Risk Stratification, Systematic Classification, and Anticipatory Management Strategies for Stent Fracture After Percutaneous Pulmonary Valve Implantation

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Background—We analyzed the incidence, risk factors and treatment options for stent fracture after percutaneous pulmonary valve (PPV) implantation (PPVI).

Methods and Results—After PPVI, 123 patients had chest x-ray in anteroposterior and lateral projection, echocardiography, and clinical evaluation during structured follow-up. Of these 123 patients, 26 (21.1%) developed stent fracture 0 to 843 days after PPVI (stent fracture–free survival at 1 year, 85.1%; at 2 years, 74.5%; and at 3 years, 69.2%). Stent fracture was classified as type I: no loss of stent integrity (n=17); type II: loss of integrity with restenosis on echocardiography (n=8); and type III: separation of fragments or embolization (n=1). In a multivariate Cox regression, we analyzed various factors, of which 3 were associated with a higher risk of stent fracture: implantation into “native” right ventricular outflow tract (P=0.04), no calcification along the right ventricular outflow tract (judged with fluoroscopy, P=0.02), recoil of PPV (qualitatively, PPV diameter in frontal or lateral plane with fully inflated balloon > diameter after balloon deflation, P=0.03). Substernal PPV location, high-pressure post-PPVI dilatation of PPV, pre-PPVI right ventricular outflow tract gradients, and other indicators of PPV compression or asymmetry did not pose increased risk. Patients with type I fracture remain under follow-up. Patients with type II fracture had 2nd PPVI or are awaiting such procedure, and 1 patient with type III fracture required surgical explantation.

Conclusion—Stent fracture after PPVI can be managed effectively by risk stratification, systematic classification, and anticipatory management strategies. Serial x-ray and echocardiography are recommended for surveillance. (Circulation. 2007;115:&NA;-.)

Key Words: catheterization ▪ echocardiography ▪ heart defects, congenital ▪ pulmonary valve
Necker Enfants Malades (Paris, France), Great Ormond Street Hospital for Children, The Heart Hospital, and Harley Street Clinic (London, United Kingdom). The performance of PPVI has been reported previously.2–5 The ethics committees at these institutions approved the study protocol, which included echocardiography and chest x-ray immediately post-PPVI and during structured follow-up at 1 month, 3 months, 6 months, 1 year, and yearly thereafter. Echocardiography (Vivid 7, GE, Medical Systems, Milwaukee, WI) was used to estimate right ventricular pressure from tricuspid regurgitation jet, and the velocity across RVOT and color flow mapping of RVOT were used to assess degree of stenosis and regurgitation. Chest x-ray was obtained at the same clinical contact and screened for structural integrity of the stent. Written informed consent was obtained from patients and parents as appropriate.

Classification
Stent fracture was classified on the basis of chest x-ray appearance. Type I indicates fracture of ≥1 strut without loss of stent integrity. Type II indicates fracture with loss of stent integrity. Type III indicates fracture associated with separation of fragments or embolization (Figure 1).

Risk Stratification
Angiograms of the PPVI procedure or chest x-rays performed after the procedure were reviewed. Independent variables analyzed for association with risk of stent fracture were morphological characteristics of RVOT (type a: “native,” any part of circumference formed by native tissue; type b: homograft or other valved or nonvalved conduit), presence of preexisting stent in RVOT, sub-ternal location of the PPV, post-PPVI dilation procedure with high-pressure balloon to relieve residual stenosis (16 to 22 mm, inflated to 8 to 12 atm; Mullins, NuMed), recoil of PPV (qualitatively, PPV diameter in frontal or lateral plane with fully inflated balloon > diameter after balloon deflation), RVOT calcification (circumferential, partial, or no calcifications along the RVOT, judged with fluoroscopy), and compression/asymmetry of PPV (assessed as ratio of anteroposterior and lateral PPV diameters at proximal, mid, and distal site). The PPV dimensions were measured (Medcon TCS Symphony image management) after calibration with the markers on Multitrack angiographic catheters (NuMed). RVOT gradients pre-PPVI (group I: RVOT gradient ≥30 mm Hg; group II: RVOT gradient <30 mm Hg) and changes in RVOT gradients post-PPVI were analyzed to assess the influence of hemodynamic values on the probability of stent fractures.

Statistics
Data are expressed as means ± SEM unless otherwise specified. Last follow-up was defined as last clinical contact or explantation. Factors for risk stratification were analyzed with multivariate Cox regression. Survival curves were obtained by Kaplan-Meier plots, and log-rank tests were performed to compare the probabilities for stent fracture-free survival. Student t test was used to evaluate differences in the initial decrease of RVOT gradients between patients with and without stent fractures. The post-PPVI echocardiogram (before stent fracture) and the first echocardiogram after detection of stent fractures were compared with Student paired t test. P < 0.05 was considered significant. Statistical analysis was performed on SPSS 13.0 (SPSS Inc, Chicago, Ill) and GraphPad InStat 3 (Graphpad Software, San Diego, Calif).

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

Results
One-hundred-twenty-three patients (median age: 17.9 ± 1.0 years, Table 1) had PPVI procedure between September 2000 and May 2006 with a mean follow-up of 13.0 ± 1.0 months. The most prevalent RVOT type was homograft conduit (100 of 123 patients) (Table 1).
At initial presentation, 20 of 26 patients had type I, 5 of 26 had type II, and 1 of 26 had type III stent fracture. Of these 26 patients, 6 experienced clinical consequences. The patient with type III stent fracture had stent embolization into the right pulmonary artery, which required surgical explantation of the PPV. The diagnosis was made 2 days after the onset of symptoms and confirmed by x-ray. All patients who initially presented with type II stent fracture had second PPVI for relief of restenosis (movies I and II, online-only data supplement). Of the 20 patients with type I fracture, 85% (17 of 20) are under medical follow-up with serial chest x-ray and echocardiography for surveillance. In 3 of 20 patients, progression to type II fracture occurred; 1 patient had second PPVI and 2 patients are awaiting second PPVI. Overall probability of freedom from type II/III stent fracture was 96.3% at 1 year, 92.5% at 2 years, and 86.5% at 3 years (Figure 2B).

**Hemodynamic Analysis**

RVOT velocities and tricuspid regurgitation jet velocities measured by echocardiography showed no difference before and after stent fracture (RVOT, 3.0±0.2 versus 3.2±0.2 m/s, P=0.06; tricuspid regurgitation jet velocity, 3.3±0.2 versus 3.6±0.2 m/s, P=0.07) (Figure 3A and 3B), although individual patients showed increasing velocities (Figure 3A and 3B).

**Risk Factors for Stent Fracture**

In 97 of 123 patients, the original angiograms of PPVI procedure or chest x-rays performed after the procedure were available for review. In a multivariate Cox regression analysis (Table 2), 3 factors were associated with higher risk of stent fracture: PPVI into “native” RVOT (B=1.8, P=0.04), noncalcified RVOT (B=−0.7, P=0.02; log-rank test, P<0.001) (Figure 4A), and recoil of PPV during balloon deflation (B=1.4, P=0.03). Presence of preexisting stent in RVOT (B=−0.3, P=0.69), subternal PPV location (B=0.6, P=0.35), post-PPVI dilatation procedure with high-pressure balloon (B=−0.1, P=0.86; log-rank test, P=0.97) (Figure 4B), other indicators for PPV compression or asymmetry [anteroposterior-to-lateral PPV diameter ratios at proximal site (B=3.7, P=0.07), mid-site (B=0.01, P=1.00),
and distal site ($B=-2.2, P=0.41$), and significant RVOT gradient pre-PPVI ($B=0.02, P=0.97$) did not pose increased risk. Changes in RVOT gradients immediately after PPVI, measured by catheterization, were not significantly different in patients with and without stent fractures ($16.9\pm2.1$ versus $18.9\pm4.5$ mm Hg, $P=0.63$).

**Discussion**

Right ventricular dysfunction after repair of congenital heart disease could result from myocardial injury during surgical repair, residual or recurrent lesions, restenosis caused by patient growth or regeneration from absence or valve degeneration in the RVOT, and the long-term consequences of all those factors. Wide experience exists in the amelioration of obstruction in right ventricle to pulmonary artery conduits with endovascular stenting. Although this stenting is successful in dealing with stenosis in the short term, potential volume overload from regurgitation and subsequent pressure overload from recurrent stenosis may further contribute to right ventricular injury. PPVI provides the advantage of a stent with an effective valve, which can eliminate the risk of chronic volume overload, but also, in principle, remains prone to all complications and consequences of endovascular stenting. A high incidence of stent fracture has been described in right ventricle to pulmonary artery conduits just as in other endovascular stents.

Peng et al reported stent fracture in 56 of 126 patients (43%) who underwent cardiac catheterization before conduit replacement surgery. They describe the potential for underestimation of stent fracture, as minor grades may be clinically silent, difficult to detect by plain radiography, or not detected at surgery if the conduit excision was en masse without dissection into it. Their cohort had 2 different types of balloon-expandable stainless steel stents: the Palmaz-Schatz and the Palmaz-Schatz Genesis. Nearly 90% of fractured stents had substernal location, which was identified as an important risk factor for fracture.

The stent used for PPVI was specifically designed for applications in congenital heart disease, particularly for use over a large range of diameters. We chose the platinum-iridium stent because of its crimpability, limited shortening during deployment, and the belief that it was the most fracture-resistant stent available. Other stents routinely used were designed for periph-

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**Table 2. Results of Multivariable Cox Regression Analysis**

<table>
<thead>
<tr>
<th></th>
<th>Multivariable Cox Regression</th>
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<tbody>
<tr>
<td></td>
<td>$B$</td>
</tr>
<tr>
<td>Outflow tract type</td>
<td>1.8*</td>
</tr>
<tr>
<td>Calcification along RVOT</td>
<td>$-0.7^*$</td>
</tr>
<tr>
<td>Recoil of PPV</td>
<td>1.4*</td>
</tr>
<tr>
<td>Presence of preexisting RVOT stent location</td>
<td>$-0.3$</td>
</tr>
<tr>
<td>Substernal stent location</td>
<td>0.6</td>
</tr>
<tr>
<td>Postdilatation with high pressure balloon</td>
<td>$-0.1$</td>
</tr>
<tr>
<td>AP-to-lateral stent diameter ratio proximal PPV</td>
<td>3.7</td>
</tr>
<tr>
<td>AP-to-lateral stent diameter ratio mid-PPV</td>
<td>0.01</td>
</tr>
<tr>
<td>AP-to-lateral stent diameter ratio distal PPV</td>
<td>$-2.2$</td>
</tr>
<tr>
<td>RVOT gradient pre-PPVI $\geq 30$ mm Hg</td>
<td>0.02</td>
</tr>
</tbody>
</table>

$AP$ indicates anteroposterior. $A$ positive $B$ value indicates a variable associated with shorter freedom from stent fracture and vice versa.

*Statistically significant.

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**Figure 4.**

A. The degree of calcification in the RVOT is inversely correlated to the risk of stent fractures ($P<0.001$). B. Post-PPVI dilatation procedure with high-pressure balloons did not pose higher risk for stent fractures ($P=0.97$).
eral vascular applications, and shortcomings have included sharp edges that lead to balloon rupture, excessive shortening, and fractures when implanted into the RVOT.\textsuperscript{8,12} For PPV, the detection accuracy of chest x-ray surveillance compared well to fluoroscopy in a small sample of patients because the PPV stent material (platinum-iridium) is very radio-opaque. However, displacement of stent components can be missed with plain radiography. Fluoroscopy has therefore an added benefit in facilitating the grading of stent fractures.

Of the 123 patients, 21.1\% (26 of 123) developed stent fracture during follow-up, which represents the most common early complication after PPVI. We identified 3 variables that pose high risk: implantation of PPV into native RVOTs, non-calcified RVOTs, and presence of PPV recoil during balloon deflation. All these factors might implicate higher cyclic compressive stresses on the PPV. In our analysis, substernal stent location or asymmetry of the PPV did not pose higher risk on multivariate analysis. This is in contrast to findings in the bare metal stent population, where both mechanisms contributed to stent fractures.\textsuperscript{8} Our analysis might be underpowered, because the more robust multivariate analysis might be too rigorous to detect statistical significance in a relatively small population. Also, we believe that not all substernal calcified conduits may be subject to cyclic compressive stress. Some conduits that are circumferentially calcified and adherent to sternum lack mobility and deformation during the cardiac cycle. This situation is often detected during angiography, where, although the cardiac chambers move during the cardiac cycle, the conduit often remains rigidly immobile behind the sternum. This immobility may, however, contribute to the risk of residual stenosis caused by failure to expand the stent to its intended dimension.

Importantly, higher grades of stent fracture are associated with restenosis, which can also be seen in other modes of early

<table>
<thead>
<tr>
<th>Age at PPVI, y</th>
<th>Sex</th>
<th>Diagnosis</th>
<th>RVOT Type</th>
<th>Initial RVOT Lesion</th>
<th>Indication for Reintervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.7</td>
<td>Male</td>
<td>Pulmonary atresia/VSD</td>
<td>18-mm Carpenter-Edwards</td>
<td>Stenosis</td>
<td>Outgrowth (explantation)</td>
</tr>
<tr>
<td>10.8</td>
<td>Female</td>
<td>TGA/pulmonary stenosis/VSD</td>
<td>Homograft</td>
<td>Mixed</td>
<td>Residual stenosis caused by muscle bundle in RVOT (explantation)</td>
</tr>
<tr>
<td>15.4</td>
<td>Male</td>
<td>Pulmonary atresia/VSD</td>
<td>18-mm Homograft</td>
<td>Mixed</td>
<td>Residual stenosis caused by Hammock effect (second PPV)</td>
</tr>
<tr>
<td>10.8</td>
<td>Male</td>
<td>Tetralogy of Fallot</td>
<td>18-mm Hancock conduit</td>
<td>Stenosis</td>
<td>Residual stenosis \rightarrow stent fracture secondary to balloon dilatation</td>
</tr>
<tr>
<td>18.0</td>
<td>Male</td>
<td>Aortic valve disease (Ross procedure)</td>
<td>20-mm Homograft</td>
<td>Stenosis</td>
<td>Hammock effect \rightarrow stent fracture secondary to balloon dilatation</td>
</tr>
<tr>
<td>25.7</td>
<td>Female</td>
<td>Tetralogy of Fallot</td>
<td>22-mm Homograft</td>
<td>Regurgitation</td>
<td>Hammock effect \rightarrow stent fracture secondary to second PPV</td>
</tr>
<tr>
<td>19.9</td>
<td>Male</td>
<td>Aortic valve disease (Ross procedure)</td>
<td>Homograft</td>
<td>Mixed</td>
<td>Residual stenosis \rightarrow stent fracture secondary to balloon dilatation</td>
</tr>
</tbody>
</table>

VSD indicates ventricular septal defect.

Figure 5. A, Lateral chest x-ray depicts multiple stent fractures, but the degree of displacement cannot be judged with still frame. B and C, Frozen images of lateral projection during fluoroscopy delineate proximal flailing of stent components into the stent lumen (arrows).
PPVI failure. This restenosis leads to significantly shorter freedom from catheter reintervention, which underscores the need for continued surveillance. If stent fracture is diagnosed at an early stage and reintervention is warranted, repeat PPVI prolongs the lifespan of the conduit and provides a reasonable alternative to surgery, thus reducing surgical explantation. A similar strategy can be found in other studies in which patients with stent fracture received additional stents to restore stent patency and enhance integrity. In our experience, successful treatment of clinical consequences of stent fracture and freedom from reoperation justify continuous surveillance.

Limitations
Although all chest x-rays from our institution were reviewed by members of our team (J.N., S.K., L.C., P.L.) and underwent quality control, a relatively large proportion of the study population (approximately 40%) was followed-up by other specialized centers as per the recommended protocol. For these patients, image resolution and less diligent interpretation could have affected the quality of reporting. Three patients were lost to follow-up. Fluoroscopy was not performed in all patients because it was not part of the ethically approved study protocol, but fluoroscopy may influence the classification of stent fractures. The assessment of stent recoil was subjective and may reflect bias. Long-term follow-up will provide further data on late incidence of stent fractures.

Conclusion
Stent fractures occur after PPVI, but they can be managed effectively by risk stratification, systematic classification, and anticipatory management strategies. Serial x-ray and echocardiography are recommended for surveillance. Detection of stent fractures at an early stage could avert serious sequelae and prolong conduit lifespan. As more stent-based applications are introduced to clinical practice, stent fracture is likely to become a frequent clinical event that requires surveillance and early intervention.

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Disclosures
Dr Khambadkone, Dr Coates, and Dr Bonhoeffer have received honors from Medtronic Inc. Dr Khambadkone, Dr Taylor, and Dr Bonhoeffer are consultants/advisory board members of Medtronic Inc. Dr Coates has received a British Heart Foundation Junior Fellowship Grant. Dr Bonhoeffer has an ownership interest in the Melody Valve (Medtronic Inc) and has received a British Heart Foundation Program Grant. The remaining authors report no conflicts.

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