Evaluation with Cardiovascular MR Imaging of Baffles and Conduits Used in Palliation or Repair of Congenital Heart Disease

Jimmy C. Lu, MD • Adam L. Dorfman, MD • Anil K. Attili, MD • Maryam Ghadimi Mahani, MD • Jonathan R. Dillman, MD • Prachi P. Agarwal, MBBS

A wide array of baffles and conduits are used in repair or palliation of congenital heart disease, which is the most common major birth defect, often with complex redirection of blood flow to achieve a more stable physiology. Cardiovascular magnetic resonance (CMR) imaging is an increasingly used modality for noninvasive assessment of anatomy and physiology both before and after surgical intervention, with highly reproducible measurements of ventricular size and function, quantification of valvular insufficiency and flow volumes, and excellent delineation of intracardiac and extracardiac anatomy. The authors review the indications, appearances on CMR images, and potential complications of various cardiovascular baffles and conduits: Mustard and Senning procedures, venoatrial baffles, intraventricular baffles, ventriculoarterial conduits, and baffles and conduits used in functional single-ventricle palliation. CMR imaging offers the most complete evaluation of single-ventricle anatomy and physiology, demonstrating the anatomy of venous pathways and pulmonary arteries and quantifying systemic ventricular size and systolic function, differential pulmonary blood flow, ratio of pulmonary to systemic blood flow, and aortopulmonary collateral flow. Anatomic and physiologic considerations are discussed, and suggested CMR imaging protocols and practical advice for performing and interpreting CMR studies are provided. The diversity and complexity of baffles and conduits complicates performance and interpretation of studies in this population, but a fundamental understanding of the goals of the procedure, postoperative physiology, and potential complications allows targeted imaging and precise reporting of clinically significant findings. Supplemental material available at http://radiographics.rsna.org/lookup/suppl/doi:10.1148/rg.323115096/-/DC1.

©RSNA, 2012 • radiographics.rsna.org

TEACHING POINTS

See last page

Abbreviations: CCTGA = congenitally corrected transposition of the great arteries, CMR = cardiovascular magnetic resonance, D-TGA = (S,D,D) transposition of the great arteries, IVC = inferior vena cava, IV = left ventricle, RV = right ventricle, SSFP = steady-state free precession, SVC = superior vena cava, VSD = ventricular septal defect

RadioGraphics 2012; 32:E107–E127 • Published online 10.1148/rg.323115096 • Content Codes: CA MR PD

1From the Department of Pediatrics and Communicable Diseases, Division of Pediatric Cardiology (J.C.L., A.L.D.), and Department of Radiology (J.C.L., A.L.D., M.G.M., J.R.D., P.P.A.), University of Michigan Congenital Heart Center, C.S. Mott Children’s Hospital, 1540 E Hospital Dr, Ann Arbor, MI 48109-4204; and Department of Radiology and Cardiology, University of Kentucky, Lexington, Ky (A.K.A.). Recipient of a Certificate of Merit award for an education exhibit at the 2010 RSNA Annual Meeting. Received April 19, 2011; revision requested July 12 and received August 15; accepted August 19. All authors have no financial relationships to disclose. Address correspondence to J.C.L. (e-mail: jimmyl@umich.edu).

©RSNA, 2012
Introduction

Congenital heart disease is the most common major birth defect, with increasing prevalence related at least in part to improved surgical outcomes (1,2). Many forms of congenital heart disease require surgical palliation or repair, often with complex redirection of blood flow to achieve a more stable physiology. Cardiovascular magnetic resonance (CMR) imaging is an important imaging modality for serial evaluation of these patients, with unrestricted access to cardiovascular anatomy and accurate and reproducible measurements of ventricular function and blood flow; however, it requires a fundamental understanding of the physiology and surgical options for precise evaluation. This article presents a discussion of anatomic and physiologic considerations in performing and interpreting CMR studies in this highly heterogeneous population. Specifically, the various types of baffles and conduits are described, with a practical and targeted approach to performance and interpretation of CMR studies after various interventions. In any evaluation of complex congenital heart disease, obtaining the original operative notes is important when interpreting the imaging data, as significant variation can result from different surgical techniques, anatomic variants, intraoperative complications, and multiple interventions. Typical features of relevant surgical procedures will be discussed, but a detailed discussion of surgical procedures is outside the scope of this article. The reader is referred to the excellent text by Kirklin and Barratt-Boyes, which illustrates the surgical techniques with step-by-step diagrams (3).

Baffles versus Conduits

Baffles and conduits are used to redirect blood flow in repair or palliation of congenital heart disease. A baffle is typically an intracardiac pathway that uses endogenous tissue and thus has some potential for growth (4), although additional material (either synthetic or fashioned from autologous pericardium) may also be used. For example, a lateral tunnel Fontan procedure (connection of the inferior vena cava [IVC] and hepatic veins to the pulmonary arteries, discussed in more detail later in this article) uses the endogenous right atrial wall and artificial material, typically a polytetrafluoroethylene-based fabric such as Goretex, to form a pathway from the IVC and hepatic veins to the branch pulmonary arteries (Fig 1a).

A conduit is typically an extracardiac pathway and thus does not use endogenous tissue (4). For example, an extracardiac Fontan procedure uses a tube-graft of artificial material (commonly Goretx) to redirect systemic venous flow from the IVC and hepatic veins to the branch pulmonary arteries (Fig 1b). Because conduits do not involve endogenous tissue, there is limited capacity for growth and they may require future revision, owing to somatic growth. The spectrum of commonly used baffles and conduits and their common clinical indications are provided in Table 1.

Imaging Modalities for Evaluation of Baffles and Conduits

Although transthoracic echocardiography remains the workhorse for serial evaluation of congenital heart disease, image quality is dependent on acoustic windows, with particular difficulty in evaluating extracardiac anatomy (5,6). These limitations are exacerbated in adult survivors of complex congenital heart disease, in whom baffles (particularly atrial baffles) are posterior, and conduits may pass behind the sternum or near the lungs. Furthermore, evaluation of the size of the RV and its systolic function is limited because of its complex shape, which becomes an important limitation in this population, in whom the RV may be the systemic ventricle. Although three-dimensional echocardiography offers promise in evaluation of the RV (7), it is still limited by acoustic windows.

Cardiac catheterization can provide excellent visualization of the lumen of baffles and conduits and allows measurement of pressure gradients and potential intervention, but it is invasive and requires ionizing radiation. Similarly, computed tomography offers excellent visualization with high spatial resolution and isotropic reformatted images in any plane, but it also requires ionizing radiation. Given the need for serial evaluation, the long-term effects of ionizing radiation should be considered (8), although these modalities can be particularly useful in patients with pacemakers or implanted cardiac defibrillators, as CMR imaging is often contraindicated.
Figure 1. Illustrations of the lateral-tunnel (a) and extracardiac conduit (b) variations of the Fontan procedure. Both examples are depictions of the anatomy after a bidirectional Glenn anastomosis.

Table 1
Summary of Baffles and Conduits Used in Repair and Palliation of Congenital Heart Disease

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Purpose</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baffles</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intraatrial (Mustard,</td>
<td>Physiologic correction of D-TGA, or combined with arterial switch</td>
<td>Redirection of SVC and IVC blood flow to the LV and pulmonary venous flow to the RV</td>
</tr>
<tr>
<td>Senning)</td>
<td>procedure or Rastelli procedure for anatomic repair of CCTGA</td>
<td></td>
</tr>
<tr>
<td>Venoatrial</td>
<td>Partial anomalous pulmonary venous connection to the SVC or right</td>
<td>Redirection of pulmonary venous blood flow across an atrial septal defect to the left atrium</td>
</tr>
<tr>
<td></td>
<td>atrium</td>
<td></td>
</tr>
<tr>
<td>Intraventricular (Rastelli</td>
<td>To connect the LV to a great artery at least partially related to the</td>
<td>Baffle directs blood flow from the LV through the VSD to a great artery (aorta or neoaorta)</td>
</tr>
<tr>
<td>procedure, if combined</td>
<td>RV (because of absent or inadequate LV outflow tract)</td>
<td></td>
</tr>
<tr>
<td>with RV–pulmonary</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemi-Fontan</td>
<td>Stage II of functional single-ventricle palliation (before Fontan</td>
<td>Intraatrial baffle directing SVC blood flow to the pulmonary arteries</td>
</tr>
<tr>
<td></td>
<td>procedure)</td>
<td></td>
</tr>
<tr>
<td>Lateral-tunnel Fontan</td>
<td>Stage III of single-ventricle palliation, separating pulmonary and</td>
<td>Intraatrial baffle directing IVC and hepatic venous blood flow to the pulmonary arteries</td>
</tr>
<tr>
<td></td>
<td>systemic flow</td>
<td></td>
</tr>
<tr>
<td><strong>Conduits</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventriculocartilal</td>
<td>To connect a ventricle to the pulmonary arteries (because of absent</td>
<td>Conduit (with or without a valve) from a ventricle (usually the RV) to the pulmonary arteries</td>
</tr>
<tr>
<td></td>
<td>or inadequate pulmonary valve)</td>
<td></td>
</tr>
<tr>
<td>Extracardiac Fontan</td>
<td>Stage III of single-ventricle palliation, separating pulmonary and</td>
<td>Conduit from the IVC and hepatic veins to the pulmonary arteries</td>
</tr>
<tr>
<td></td>
<td>systemic flow</td>
<td></td>
</tr>
</tbody>
</table>

Note.— CCTGA = congenitally corrected transposition of the great arteries, D-TGA = {S,D,D} transposition of the great arteries, LV = left ventricle, RV = right ventricle, SVC = superior vena cava, VSD = ventricular septal defect.
CMR imaging offers important advantages over other modalities, with highly reproducible measurement of ventricular size and function (9), quantification of valvular insufficiency, and excellent delineation of intracardiac and extracardiac anatomy. However, CMR imaging may require sedation and, in a minority of patients, can be limited by susceptibility artifacts from coils, stents, and other postoperative hardware, with a contraindication in patients with pacemakers or implanted cardiac defibrillators.

**CMR Imaging Assessment of Baffles and Conduits**

Although the CMR imaging protocol varies by indication and institutional preference, our general approach uses the techniques described herein. Specific features of the various baffles and conduits and choices of techniques and imaging planes will be presented later in this review.

**Cine Two-dimensional Steady-State Free Precession (SSFP) Imaging**

We obtain an image stack in the short-axis plane of the ventricles for assessment of ventricular function. We also obtain images in other standard cardiac planes (four-chamber, two-chamber of the RV and LV) and targeted imaging planes through the baffles and conduits, as needed. Additional cine imaging in the axial or coronal planes or both, particularly in cases of complex congenital heart disease, may be helpful in detailed morphologic assessment. An axial image stack can also be used for quantification of RV function, which has been shown by some authors to be associated with lower inter- and intraobserver variability than short-axis imaging (10).

**Turbo Spin-Echo Black Blood Imaging**

Turbo spin-echo black blood imaging (T1- or proton-density–weighted) is performed as needed, particularly to avoid potential susceptibility artifact (11) due to adjacent surgical clips or stents or for the increased spatial resolution needed for evaluation of pulmonary venous or coronary artery anatomy.

**Contrast-enhanced MR Angiography**

Contrast-enhanced MR angiography is most useful for extracardiac vascular anatomy (as this sequence is not gated to the cardiac cycle). It can be performed in two or more time-resolved phases after contrast agent administration to highlight different portions of the vascular anatomy.

**Three-dimensional SSFP**

Three-dimensional SSFP is an isotropic pulse sequence that can be reformatted in any desired plane, which can be particularly useful for intracardiac pathways. It does not require administration of intravenous contrast agents (12). This imaging technique is gated to the cardiac cycle and can be obtained either in a single phase (usually end-diastole) or in two cardiac phases (end-systole and end-diastole) (13). It uses a navigator to monitor diaphragmatic motion and to correct for respiratory motion.

**Phase-Contrast Imaging**

Flow quantification with phase-contrast imaging is typically performed in the main pulmonary artery and ascending aorta to help exclude residual shunts (14) and to quantify regurgitation. The utility of additional flow measurements will be described later in this review.

**Late Gadolinium Enhancement Imaging**

Late gadolinium enhancement of myocardium may occur in a subendocardial or transmural pattern, representing infarction (Fig 2, Movie 1), but may also be seen in nonischemic patterns, representing fibrosis, which in multiple populations
with congenital heart disease has been shown to correlate with clinical markers of poor prognosis (15–17). This pulse sequence can be used as needed on an individual basis.

**Baffles**

Baffles include intraatrial (ie, the atrial switch procedure), venoatrial (directing anomalous pulmonary venous connections to the left atrium), and intraventricular baffles (directing flow from the LV through a VSD to the aorta). Fontan palliation can be achieved by using both baffles and conduits and will be discussed at the end of this article.

**Atrial Switch Procedure (Intraatrial Baffle)**

**Indications.**—The commonly used acronym D-TGA is more properly described as \{S,D,D\} - TGA (18). S refers to atrial situs solitus, with the morphologic right atrium on the right; the first D refers to D-looping of the ventricles, with the morphologic RV on the right; and the second D refers to an anterior and rightward aortic valve, which thus arises from the RV, with the pulmonary valve arising from the LV. With atrioventricular concordance and ventriculoarterial discordance, the hemodynamic result is two parallel circulations rather than circulation in series (Fig 3a). Although the current standard of care is the arterial switch operation during the neonatal period (transecting the aorta and main pulmonary artery, transferring the great arteries to correct the ventriculoarterial discordance, and transferring coronary arteries to the neoaortic root), the predominant approach until the 1980s was an atrial switch procedure. Surgical techniques for this procedure vary, using either native atrial septum (Senning procedure) or pericardial tissue (Mustard procedure) (3), the common result being a baffle that repartitions the atria, with systemic venous flow (SVC and IVC) on one side of the baffle directed to the mitral valve and pulmonary venous flow on the other side of the baffle directed to the mitral valve (Fig 4). Consequently, after an atrial switch procedure (Mustard or Senning procedures), patients have both atrioventricular and ventriculoarterial discordance, resulting in physiologic (but not anatomic) repair, leaving the RV in a systemic position (19) (Fig 3b).
Although the atrial switch procedure is not favored for D-TGA, it is still currently used in combination with an arterial switch procedure (a “double switch”) or Rastelli procedure (described later) for anatomic CCTGA, also commonly called L-TGA or \{S,L,L\}-TGA, with the morphologic RV on the left, giving rise to an anterior and leftward aortic valve (20). In CCTGA, with both atrioventricular and ventriculoarterial discordance (physiologically equivalent to D-TGA after an atrial switch [Fig 3b]), there may be no hemodynamic shunt, but the systemic RV can progressively dilate and fail, with significant tricuspid regurgitation (21). Intervention at both the atrial and arterial levels corrects the anatomic connections, leading to a systemic morphologic LV. Although patient selection is somewhat controversial, this procedure has become the approach of choice at some centers (22).

**Potential Complications.**—Because of the increased demands of systemic afterload and mismatch of coronary flow to demand (23,24), RV dysfunction is common. This can be exacerbated by tricuspid regurgitation, which may result from altered geometry of the septal leaflet and the tricuspid annulus, with systemic RV pressure (21,25). Baffle stenosis is more common in the systemic venous circulation than in the pulmonary venous circulation and typically involves the SVC pathway (26) (Fig 5a). Baffle leak may be present in approximately 20% of patients after the

---

**Figure 4.** (a) Illustration of the atrial switch procedure, in which the SVC and IVC are baffled to the LV, and the pulmonary veins (PV) are baffled to the RV. (b–d) Axial (b) and coronal oblique (c, d) SSFP images show the pulmonary venous (b), SVC (c), and IVC (d) pathways.
atrial switch procedure (27), although typically the leak is hemodynamically insignificant and only a small percentage of cases require intervention, either surgically or by catheterization.

Atrial arrhythmias (such as atrial fibrillation or flutter) are common in this population and can complicate vectorcardiographic gating, as only 40% of these patients are in sinus rhythm 20 years after the atrial switch procedure (28).

**Table 2**

<table>
<thead>
<tr>
<th>Suggested Protocol</th>
<th>Imaging Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cine SSFP imaging</strong></td>
<td></td>
</tr>
<tr>
<td>Axial stack</td>
<td>Anatomy, pulmonary venous pathway</td>
</tr>
<tr>
<td>SVC pathway (coronal oblique view through the SVC and mitral valve, or defined by three points: SVC, narrowest point of the pathway, and mitral valve)</td>
<td>SVC pathway stenosis</td>
</tr>
<tr>
<td>IVC pathway (coronal oblique view through the IVC and mitral valve)</td>
<td>IVC pathway stenosis</td>
</tr>
<tr>
<td>Short axis of the ventricles</td>
<td>RV size and systolic function</td>
</tr>
<tr>
<td><strong>Three-dimensional SSFP imaging</strong></td>
<td>Multiplanar reformations of venous pathways</td>
</tr>
<tr>
<td><strong>Phase-contrast imaging</strong></td>
<td></td>
</tr>
<tr>
<td>Ascending aorta and main pulmonary artery</td>
<td>Baffle leak</td>
</tr>
<tr>
<td>Tricuspid valve</td>
<td>Quantification of tricuspid regurgitation</td>
</tr>
<tr>
<td>Azygos vein (if SVC pathway stenosis)</td>
<td>Determine direction of flow</td>
</tr>
<tr>
<td>Axial through the atrial baffle, with in-plane velocity encoding (optional)</td>
<td>Qualitative evaluation of baffle leak</td>
</tr>
<tr>
<td>Late gadolinium enhancement imaging (optional)</td>
<td></td>
</tr>
</tbody>
</table>

**CMR Imaging Appearance and Imaging Considerations.**—Imaging goals and a suggested CMR imaging protocol are presented in Table 2, with particular attention to the presence or absence of the potential complications discussed previously.
Mesocardia in a 17-year-old girl with an interrupted IVC and azygous continuation to the left SVC and essentially a common atrium, status post Mustard-type baffle of the systemic veins to the mitral valve and repair of the mitral valve cleft. Axial proton density–weighted turbo spin-echo images demonstrate intact systemic venous (SV) and pulmonary venous (PV) pathways superiorly (a), whereas more inferiorly (b) a large baffle defect (*) is seen between the systemic and pulmonary venous pathways.

The Mustard and Senning procedures result in a complicated three-dimensional geometry of the venous pathways (Fig 4a). The pulmonary venous pathway is in the axial plane (Fig 4b), diverting pulmonary venous flow rightward and anterior to the tricuspid valve. The SVC and IVC pathways are in a coronal oblique plane and can be pictured as the legs of a pair of pants, with the “waist” at the mitral valve (Fig 4c, 4d). Oblique coronal cine SSFP imaging of the systemic venous baffles can demonstrate anatomic narrowing and a dephasing jet, indicating turbulent flow due to stenosis. With more severe SVC pathway stenosis, there may be upstream dilatation (Fig 5b) and reversal of blood flow in the azygos vein (26); blood flow direction can be determined by using phase-contrast imaging.

Baffle leak may be difficult to visualize with cine SSFP imaging (Movie 2a); axial phase-contrast imaging through the atrial baffle, with in-plane velocity encoding (Movie 2b), may help identify the leak in these cases. The location and direction of flow from the baffle leak and an estimated ratio of pulmonary to systemic flow (Qp:Qs) can be helpful in determining the need for and type of intervention. Pulmonary and systemic flow can be estimated with phase-contrast volume measurements in the main pulmonary artery and ascending aorta, respectively; these measurements can often be performed in the same plane, as the aorta and main pulmonary artery course in parallel. An extreme example of a baffle defect is shown in Figure 6 and Movie 3.

RV volumes and ejection fraction can be calculated from axial or short-axis cine SSFP images, depending on user preference. Tricuspid regurgitation is difficult to measure directly with phase-contrast imaging through atrioventricular valves because of considerable through-plane annular motion, but it can be quantified by comparison of RV stroke volume to total aortic forward flow or tricuspid diastolic inflow to aortic stroke volume (29).

Venoatrial Baffle

Indications.—With anomalous pulmonary venous connections, one or more pulmonary veins connect ultimately to the right atrium and need to be redirected to the left atrium. In total anomalous pulmonary venous connections, if all pulmonary veins connect to a confluence posterior to the left atrium before draining into the systemic venous system, incisions can be made both in the confluence and the adjacent posterior wall of the left atrium, with a side-to-side anastomosis and ligation of the vertical vein that connects to the systemic venous system (for supracardiac and infracardiac types of anomalies) (3). If the pulmonary veins connect to a dilated coronary sinus, the wall between the coronary sinus and left atrium can be excised and the coronary sinus ostium closed (3); however, with partial anomalous pulmonary
venous connections to the SVC or right atrium, a baffle can be used to redirect pulmonary blood flow to the left atrium. In this case, the surgeon uses a patch to separate the pulmonary veins from the right atrium or SVC, redirecting the flow across an atrial septal defect (either preexisting or created by the surgeon) to the left atrium (Fig 7). With anomalous connections to the proximal SVC, the baffle may partially occlude the SVC, in which case the SVC may be enlarged with a patch, or the SVC can be ligated superior to the pulmonary veins and reconnected to the right atrium (known as the Warden procedure).

**Potential Complications.**—Obstruction can occur in the pulmonary venous baffle or in the SVC. Patients can also have a residual left-to-right shunt due to baffle leak or to residual anomalous pulmonary venous connections or both. In some cases, an accessory pulmonary vein may enter into the SVC superiorly and may not be amenable to a baffle. Typically, one anomalous pulmonary vein will not cause a hemodynamically significant shunt, and so the surgeon may leave this vein draining into the right heart.

**CMR Appearance and Imaging Considerations.**—Because of the degree of variability in anomalous pulmonary venous connections and the potential location of the baffle, every attempt should be made to obtain the original operative notes before the study is performed and interpreted. Goals of CMR imaging include characterization of pulmonary venous anatomy, evaluation of systemic venous anatomy (if affected by the pulmonary venous baffle), and assessment of ventricular function. A suggested CMR imaging protocol is presented in Table 3. Any narrowing of the pulmonary venous baffle should be described, and differential

---

**Table 3**

**Suggested CMR Protocol and Imaging Goals for Venoatrial Baffles**

<table>
<thead>
<tr>
<th>Suggested Protocol</th>
<th>Imaging Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cine SSFP imaging</td>
<td>Anatomy, baffle, all pulmonary veins</td>
</tr>
<tr>
<td>Axial stack</td>
<td>SVC stenosis</td>
</tr>
<tr>
<td>Sagittal/coronal oblique through the SVC (if anomalous veins to the SVC)</td>
<td></td>
</tr>
<tr>
<td>Short axis of the ventricles</td>
<td>RV size and systolic function</td>
</tr>
<tr>
<td>Turbo spin echo: axial or coronal (optional)</td>
<td>Characterization of individual veins</td>
</tr>
<tr>
<td>Contrast-enhanced MR angiography timed for contrast material in the pulmonary veins</td>
<td>Individual pulmonary veins, stenosis of the veins or pathway</td>
</tr>
<tr>
<td>Phase-contrast imaging</td>
<td>Calculation of Qp:Qs</td>
</tr>
<tr>
<td>Ascending aorta and main pulmonary artery</td>
<td>Differential pulmonary blood flow</td>
</tr>
<tr>
<td>Left and right pulmonary arteries</td>
<td>Determination of direction of flow</td>
</tr>
<tr>
<td>Azygos vein</td>
<td></td>
</tr>
<tr>
<td>Late gadolinium enhancement imaging (optional)</td>
<td></td>
</tr>
</tbody>
</table>

---

*Figure 7.* Axial oblique two-dimensional SSFP image in a 20-year-old woman with partial anomalous pulmonary venous connections (right pulmonary veins to the right atrium) and an intact atrial septum, status post repair. The right pulmonary veins were baffled through a surgically created atrial septal defect to the left atrium (LA).
Intraventricular Baffle

**Indications.**—Intraventricular baffles are currently used in many forms of congenital heart disease amenable to biventricular repair, in which the aortic or neoaortic valve arises from the RV (eg, forms of double-outlet RV or interrupted aortic arch with hypoplastic aortic valve). With an inadequate or absent LV outflow, the native VSD becomes the origin of the LV outflow tract and a patch is placed to direct systemic blood flow to the aortic or neoaortic valve, separating the newly created LV outflow tract from the RV (Fig 8a, 8b). If no other outflow remains for the RV, a conduit is

pulmonary blood flow can be measured from branch pulmonary artery flows (31). If the surgical repair involved the SVC, the SVC should also be carefully evaluated. With significant SVC narrowing, phase-contrast imaging can demonstrate whether a dilated azygos vein drains inferior to the IVC system. Evaluation of left-to-right shunting can be done by calculating the Qp:Qs from the main pulmonary artery and ascending aortic blood flows; a ratio greater than 1.5:1 or RV dilatation would be a concern for a hemodynamically significant residual left-to-right shunt (32).

**Figure 8.** Illustrations of repair of D-TGA with VSD and pulmonary stenosis. Owing to pulmonary or subpulmonary stenosis (a), the arterial switch operation may not be feasible. The LV is baffled to the aortic valve (b), with placement of an RV-to–pulmonary artery conduit (c). Ao = aorta.

**Figure 9.** D-TGA with VSD and pulmonary stenosis in a 17-month-old boy, status post Rastelli procedure and subsequent resection of subaortic stenosis and conduit replacement. Volume-rendered image from contrast material–enhanced MR angiography demonstrates a large pseudoaneurysm (arrow). The conduit has been removed from this image to better demonstrate the LV outflow tract and pseudoaneurysm. Ao = aorta.
placed from the RV to the pulmonary artery (Fig 8c). The combination of an intraventricular baffle and an RV-to–pulmonary artery conduit is called the Rastelli procedure and was initially described for patients with D-TGA, VSD, and pulmonary stenosis (3,33).

**Potential Complications.**—The pathway from the LV to the ascending aorta can become obstructed, particularly at the site of the native VSD. Baffle leak can sometimes be seen on cine SSFP images or may be suggested by greater pulmonary artery than aortic stroke volume. A less common but potentially worrisome development is a pseudoaneurysm of the LV outflow tract (Fig 9). This is clinically significant, as surgical intervention may be required because of potential for thrombus formation or rupture. If an RV-to–pulmonary artery conduit is also present (Rastelli procedure), additional concerns related to the conduit and the effect on the RV should also be evaluated (discussed in a later section).

**CMR Imaging Appearance and Imaging Considerations.**—The appearance of intraventricular baffles on CMR images is variable, depending on the relative positions of the VSD, tricuspid valve, and aortic (or neoaortic) valve and on other necessary surgical interventions (eg, repair of an atrioventricular septal defect). In double-outlet RV with a subaortic VSD, the anatomy may appear nearly normal, similar to that after VSD closure (although the aortic valve will be superior to the native RV, usually with subaortic conus). However, a tortuous baffle may be necessary, depending on individual anatomy (Movie 4). The intraventricular tunnel should be visualized in two planes (typically sagittal oblique and coronal oblique) to determine the location and severity of the obstruction. A suggested protocol is given in Table 4.

Conventionally, outflow tracts are included in the ventricular volumes; however, it should be noted that inclusion of the baffle with LV volumes will decrease the overall ejection fraction of the LV, as the intraventricular tunnel is typically noncontractile. Reports should thus specify whether the baffle is included in the ventricular volumes.

**Conduits**

Conduits primarily include ventriculoarterial conduits and conduits used for extracardiac Fontan repair. Rare variations include apicoaortic conduits (from the LV apex to the descending aorta in cases of severe LV outflow tract obstruction not amenable to other interventions) (34), and aortoaoartic conduits (from the ascending aorta to the descending aorta in cases of complex aortic arch obstruction) (35).

**Ventriculoarterial Conduits**

**Indications.**—Ventriculoarterial conduits are used to establish continuity between a ventricle and the pulmonary arteries in cases of atresia or absence of a pulmonary valve (eg, tetralogy of Fallot with pulmonary atresia or truncus arteriosus) or RV outflow tract obstruction in which coronary artery anatomy prevents a transannular patch (eg, tetralogy of Fallot), or they are used in

---

**Table 4**

**Suggested CMR Protocol and Imaging Goals for Intraventricular Baffles**

<table>
<thead>
<tr>
<th>Suggested Protocol</th>
<th>Imaging Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cine SSFP imaging</td>
<td></td>
</tr>
<tr>
<td>Axial stack</td>
<td>Anatomy, associated lesions</td>
</tr>
<tr>
<td>LV outflow tract in two planes</td>
<td>Geometry and location of stenosis (if any) of</td>
</tr>
<tr>
<td>(sagittal and coronal oblique)</td>
<td>the intraventricular pathway</td>
</tr>
<tr>
<td>Short axis of the ventricles</td>
<td>Ventricular size and systolic function</td>
</tr>
<tr>
<td>Three-dimensional SSFP imaging</td>
<td>Multiplanar reformation of the pathway</td>
</tr>
<tr>
<td>Phase-contrast imaging</td>
<td></td>
</tr>
<tr>
<td>Ascending aorta and main pulmonary</td>
<td>Baffle leak</td>
</tr>
<tr>
<td>artery</td>
<td></td>
</tr>
<tr>
<td>Additional imaging if there are</td>
<td></td>
</tr>
<tr>
<td>associated lesions or interventions</td>
<td></td>
</tr>
<tr>
<td>(eg, RV-to–pulmonary artery conduit)</td>
<td></td>
</tr>
</tbody>
</table>
combination with surgical approaches that incorporate the native pulmonary valve into a neoaortic root (eg, with a hypoplastic native aortic valve) or translocate the pulmonary valve into the aortic position (referred to as the Ross procedure). A ventriculotomy is performed, and the conduit is anastomosed to the incision proximally, with an end-to-end anastomosis to the pulmonary arteries distally (3). Such a conduit can also be used in conjunction with a modified Norwood procedure during the neonatal period (also known as the Sano modification) for first-stage palliation with a functional single ventricle (36) (further described later) or as part of the Rastelli procedure (33) (described previously).

Most commonly, these conduits arise from the RV, although LV-to–pulmonary artery conduits have been used in physiologic correction of CCTGA with VSD and pulmonary stenosis or atresia. Closure of the VSD and creation of an LV-to–pulmonary artery conduit leads to a physiologic biventricular repair and leaves the RV as the systemic ventricle.

**Potential Complications.**—Conduits have limited long-term durability and are prone to stenosis and regurgitation. The level of stenosis may be proximal, at the level of the valve, or at the distal anastomosis; the latter is particularly true if the branch pulmonary arteries are hypoplastic. The hemodynamic result of conduit stenosis is RV pressure overload, with resulting RV hypertrophy and potential systolic and diastolic dysfunction. The hemodynamic result of conduit insufficiency is RV volume overload, with resulting RV dilatation and potential systolic and diastolic dysfunction.

Timing of conduit replacement is controversial, with the majority of available data related to pulmonary valve replacement for insufficiency in patients with repaired tetralogy of Fallot (37–40). Although the optimal timing for replacement is not known, factors such as symptoms, RV end-systolic and end-diastolic volume, RV and LV ejection fractions, or changes in these factors are taken into consideration (41). For conduit stenosis, the decision to intervene depends on exercise tolerance, RV systolic pressure and gradient across the conduit, and RV size and systolic function (42).

Less common complications include pseudoaneurysm formation, typically at the base of the conduit (Fig 10, Movie 5) and with risk of subsequent spontaneous rupture or violation at reoperation, and dissection (Fig 11).
Figure 11. Proton-density–weighted turbo spin-echo (a) and contrast material–enhanced MR angiographic (b) images in an 18-month-old girl with interrupted aortic arch type B, status post Norwood and Rastelli procedures, complicated by dissection (arrow) between an intimal peel and the conduit wall, resulting in severe conduit stenosis. C = conduit.

CMR Imaging Appearance and Imaging Considerations.—The conduit may arise in the orthotopic position (eg, after a Ross procedure) but more commonly arises from the anterior wall of the RV and can be best visualized in a sagittal-oblique plane. The position of the conduit with respect to the sternum should be reported to alert the surgeon before potential intervention, as opening the chest may result in violating the conduit, which can be catastrophic. The position of LV-to-pulmonary artery conduits may be more variable (Fig 12).

Conduit stenosis can be visualized on cine SSFP images, with a dephasing jet at the site of obstruction (Movie 6), or on turbo spin-echo images, which may better delineate the level of obstruction (Fig 13). In the presence of significant stenosis, a high phase-contrast-encoding velocity is necessary to avoid aliasing, which increases potential error in blood flow measurements. Blood flow measurements can be more accurately measured in the outflow tract below the level of stenosis (43). A suggested protocol is provided in Table 5.
For conduit stenosis or insufficiency or both, transcatheter pulmonary valve placement (Melody valve; Medtronic, Minneapolis, Minn) is an option in conduits 16 mm or more in diameter (at time of initial placement) (44). In preparation for such an intervention, the anatomy of the RV outflow tract should be well delineated, with a careful description of the location and severity of obstruction, degree of insufficiency, and relationship of the coronary arteries to the level of obstruction (because of potential compression from the stent). Associated branch pulmonary artery stenoses should also be described, with measurement of differential left and right pulmonary artery flow, to determine the need for other catheter-based interventions, such as balloon angioplasty or stent placement.

**Baffles and Conduits Used in Staged Fontan Palliation**

Patients with a functional single ventricle (such as hypoplastic left heart syndrome, tricuspid atresia, or double-inlet LV) require staged palliation to Fontan physiology, in which systemic venous...
blood flows directly to the pulmonary arteries, bypassing the ventricles. The goals of the initial stage (performed during the neonatal period) are to ensure unobstructed systemic outflow and restrictive but stable pulmonary outflow. This may involve anastomosis of the native pulmonary valve and root to the aortic root (Damus-Kaye-Stansel anastomosis) and aortic arch reconstruction (Norwood procedure), with a modified Blalock-Taussig shunt (from the right innominate artery to the pulmonary arteries) or an RV-to–pulmonary artery conduit (Sano modification) (45). Subsequent stages may use baffles (hemi-Fontan and lateral-tunnel Fontan) or a conduit (extracardiac Fontan). For further reading on stages and variations of the Fontan procedure, the reader may refer to Kirklin and Barratt-Boyes (3).

**Hemi-Fontan Procedure**

**Indications.**—The second stage of Fontan palliation (at 4–6 months of age) involves some form of superior cavopulmonary anastomosis. This may consist of a modified bidirectional Glenn anastomosis, which is a direct end-to-side anastomosis of the SVC to the pulmonary arteries, or a hemi-Fontan procedure, in which the dome of the right atrium is anastomosed to the pulmonary arteries, with a baffle separating the SVC flow from the remainder of the right atrium (Fig 14). The hemi-Fontan simplifies conversion to the lateral-tunnel Fontan, providing the most efficient fluid dynamics relative to other Fontan pathways (46).

CMR imaging offers the most complete non-invasive anatomic and physiologic evaluation of the functional single ventricle during staged conversion to a Fontan circulation, as evaluation of branch pulmonary artery anatomy, extracardiac anatomy such as collaterals, ventricular systolic function, differential pulmonary blood flow, and valvular regurgitation influence the decision to proceed with Fontan palliation. Although CMR imaging cannot measure ventricular end-diastolic pressure or pulmonary artery pressure, studies suggest that CMR imaging evaluation is often adequate for preoperative planning in many patients, with decreased cost and decreased risk of complications (47,48).

**Potential Complications.**—In a patient with a superior cavopulmonary anastomosis and with more than the expected hypoxemia, several potential causes of the hypoxemia should be evaluated. Development of systemic venous collaterals decompressing the high-pressure SVC system to veins draining into the IVC or atrium allows blood to bypass the lungs, leading to a physiologic right-to-left shunt. These patients are also at risk for development of pulmonary arteriovenous malformations, postulated to be the result of an unidentified “hepatic factor” that bypasses the lungs (49). This results in an intrapulmonary right-to-left shunt, which may sometimes resolve after Fontan completion (49).
Another possibility in the hemi-Fontan procedure is a baffle leak; a small baffle leak found at pre-Fontan evaluation, however, may not be important (as the baffle will be taken down for completion to the lateral-tunnel Fontan).

Other important complications that may be detected at CMR imaging include branch pulmonary artery narrowing, valvular regurgitation, aortic arch and great vessel stenosis, hemi-Fontan pathway narrowing, and aortopulmonary collaterals. Close attention should be paid to the pulmonary arteries; because of passive pulmonary blood flow, even seemingly minor pulmonary artery stenosis may be hemodynamically significant.

**CMR Imaging Appearance and Imaging Considerations.**—The overall goal of imaging is to assess cardiovascular anatomy and ventricular and valvular (atrioventricular and neoaortic) function, and to ensure pathway patency and identify postsurgical complications. A suggested protocol is provided in Table 6. In cases in which the initial operation is unclear from available information, a bidirectional Glenn anastomosis can be readily differentiated from a hemi-Fontan connection at imaging because the SVC connects directly to the branch pulmonary arteries in the Glenn procedure, whereas the SVC in a hemi-Fontan procedure connects to the right atrium in the orthotopic position, with an atrial connection to the pulmonary arteries. The field of view for MR angiography should be sufficient to evaluate the lung fields for pulmonary arteriovenous malformations, systemic venous collaterals, and aortopulmonary collaterals. Finally, the original congenital heart anomaly and complications related to its repair should be assessed. For example, the native aortic-to-neoaortic anastomosis (if present) and the aortic arch should be carefully evaluated. Prolonged deceleration in the descending aortic flow pattern at phase-contrast imaging suggests residual arch obstruction.

Much of the complexity in imaging of a patient with a functional single ventricle is interpre-

---

### Table 6

**Suggested CMR Imaging Protocol and Imaging Goals for Bidirectional Glenn, Hemi-Fontan, and Fontan Procedures**

<table>
<thead>
<tr>
<th>Suggested Protocol</th>
<th>Imaging Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cine SSFP imaging</strong></td>
<td>Fontan pathway, associated lesions and interventions</td>
</tr>
<tr>
<td>Axial stack</td>
<td>Fontan pathway and branch pulmonary arteries</td>
</tr>
<tr>
<td>Coronal stack</td>
<td>Ventricular size and systolic function</td>
</tr>
<tr>
<td>Short axis of the ventricle</td>
<td>Essential if there is a coil or stent artifact</td>
</tr>
<tr>
<td><strong>Black blood imaging (optional)</strong></td>
<td>Fontan pathway, pulmonary arteries, aortic arch, collaterals</td>
</tr>
<tr>
<td><strong>Contrast material–enhanced MR angiography</strong></td>
<td>Fontan pathway, pulmonary arteries, aortic arch, collaterals</td>
</tr>
<tr>
<td><strong>Three-dimensional SSFP imaging</strong></td>
<td><strong>Phase-contrast imaging</strong></td>
</tr>
<tr>
<td><strong>Ascending aorta</strong></td>
<td>Total cardiac output</td>
</tr>
<tr>
<td>SVC and IVC</td>
<td>Systemic blood flow (Qs)</td>
</tr>
<tr>
<td>Left and right pulmonary arteries</td>
<td>Differential pulmonary blood flow</td>
</tr>
<tr>
<td>Left and right pulmonary veins (sagittal oblique views)</td>
<td>Pulmonary blood flow (Qp)</td>
</tr>
<tr>
<td>Atrioventricular valve</td>
<td>Atrioventricular valve regurgitation</td>
</tr>
<tr>
<td>Descending aorta, if there is concern for residual arch obstruction</td>
<td>Prolonged deceleration as evidence of obstruction</td>
</tr>
<tr>
<td>Late gadolinium enhancement imaging (optional)</td>
<td></td>
</tr>
</tbody>
</table>
Figure 15. Three-dimensional reconstruction from contrast material–enhanced MR angiography demonstrates a large venovenous collateral (*) draining into a left pulmonary vein (PV) in a patient status post Fontan procedure.

Prior to completion of the Fontan procedure, measurement of the flow data. If not appreciated at cine SSFP imaging, a baffle leak can be suggested by a discrepancy in flow data (SVC flow greater than flow in the branch pulmonary arteries or ascending aortic flow greater than IVC and pulmonary venous flows). Owing to the common occurrence of aortopulmonary collaterals, flow in the ascending aorta may overestimate systemic cardiac output; total flow in the SVC and IVC is a more reliable measure of systemic flow, although the plane for measurement of IVC flow must be selected carefully to ensure that all hepatic veins are included in the caval flow. Similarly, flow in the left and right pulmonary arteries does not include the aortopulmonary collaterals, and thus total flow in the left and right pulmonary veins is a more reliable measure of pulmonary flow when calculating Qp:Qs ratios (50,51).

Fontan Procedure: Variants of Total Cavopulmonary Connection

Indications.—The completion of functional single-ventricle palliation to total cavopulmonary connection is done typically between 18 months and 4 years of age, and allows higher oxygen saturation (by directing deoxygenated blood from the IVC and hepatic veins to the pulmonary arteries instead of the systemic ventricle) and prevents formation of pulmonary arteriovenous malformations (49). Many variations of the Fontan procedure have been developed (52) (their extent being beyond the scope of this article), but two major variations are currently in use. A lateral-tunnel Fontan (Fig 1a, Movie 7) consists of a baffle in the right atrium that diverts blood flow from the IVC and hepatic veins to the pulmonary arteries; it can be placed after either the bidirectional Glenn or hemi-Fontan procedure. An extracardiac conduit (Fig 1b) consists of a circumferential tube of prosthetic material (commonly GoreTex) that courses lateral to the right atrium, connecting the IVC and hepatic veins to the pulmonary arteries, and is placed after the bidirectional Glenn procedure. Although an extracardiac conduit does not require intervention in the heart and may decrease cardiopulmonary bypass time, there is no potential for growth and there is an increased risk of thrombosis and stenosis (53).

In either procedure, a fenestration can be created between the Fontan pathway and the pulmonary venous atrium (Movie 7), which is a source of right-to-left shunting, but it can improve the early postoperative course by decreasing systemic venous pressure and augmenting cardiac output (54). This fenestration may close spontaneously or may be closed percutaneously with a device in the catheterization laboratory if there is persistent hypoxia.

Potential Complications.—Complications involving the Fontan pathway include narrowing or leak. Anatomic causes of cyanosis after Fontan completion may include a patent fenestration, baffle leak, venovenous collaterals decompressing the systemic veins to the pulmonary veins (Fig 15), or pulmonary arteriovenous malformations. Although sometimes seen after bidirectional the Glenn or hemi-Fontan procedure, the presence of a thrombus is more commonly seen after the Fontan procedure, particularly in
older patients with variations of the atriopulmonary Fontan procedure in whom the atrium can become dilated with slow flow, or in patients with frequent or persistent atrial arrhythmias such as atrial flutter or fibrillation (55). This may be seen at cine SSFP imaging and turbo spin-echo imaging and can be accentuated with a late gadolinium enhancement sequence with a long inversion time (~600 msec) (56).

Other long term risks include protein-losing enteropathy, plastic bronchitis, and heart failure (57).

**CMR Imaging Appearance and Imaging Considerations.**—Similarly to the evaluation after the bidirectional Glenn or hemi-Fontan procedure, branch pulmonary artery anatomy and areas of previous intervention should be carefully evaluated. Any narrowing in the Fontan pathway should be characterized. Axial cine SSFP images (Movie 7) should demonstrate the anatomy, but the Fontan pathway and branch pulmonary arteries should also be evaluated in an orthogonal view (typically the coronal plane). In patients who have undergone coil embolization of collaterals, CMR imaging can be limited by signal void from metal artifacts; in that case, turbo spin-echo imaging may give some anatomic information. A fenestration (Movie 7) or baffle leak after total cavopulmonary connection is typically seen in the axial plane.

Although the imaging protocol for the Fontan procedure is essentially the same as that for a bidirectional Glenn or hemi-Fontan procedure (Table 6), interpretation of flow data differs. Total caval blood flow (SVC + IVC, or SVC + descending aorta) is the most reliable measure of systemic flow and should equal the flow in the branch pulmonary arteries, whereas total...
pulmonary venous flow is the most reliable measure of pulmonary blood flow. Flow across a fenestration or baffle leak can be estimated as the difference between total caval (SVC + IVC) flow and pulmonary arterial flow. The total flow in the left and right pulmonary veins is the most reliable measure of pulmonary blood flow, and flow from aortopulmonary collaterals can be estimated as either the difference between pulmonary venous flow and pulmonary arterial flow or the difference between ascending aortic flow and caval flow (ie, total cardiac output minus systemic flow), in the absence of significant venovenous collaterals (50,51). The location of phase-contrast flow measurements is demonstrated in Figure 16.

Summary

CMR imaging is an indispensable imaging modality for evaluation of baffles and conduits used in repair or palliation of complex congenital heart disease, providing a noninvasive assessment of anatomy, function, and flow without the use of ionizing radiation. However, the diversity and complexity of baffles and conduits complicates performance and interpretation of studies in this population. A fundamental understanding of the goals of the procedure, postoperative physiology, and potential complications is necessary for targeted imaging and precise reporting of clinically significant findings. Communication with the referring physician is essential to ensure that the clinical questions are answered and that findings of concern are identified and clearly reported.

References


Evaluation with Cardiovascular MR Imaging of Baffles and Conduits Used in Palliation or Repair of Congenital Heart Disease

Jimmy C. Lu, MD • Adam L. Dorfman, MD • Anil K. Attili, MD • Maryam Ghadimi Mahani, MD • Jonathan R. Dillman, MD • Prachi P. Agarwal, MBBS

RadioGraphics 2012; 32:E107–E127 • Published online 10.1148/rg.323115096 • Content Codes: CA MR PD

Page E110
CMR imaging offers important advantages over other modalities, with highly reproducible measurement of ventricular size and function (9), quantification of valvular insufficiency, and excellent delineation of intracardiac and extracardiac anatomy. However, CMR imaging may require sedation and, in a minority of patients, can be limited by susceptibility artifacts from coils, stents, and other postoperative hardware, with a contraindication in patients with pacemakers or implanted cardiac defibrillators.

Page E114 (Figure 4 on page E112. Figure 5 on page E113.)
The Mustard and Senning procedures result in a complicated three-dimensional geometry of the venous pathways (Fig 4a). The pulmonary venous pathway is in the axial plane (Fig 4b), diverting pulmonary venous flow rightward and anterior to the tricuspid valve. The SVC and IVC pathways are in a coronal oblique plane and can be pictured as the legs of a pair of pants, with the “waist” at the mitral valve (Fig 4c, 4d). Oblique coronal cine SSFP imaging of the systemic venous baffles can demonstrate anatomic narrowing and a dephasing jet, indicating turbulent flow due to stenosis. With more severe SVC pathway stenosis, there may be upstream dilatation (Fig 5b) and reversal of blood flow in the azygos vein (26); blood flow direction can be determined by using phase-contrast imaging.

Page E118
The hemodynamic result of conduit stenosis is RV pressure overload, with resulting RV hypertrophy and potential systolic and diastolic dysfunction. The hemodynamic result of conduit insufficiency is RV volume overload, with resulting RV dilatation and potential systolic and diastolic dysfunction.

Page E122
In cases in which the initial operation is unclear from available information, a bidirectional Glenn anastomosis can be readily differentiated from a hemi-Fontan connection at imaging because the SVC connects directly to the branch pulmonary arteries in the Glenn procedure, whereas the SVC in a hemi-Fontan procedure connects to the right atrium in the orthotopic position, with an atrial connection to the pulmonary arteries.

Page E125
Flow across a fenestration or baffle leak can be estimated as the difference between total caval (SVC + IVC) flow and pulmonary arterial flow. The total flow in the left and right pulmonary veins is the most reliable measure of pulmonary blood flow, and flow from aortopulmonary collaterals can be estimated as either the difference between pulmonary venous flow and pulmonary arterial flow or the difference between ascending aortic flow and caval flow (ie, total cardiac output minus systemic flow), in the absence of significant venovenous collaterals (50,51).