries.

Four models were developed (Fig 1A). The nominal (Nom) model corresponds to the standard HN configuration of banded BPA and stenting of the PDA with "typical" hypoplasia of the aortic arch. In the second model (Sten), part of the computational domain was removed at a point proximal to the PDA and distal to the LSA (aortic isthmus) to represent severe discrete stenosis. A reduction in lumen cross-sectional area of 89.3% was produced through an aortic isthmus reduction from a nominal area of 21.46 to 2.30 mm^2 (Fig 1B). The third (Nom-RBTS) and fourth (Sten-RBTS) models were developed by modifying the Nom and Sten models, respectively, by incorporating an RBTS (4- $\times$ 21-mm bypass graft from the MPA to the IA). The proximal end of the RBTS was modeled proximal to the pulmonary bifurcation and anastomosed to the anterior wall of the MPA. The distal graft was anastomosed to the IA in an end-to-side fashion. A BPA band diameter of 2 mm was used. Vessel diameters and other important dimensions along the aortic arch are depicted in Figures 2A and B.

CFD Model

Solid models were imported into the finite volume-based CFD software Star-CCM+ (CD-Adapco, Melville, NY). A high-quality mesh was obtained for all models, providing grid-independence and adequate capture of the boundary layer and detailed flow features [13, 14]. Figure 2C shows overall element distribution and mesh detail.

Blood was modeled as an incompressible Newtonian fluid with density of $\rho = 1{,}060$ kg/m^3 and viscosity of $\mu =$

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