During the past 20 years, the intracardiac lateral tunnel (LT) method has been one of the most widely used variants of the Fontan operation for functionally univentricular heart disease. In the LT operation, one wall of the tunnel is native right atrium (RA), whereas the remainder of the circumference is composed of a baffle that is sewn within the atrium. Theoretically, the inclusion of native RA tissue permits the tunnel to grow with the patient, a factor that is invoked as one of the rationales for performing the LT procedure rather than Fontan modifications that use circumferential synthetic conduits.

There is debate about the relative benefits and drawbacks of the LT Fontan compared with an extracardiac conduit Fontan procedure, a method in which the inferior vena cava to pulmonary artery connection is constructed from a circumferential tube. Unlike the LT, extracardiac conduit Fontan connections do not have growth potential (with the exception of those constructed from pedicled pericardium). When an extracardiac conduit Fontan is performed, the operation is frequently delayed until an older age than is typical for the LT Fontan so that the patient can grow to accommodate a graft large enough to serve an adult.

Although the LT operation has been one of the factors that has contributed to improved outcomes among patients undergoing a Fontan procedure, it can be associated with various morbidities, including obstruction within the LT. Little has been written about causes of, risk factors for, and outcomes in patients with LT stenosis. LT stenosis may be attributed to various factors, such as growth failure of a segment of the native RA, an inadequate baffle patch, compression or constriction by intravascular devices, purse-string sutures, or anatomic structures, and potentially other causes. One method of treating LT obstruction is transcatheter stent implantation, but there is limited information about this approach. The unique construction and material configuration of the LT make it different from essentially all other cardiovascular lesions, and it is unknown how the atrial wall, baffle material, and longitudinal suture lines will respond to significant expansion.

Background—Factors associated with obstruction of the cavopulmonary pathway in patients with a lateral tunnel (LT) Fontan connection and outcomes of percutaneous stent implantation for this complication have not been characterized.

Methods and Results—Between 1999 and 2011, 51 patients underwent stent implantation for LT pathway stenosis at a median age of 10.2 years and a median of 6.9 years after Fontan completion. Compared with control patients undergoing catheterization for other indications, patients had significantly higher inferior vena cava pressures (15.6 versus 13.7 mm Hg; P=0.007), but only 18 (35%) had a measurable pressure gradient in the catheterization laboratory. The morphology of the obstructions varied considerably and was not amenable to straightforward classification. Stenting increased mean diameter of the LT stenosis from 8.5 to 14.2 mm (P<0.001) and eliminated the pressure gradient when present. After stenting, 1 patient developed a significant new baffle leak that was treated with surgical Fontan revision 1.2 months later. A trivial baffle leak was observed in 1 other patient after stenting but required no treatment. Eight patients (16%) underwent successful redilation of the LT stent because of patient growth, symptomatic presentation, or during catheterization for other indications, but 1 developed a new baffle leak during redilation.

Conclusions—It was possible to enlarge the narrowed LT baffle substantially in patients with a variety of forms of obstruction, with few adverse events. The physiological implications of LT narrowing and target size for stenting deserve further investigation.

Key Words: adult congenital heart disease • bare metal stent • Fontan procedure • percutaneous treatment • stenosis

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**WHAT IS KNOWN**

- Stent placement within the surgically created lateral tunnel in intracardiac Fontan patients is becoming more common.
- Little has been written about risk factors for development of lateral tunnel obstruction, the indications for treatment, and the potential for adverse events.

**WHAT THE STUDY ADDS**

- Intracardiac lateral tunnel obstructions are morphologically diverse and present at various time points after Fontan completion.
- Lesions may be clinically significant even in the absence of a measurable pressure gradient in this low pressure system.
- Stent placement within the lateral tunnel was generally safe and substantially alleviated lateral tunnel stenosis, but enlargement of the pathway may result in a new or increased baffle leak in a small number of patients.

**Methods**

**Patients**

Data from patients who underwent LT Fontan palliation at any institution during any year and subsequently had placement of one or more bare metal stents (ie, nonvalved, noncovered stents) within the LT at Boston Children’s Hospital between January 1999 and May 2011 were reviewed. Patients who had balloon dilation of the LT but not stent placement were excluded. Patients who received a covered stent \( (n=6) \) were excluded if the primary indication for stent placement was baffle leak rather than obstruction. Cases were indexed by the first catheterization during which a stent was placed in the LT.

Patients with LT Fontan who underwent catheterization at Boston Children’s Hospital after Fontan completion but did not have intervention for pathway obstruction were randomly selected as controls, in a 1:1 ratio with cases. Controls were selected from patients whose most recent catheterization occurred between January 1999 and May 2011 but were not matched to cases on any other variable. Data on controls were collected from the most recent catheterization at which LT pathway angiography was performed.

**LT Stenting**

Before intervention, hemodynamic and angiographic assessment of the LT was performed. In general, the LT stenosis was predilated with \( \geq 1 \) angioplasty balloon, both to achieve therapeutic benefit and to characterize the lesion. A stent was then deployed using standard techniques and, in some cases, redilated after deployment. Palmaz XL stainless steel stents (Cordis Endovascular, Warren, NJ), Palmaz Genesis XD stents (Cordis Endovascular, Miami, FL), or Intrastent Max LD stents (ev3 Endovascular, Plymouth, MN) were used. Stent type, length, and balloon size were selected at the operator’s discretion and varied according to multiple factors, including current inventory.

**Demographic, Diagnostic, and Adverse Event Data**

Demographic, diagnostic, and procedural data were obtained from the medical chart. Because many different surgeons performed the Fontan procedures, surgeons with \(< 5 \) LT Fontan patients in the entire cohort were pooled and analyzed as a single group.

**Hemodynamic and Angiographic Data**

Hemodynamic and angiographic data were recorded at the start of the catheterization and (for cases) after LT stenting. Angiograms were analyzed by a single investigator, with a random sample of 15 cases also reviewed by a second investigator. Measurements were taken in anteroposterior views on images with contrast, as depicted in Figure 1. The diameters of the superior vena cava and the narrowest point in the LT were measured perpendicular to the long axis.

**Figure 1.** Angiogram images demonstrating the locations at which measurements were made. Lateral tunnel (LT) diameters were measured perpendicular to the direction of flow at the narrowest (A and D) points in both the anteroposterior and lateral projections. Tunnel length (B) and stenosis length (C) were also measured as shown. Superior vena cava (SVC) diameters (not shown) were measured similarly. Measurements were repeated on post-stent angiograms. The scooped-out appearance of this LT baffle, with most pronounced narrowing at the level of the fenestration closure device in both views, was relatively common among the case cohort.
Corresponding measurements were also taken in lateral projections. To the extent possible, measurements were taken from segments without baffle leaks, anastomoses, or areas with tapering or flaring diameter.

Minimum LT diameter was reported as the lesser of the minimum diameters measured in the anteroposterior and lateral projections. The cross-sectional area (CSA) of each vessel was calculated by assuming the segment to be an ellipse and taking the anteroposterior and lateral diameters as perpendicular axes. In patients with bilateral superior vena cavae, the combined CSA of both superior vena cavae was calculated. The minimum LT diameter and LT CSA were indexed to body surface area, and the minimum LT CSA was indexed to superior vena cava CSA by dividing the former by the latter. The ratio of the maximum balloon diameter to the stenosis diameter (balloon:stenosis ratio) was calculated based on the initial minimum LT diameter.

### Lesion Morphology

The length of each LT and lesion was measured exclusively in the anteroposterior view to maximize consistency (Figure 1). Total LT length was measured in the center of the LT pathway from the superior aspect of the hepatic veins to the inferior aspect of the pulmonary arteries. Stenosis length was measured from the most superior to most inferior aspect of the lesion along the edge of the LT. If the stenosis was appreciable on both the right and left edges of the LT, an average length was recorded.

Lesions were also classified as atrial-sided or baffle-sided if they were limited to the native atrial wall or exogenous baffle, respectively. Narrowings that affected both the atrial wall and baffle were classified as bilateral. Lesions through which flow could not be visualized were denoted as “total occlusion.” Lesions were described as being superior to, inferior to, or at the level of the fenestration based on the location of the narrowest segment of the lesion relative to the fenestration.

### Data Analysis

Demographic, diagnostic, and procedural data were reported and compared between cases and controls. In the case cohort, the primary outcomes assessed were changes in minimum LT diameter, LT CSA, and pressure gradient after stent placement. For between-group comparisons of means and proportions, an independent-samples t test and either χ² analysis or Fisher exact test were used, respectively. For paired data, paired-samples t test with 2 tails was used. The χ² test was used to compare proportions of cases and controls among surgeons. A multilevel logistic regression model was used to compare proportions of cases and controls among surgeons while adjusting for year of Fontan operation and year of stent implantation. Data are presented as mean±SD, median (range), or frequency (percentage).

The study was approved by the Boston Children’s Hospital Institutional Review Board.

### Results

#### Patients

From January 1999 through May 2011, stents were implanted in 51 patients for treatment of LT obstruction. Demographic and diagnostic data for cases and 51 randomly selected controls are summarized in Table 1. All of the patients originally underwent a fenestrated intracardiac LT Fontan procedure, and all but 3 cases and all controls underwent the Fontan operation at Boston Children’s Hospital. Of the 42 cases (82%) for which baffle material was noted in the medical chart, the baffle was constructed of expanded polytetrafluoroethylene in 40, Dacron in 1, and bovine pericardium in 1. The baffle was composed of expanded polytetrafluoroethylene in all 45 controls for which the

### Table 1. Demographic and Diagnostic Data in Patients Who Underwent Fontan LT Stenting and Controls

<table>
<thead>
<tr>
<th>Variable</th>
<th>LT Stent (N=51)</th>
<th>Controls (N=51)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>14 (27)</td>
<td>20 (39)</td>
<td>0.21</td>
</tr>
<tr>
<td>Age at time of Fontan, y</td>
<td>2.7 (1.4–11.9)</td>
<td>2.7 (1.0–37.8)</td>
<td>0.55</td>
</tr>
<tr>
<td>Year of Fontan procedure</td>
<td>1989–1999</td>
<td>18 (35)</td>
<td>0.42</td>
</tr>
<tr>
<td>2000–2011</td>
<td>29 (57)</td>
<td>33 (65)</td>
<td></td>
</tr>
<tr>
<td>Primary Fontan surgeon*</td>
<td></td>
<td></td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Surgeon A</td>
<td>6 (13)</td>
<td>16 (31)</td>
<td></td>
</tr>
<tr>
<td>Surgeon B</td>
<td>2 (4)</td>
<td>19 (37)</td>
<td></td>
</tr>
<tr>
<td>Surgeon C</td>
<td>31 (65)</td>
<td>11 (22)</td>
<td></td>
</tr>
<tr>
<td>Surgeon D</td>
<td>9 (19)</td>
<td>5 (10)</td>
<td></td>
</tr>
<tr>
<td>Duration from Fontan to index catheterization, y†</td>
<td>6.9 (0.0–18.3)</td>
<td>4.0 (0.5–17.4)</td>
<td>0.32</td>
</tr>
<tr>
<td>Year of index catheterization‡</td>
<td>1999–2006</td>
<td>29 (56)</td>
<td>0.005</td>
</tr>
<tr>
<td>2007–2011</td>
<td>35 (68)</td>
<td>22 (43)</td>
<td></td>
</tr>
<tr>
<td>Age at catheterization, y</td>
<td>10.2 (2.3–23.4)</td>
<td>8.1 (2.1–47)</td>
<td>0.08</td>
</tr>
<tr>
<td>Weight at catheterization, kg</td>
<td>25.5 (10.5–90.6)</td>
<td>22.7 (8.8–97.5)</td>
<td>0.32</td>
</tr>
<tr>
<td>BSA at catheterization, m²</td>
<td>0.96 (0.49–2.00)</td>
<td>0.88 (0.45–2.12)</td>
<td>0.27</td>
</tr>
<tr>
<td>Primary cardiac diagnosis</td>
<td></td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td>Hypoplastic left heart syndrome</td>
<td>18 (35)</td>
<td>18 (35)</td>
<td></td>
</tr>
<tr>
<td>Tricuspid atresia</td>
<td>10 (20)</td>
<td>13 (25)</td>
<td></td>
</tr>
<tr>
<td>Double-inlet left ventricle</td>
<td>7 (14)</td>
<td>6 (12)</td>
<td></td>
</tr>
<tr>
<td>Heterotaxy</td>
<td>5 (10)</td>
<td>5 (10)</td>
<td></td>
</tr>
<tr>
<td>Other‡</td>
<td>11 (22)</td>
<td>9 (18)</td>
<td></td>
</tr>
<tr>
<td>Precatheterization clinical status</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protein-losing enteropathy and/or ascites</td>
<td>6 (12)</td>
<td>2 (4)</td>
<td>0.14</td>
</tr>
<tr>
<td>Cyanosis or low oxygen saturation at rest</td>
<td>11 (22)</td>
<td>18 (35)</td>
<td>0.12</td>
</tr>
<tr>
<td>Other acute presentation§</td>
<td>4 (8)</td>
<td>1 (2)</td>
<td>0.62</td>
</tr>
<tr>
<td>Nonelective catheterization</td>
<td>5 (10)</td>
<td>3 (6)</td>
<td>0.46</td>
</tr>
<tr>
<td>Fenestration status</td>
<td></td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>Closed with device previously</td>
<td>21 (41)</td>
<td>15 (29)</td>
<td></td>
</tr>
<tr>
<td>Closed spontaneously</td>
<td>6 (12)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>Closed at present catheterization</td>
<td>19 (37)</td>
<td>36 (71)</td>
<td></td>
</tr>
<tr>
<td>Patien at end of this catheterization</td>
<td>5 (10)</td>
<td>0 (0)</td>
<td></td>
</tr>
</tbody>
</table>

Data are presented as median (minimum-maximum) or frequency (%). BSA indicates body surface area; and LT, lateral tunnel.

*Data show the analysis of 48 cases and 51 controls who underwent the Fontan procedure at our institution. Surgeon group D consists of 5 surgeons who performed fewer than 5 LT Fontan procedures in the overall cohort.

†Index catheterization was the stent implant in cases or most recent catheterization in controls.

‡Data include double outlet right ventricle, tetralogy of Fallot, ventricular inversion, pulmonary stenosis, and transposition of the great arteries.

§Data include thrombus, hematemesis, and hemoptysis.

‖Comparison between previously closed (prior intervention or spontaneously) and not previously closed.
Table 2. Procedural Data in Patients Who Underwent Fontan LT Stenting and Controls

<table>
<thead>
<tr>
<th>Variable</th>
<th>Fontan LT Stenting (N=51)</th>
<th>Fontan LT Controls (N=51)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline hemodynamics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IVC or inferior Fontan LT pressure, mm Hg</td>
<td>15.6±3.8</td>
<td>13.3±3.3</td>
<td>0.007</td>
</tr>
<tr>
<td>SVC pressure, mm Hg*</td>
<td>14.8±2.8</td>
<td>13.2±3.5</td>
<td>0.01</td>
</tr>
<tr>
<td>Systemic ventricular end-diastolic pressure, mm Hg†</td>
<td>8.9±4.1</td>
<td>7.4±3.1</td>
<td>0.06</td>
</tr>
<tr>
<td>Aortic O₂ saturation, %</td>
<td>90±6</td>
<td>88±12</td>
<td>0.44</td>
</tr>
<tr>
<td>Interventions performed at this catheterization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stent placement in Fontan LT</td>
<td>51 (100)</td>
<td>0 (0)</td>
<td>0.001</td>
</tr>
<tr>
<td>Closure of fenestration or baffle leak</td>
<td>23 (45)</td>
<td>38 (75)</td>
<td>0.63 ‡</td>
</tr>
<tr>
<td>Angioplasty/stenting of vessel(s) other than Fontan LT</td>
<td>13 (26)</td>
<td>10 (20)</td>
<td></td>
</tr>
<tr>
<td>Occlusion of anomalous vasculature</td>
<td>16 (31)</td>
<td>20 (39)</td>
<td></td>
</tr>
<tr>
<td>Fenestration creation or dilation</td>
<td>2 (4)</td>
<td>1 (2)</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>7 (14)</td>
<td>5 (10)</td>
<td></td>
</tr>
<tr>
<td>Number of interventions at this catheterization</td>
<td>2 (1–4)</td>
<td>1 (0–3)</td>
<td>0.05</td>
</tr>
<tr>
<td>Adverse events</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total adverse events</td>
<td>13 (25)</td>
<td>16 (31)</td>
<td>0.61</td>
</tr>
<tr>
<td>New baffle leak§</td>
<td>2 (4)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>LT stent embolization</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>Coil or device removed for misplaced/embolization</td>
<td>3 (6)</td>
<td>4 (8)</td>
<td></td>
</tr>
<tr>
<td>Arrhythmia#</td>
<td>5 (10)</td>
<td>5 (10)</td>
<td></td>
</tr>
<tr>
<td>Respiratory distress or hemoptysis</td>
<td>1 (2)</td>
<td>3 (6)</td>
<td></td>
</tr>
<tr>
<td>Hematoma at access site</td>
<td>3 (6)</td>
<td>2 (4)</td>
<td></td>
</tr>
<tr>
<td>Blood loss or hypotension</td>
<td>2 (4)</td>
<td>2 (4)</td>
<td></td>
</tr>
</tbody>
</table>

Data are presented as median (minimum–maximum), mean±SD, or frequency (%). IVC indicates inferior vena cava; LT, lateral tunnel; and SVC, superior vena cava.

*VC pressure was not obtained in 1 case and 5 controls.
†Ventricular end-diastolic pressure was not obtained in 6 cases and 5 controls.
‡All of the other interventions were combined and compared between groups.
§Data refer to the index catheterization. One additional patient developed a new baffle leak during redilation 9.6 y after stent placement.
‖Data were obtained for collaterals; none were related to stent deployment.
#All of the arrhythmias were transient and resolved before completion of catheterization.

LT Stenting

Procedural data describing the Fontan LT before and after stenting are summarized in Table 3. The appearance of the LT lesions varied considerably; they were not amenable to straightforward and clinically useful morphological classification (Figures 2 through 4). The length of the narrowed segment of the baffle varied considerably. Almost all of the lesions (88%) were <40 mm in length; the stenosis length:total LT length ratio ranged from 0.16 to 0.99 (median, 0.50).

Of the 40 cases with an interventional fenestration closure, 27 obstructions (68%) were colocalized with the device along the longitudinal axis (neither superior nor inferior to the fenestration) and in terms of orientation (baffle-sided or bilateral). It is possible that fenestration devices are at least partially responsible for these 27 obstructions, but the remaining 24 lesions (47%) in this cohort developed independently from an intravascular device. All of the cases had

Material was recorded. There was a significant difference in the proportion of cases and controls among surgeons, even after adjustment for year of Fontan operation and year of stent implantation. In comparison with randomly selected controls, patients who underwent LT stenting were more likely to have undergone index catheterization after 2006 and to have had previous fenestration closure compared with controls.

Catheterization

Baseline hemodynamic data, interventions performed at the index catheterization, and adverse events are summarized in Table 2. Pressures in the Fontan circuit were higher on average in cases than in controls.
a single stent placed at the index procedure except for 1, who had 2 overlapping stents. Eight patients received a Palmaz stent (16%), 37 received a Palmaz Genesis XD stent (72%, including both stents in the patient with 2), and 6 received an Intrastent (12%). Stent length was ≤20 mm in 7 patients, 21 to 30 mm in 20, and 31 to 40 mm in 24 (including both stents in the patient with 2).

Predilation of the LT before stent deployment was performed in 47 cases (92%), with a median initial balloon diameter of 14 mm (4–20 mm). The median diameter of the largest balloon used during stent deployment or further dilation was 16 mm (12–25 mm). On average, the balloon used to implant the stent was 2.0±2.3 mm larger than the first predilation balloon, but in 11 patients (22%) they were the same size. Postdilation with a larger balloon after stent deployment was performed in 18 patients (35%). The balloon:stenosis diameter ratio for predilation was 1.7±0.4 on average and ranged from ≈1 to ≈3. The ratio of the maximum balloon diameter (including deployment and redilation in the index catheterization) to the initial stenosis diameter averaged 2.1±0.6 (range, 1.3–4.8).

In 2 patients, the obstruction in the LT pathway was clearly related to thrombus. One patient had incomplete occlusion of

Figure 2. Angiograms demonstrating (A) a focal, ledge-like stenosis on the rightward/atrial and posterior aspects of a narrowed lateral tunnel (LT) pathway above the level of the fenestration device and (B) the LT pathway after implantation of a stent. This lesion had a 2-mm Hg initial resting gradient, which resolved after stenting.

Figure 3. An example of a long-segment narrowing near the level of the fenestration, before (A) and after (B) stenting.
the LT pathway attributed to torsion of and thrombus within the LT. The thrombus was crossed with a wire, then predilated and stented. The other had a complete thrombotic occlusion of the LT; the thrombus was crossed with a Brockenbrough needle, predilated with a small balloon, then stented and dilated further.

The average minimum LT diameter increased from 8.5±2.5 mm to 14.2±2.8 mm (P<0.001) in patients who received an LT stent, with no appreciable difference in cases with a pressure gradient or baffle leak (Figure 5). All of the 18 patients with an initial resting pressure gradient across the LT obstruction had complete resolution of the gradient after stent placement.

Acute and Subacute Adverse Events
Procedural results are summarized in Table 2. There were no deaths, strokes, myocardial infarctions, cardiac perforations, or instances of LT stent migration or embolization in patients who underwent LT stenting. Two patients were noted to have a new or increased baffle leak after stent deployment. In 1 case, detailed in Figure 6, a pre-existing baffle leak was markedly larger after stenting. A septal closure device was placed across the baffle leak in the same catheterization, but the patient presented 1.2 months later with worsening mitral regurgitation (the primary indication for catheterization), a recurrent, medication-resistant atrial arrhythmia, and a residual right-to-left shunt related to a leak at the posterior baffle suture line. The patient underwent surgical conversion to a full circumferential intracardiac conduit, annuloplasty for regurgitation of a common atroventricular valve, and partial RA cryoablation.

In another patient, a new small baffle leak was noted after stent implant. However, this baffle leak was determined to be clinically insignificant and was not treated. The maximum balloon:stenosis ratio in both patients with baffle leaks (2.1 and 2.2, respectively) was near the mean of the entire cohort (2.1).

In the stent group, there were 5 transient arrhythmias, including 2 that occurred during predilation of the LT stent after uncomplicated predilation and deployment. One case developed heart block that resolved after 6 chest compressions, and another developed a junctional rhythm that resolved spontaneously. Transient arrhythmias in 3 other cases (1 heart block and 2 supraventricular tachycardias) were unrelated to interventions on the LT. The frequencies of other adverse events not specific to LT stent deployment were similar between cases and controls.

Follow-up
During a median follow-up of 3.7 years, there were no deaths in the study cohort, no surgical interventions on the baffle other than the one described above for multiple indications including stent-induced baffle leak, and no stent fractures or embolizations were identified in patients who underwent further catheterization or chest imaging for purposes unrelated to this study.

Figure 4. These images demonstrate a complex stenosis in the lateral tunnel (LT) pathway, with a relatively long narrowed segment inferiorly and an atypical twisted morphology and discrete shelf from the atrial wall aspect of the pathway just superior to the fenestration closure device, before (A) and after (B) stent placement. Predilation and maximum dilation balloon:stenosis diameter ratios were 2.1 and 2.8, respectively. The initial gradient of 8 mmHg resolved after stenting (≤16-mm balloon). Of the 51 cases presented here, this is 1 of 2 with a twisted or tortuous morphology that differed qualitatively from the other lesions in the series.

Figure 5. The mean lateral tunnel (LT) minimum diameter increased from 9.5±2.9 to 15.1±3.3 mm in patients receiving an LT stent. Cases without hemodynamic gradients (solid triangles connected by broken lines) had similar distributions of minimum diameter and improvements in diameter as cases with gradients (clear diamonds connected with solid lines). Red squares denote cases with new baffle leaks.

Figure 6. These images demonstrate a complex stenosis of the lateral tunnel (LT) pathway, with a relatively long narrowed segment inferiorly and an atypical twisted morphology and discrete shelf from the atrial wall aspect of the pathway just superior to the fenestration closure device, before (A) and after (B) stent placement. Predilation and maximum dilation balloon:stenosis diameter ratios were 2.1 and 2.8, respectively. The initial gradient of 8 mmHg resolved after stenting (≤16-mm balloon). Of the 51 cases presented here, this is 1 of 2 with a twisted or tortuous morphology that differed qualitatively from the other lesions in the series.
Eight patients (16%) underwent further dilation and/or stenting during a separate catheterization 0.5 to 9.6 years after the initial stent implantation (median, 2.3 years). The first stent placement in all 8 patients had been successful at relieving angiographic stenosis. Angiography did not reveal significant neointimal narrowing in any of these 8 patients, and only 1 returned with an LT minimum diameter measurement (8.4 mm) that was smaller than the poststent measurement (9.2 mm). All 8 of the stents were expanded to a larger diameter than in the index catheterization. The indications for redilation included development of protein-losing enteropathy ($n=3$), LT thrombus ($n=1$), device repositioning at the time of fenestration closure ($n=3$, including 1 who received a second stent), and mild angiographic narrowing ($n=1$). One patient was redilated twice, once for LT thrombus and a second time 7.5 years later for protein-losing enteropathy. In addition, 1 patient presented 9.6 years after stent placement with decreased exercise tolerance, orthopnea, and increased Fontan pressure. The stent, originally dilated with an 18-mm balloon, was redilated with 20- and 22-mm balloons (a maximum redilation diameter:stenosis diameter ratio of 1.6), after which a new significant baffle leak was observed along the posterior aspect of the pathway. The baffle leak resolved after placement of a septal occlusion device.

**Discussion**

**LT Pathway Obstruction**

Because the number of LT Fontan patients under follow-up care has grown significantly during the past 10 years, LT stent placement is becoming more common. Whether this is related to an increase in the frequency of LT obstruction or a change in clinical practice is not completely clear, but the latter seems to play at least a partial role. The LT obstructions in this series were heterogeneous in terms of morphology, complicating efforts to infer a simple etiology for LT stenosis. However, the few obstructions caused by thrombus were clearly distinct in cause. Often, the narrowing appeared more prominent after device closure of the fenestration, and 53% of lesions colocalized with a fenestration closure device. Although devices seem to contribute to LT stenosis, they clearly are not responsible for all of the lesions.

It was not possible to elucidate specific surgical factors that predisposed to LT stenosis. Surgeons perform the LT Fontan procedure differently in several respects, often with patient-specific adjustments. For example, one surgeon in this study reports a tendency to maintain a low baffle profile in select patients to minimize the possibility of baffle-related pulmonary venous obstruction. Despite the lack of specific operative details in this report, it is likely that technical differences are important factors in the development of LT pathway obstruction in some cases. Contributions from altered RA growth patterns also cannot be ruled out.

**LT Hemodynamics**

Fewer than half of the cases had a measurable pressure gradient across the obstruction. However, patients underwent catheterization at rest, under conscious sedation, or general anesthesia, so LT blood flow was likely lower than in conscious, active patients. As shown previously, catheterizations tend to underestimate the magnitude of physiological deficits in similar patients.\textsuperscript{16–18} Exercise tolerance is abnormal in Fontan patients because of a combination of factors,\textsuperscript{19,20} one of which may be energy loss in the LT.\textsuperscript{21–25} Accordingly, any
benefits derived from LT stenting are likely related to reduction in the resistance of and consequent energy loss across the LT.

Outcomes of LT Stenting
Based on this experience, enlargement of the baffle and resolution of any measurable pressure gradient can be expected after stent placement, whether soon after Fontan completion or years later. In some cases the LT diameter was nearly tripled, suggesting that even severe narrowings can be enlarged sufficiently when indicated. However, the available data do not allow determination of hemodynamic or clinical benefit.

Given the unique construction of the LT, with longitudinal suture lines and baffle composed of different materials, there is little experience with which to estimate risk profiles. Although not a major problem, baffle leak attributed to disruption at the baffle-atrium suture line did occur in 3 patients, including 1 undergoing redilation years after stent implantation. It is reasonable to suspect that overdilation of the narrowed segment increases the risk of baffle disruption. However, there is not sufficient evidence to support this hypothesis, because in all 3 of the cases the balloon:stenosis ratio fell well within the range used in the rest of the cohort. Thus, it is difficult to predict which patients are at risk for developing a significantly increased baffle leak.

Hypothetically, stenting of the LT, which entails contact of the stent with and presumably stretching or tearing of the atrial wall component of the pathway, may introduce a risk of atrial arrhythmia, but no evidence of new persistent arrhythmia was observed in this cohort. Stent fracture, embolization, and restenosis were not observed among cases in the course of subsequent clinical care. Most patients were left on their present antiplatelet or anticoagulant therapy.

LT Stent Redilation
Reintervention does not seem to be universally necessary after LT stenting. Lagging growth of stented segments and new symptoms contributed to the decision to intervene in 5 of the 8 patients who underwent redilation, and the presence of a new thrombus or fenestration device was important for 4 patients. Additional expansion of the LT stent should be possible in young patients with significant growth potential remaining, as in these 8 cases. Even in adults, stents were generally not redilated beyond 20 mm, so most of the large diameter stents commonly used in the United States were adequately sized. However, as evidenced by 1 of these 8 cases, redilation may introduce a new or increased baffle leak, just as in the initial stent implantation.

Recommendations
One means of reducing the likelihood of LT obstruction and stenting may be to place the fenestration away from the central, waisted segment of the baffle patch. Small baffle size may increase the likelihood of developing LT stenosis, but tradeoffs associated with a larger baffle remain unclear.

Ultimately, precatheterization energy loss estimates from computational fluid dynamics simulations may help determine whether the benefits of LT stenting outweigh the risks for individual patients and aid in defining a target dilation diameter. In the interim, stents may be placed in the LT pathway with relative safety in patients with pressure gradients and those whose LT obstruction becomes clinically apparent or is discovered in the course of other procedures.

It is probably prudent to perform the initial predilation with a balloon:stenosis diameter ratio <2.5, followed by angiographic reevaluation and gradual increases if indicated. In cases of tight stenosis, it seems reasonable to perform gradual, sequential dilation so that any disruption can be identified early or avoided altogether, but this study does not clearly provide data to support such an approach. An average final stent LT diameter in the range of 15 to 16 mm/m² was achieved, and this seems to be a reasonable target in general. Angiography should be performed after intervention so that baffle leaks can be discovered and addressed. It is reasonable to be prepared with septal occlusion devices and covered stents so that a significant new baffle leak can be treated immediately if indicated.

Further expansion of LT stents at subsequent catheterizations may be performed if indicated, although it may not be necessary, and the risk for creation of a new baffle leak remains. Although the maximum expanded diameter of most stents in this cohort was <18 mm, in general it is probably worthwhile to implant a type of stent that can be expanded beyond that size.

Limitations
Angiographic measurements in this study were made retrospectively and may be subject to multiple sources of inaccuracy. Planes were often adjusted between preintervention and postintervention angiography, which likely confounded comparisons of vessel dimensions to some degree. The calculation of CSA rested on assumptions of perpendicular anteroposterior and lateral planes that were both parallel to the direction of blood flow. These conditions were not always satisfied, because planes were chosen based on procedural usefulness.

The data presented in this study do not constitute evidence concerning the frequency of LT pathway obstruction or the adequacy of LT pathway growth over time. Similarly, our findings provide only limited information about risk factors for the development of LT stenosis and cannot be generalized beyond this selected population. Stent placement was used retrospectively as a surrogate indicator of LT obstruction, and there are almost certainly both ascertainment and selection bias in this approach. Similarly, this study does not provide definitive evidence of clinical or hydrodynamic benefits related to LT pathway stenting.

Conclusions
Obstruction of an LT pathway can take many forms and present at various time points after Fontan completion. Diagnosis of LT stenosis and assessment of the benefits of stenting remain difficult in the low-pressure cavopulmonary system, where narrowings may be clinically relevant in ambulatory patients even if a hemodynamic gradient is not observed at rest during catheterization. Although surgical and patient-specific factors may play a role, no simple etiology for obstruction was elucidated. Because narrowing in the LT often appeared worse after fenestration closure with a septal occlusion device, placement of the fenestration at a site other
than the narrowest point in the LT may reduce the impetus for LT stenting. Stent placement within the LT was generally safe and substantially alleviated LT stenosis, but enlargement of the pathway may result in a new or increased baffle leak in a small number of patients.

Disclosures

None.

References

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