PEDIATRIC AND CONGENITAL HEART DISEASE

Original Studies

Stenting vs. Balloon Angioplasty for Discrete Unoperated Coarctation of the Aorta in Adolescents and Adults

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More information is needed to clarify whether stenting is superior to balloon angioplasty (BA) for unoperated coarctation of the aorta (CoA). From September 1997, 21 consecutive adolescents and adults (24 ± 11 years) with discrete CoA underwent stenting (G1). The results were compared to those achieved by BA performed in historical group of 15 patients (18 ± 10 years; P = 0.103; G2). After the procedure, systolic gradient reduction was higher (99% ± 2% vs. 87% ± 17%; P = 0.015), residual gradients lower (0.4 ± 1.4 vs. 5.9 ± 7.9 mm Hg; P = 0.019), gain at the CoA site higher (333% ± 172% vs. 190% ± 104%; P = 0.007), and CoA diameter larger (16.9 ± 2.9 vs. 12.9 ± 3.2 mm; P < 0.001) in G1. Aortic wall abnormalities were found in eight patients in G2 (53%) and in one in G1 (7%; P < 0.001). There was no major complication. Repeat catheterization (n = 33) and/or MRI (n = 2) was performed at a median follow-up of 1.0 year for G1 and 1.5 for G2 (P = 0.005). Gradient reduction persisted in both groups, although higher late gradients were seen in G2 (median of 0 mm Hg for G1 vs. 3 for G2; P = 0.014). CoA diameter showed no late loss in G1 and a late gain in G2 with a trend to being larger in G1 (16.7 ± 2.9 vs. 14.6 ± 3.9 mm; P = 0.075). Two patients required late stenting due to aneurysm formation or stent fracture in G1. Aortic wall abnormalities did not progress and one patient required redilation in G2. Blood pressure was similar in both groups at follow-up (126 ± 12/81 ± 11 for G1 vs. 120 ± 15/80 ± 10 mm Hg for G2; P = 0.149 and 0.975, respectively). Although satisfactory and similar clinical outcomes were observed with both techniques, stenting was a better means to relieve the stenosis and minimize the risk of developing immediate aortic wall abnormalities. Catheter Cardiovasc Interv 2005;64:495–506.

Key words: coarctation of the aorta; stents, balloon; congenital heart disease; interventional cardiology

INTRODUCTION

Coarctation of the aorta (CoA) may occasionally present in adolescence or adulthood in the context of investigation for hypertension [1,2]. In these patients, the usual morphological pattern is that of a discrete stenosis distal to the left subclavian artery [1,2]. Because the natural history of untreated coarctation is complicated by cerebrovascular accidents, coronary artery disease, and premature death [3], relief of the obstruction should be undertaken in the setting of an arm-leg gradient over 20 mm Hg [1–3]. Although
surgical correction improves the natural history and assists in control of hypertension, significant immediate morbidity may occur in the adult population due to postoperative pain, bleeding, and paradoxical hypertension [4,5]. Balloon angioplasty of unoperated coarctation has been successfully employed as an alternative to surgery [6–12], although some have considered older age as a risk factor for suboptimal outcomes [13]. In addition, recoarctation and aneurysm formation may also be encountered as late complications [6–12]. In order to overcome these limitations, endovascular stents have been applied in the management of unoperated CoA with good immediate and midterm results [14–28]. Although it has been suggested that balloon angioplasty and stenting have provided similar outcomes for the adult with a discrete lesion [29], more information and clinical experience are needed in this common clinical scenario. Therefore, this study was conducted in order to clarify whether primary stenting would provide better outcomes than angioplasty in adolescents and adults with a discrete and unoperated CoA.

MATERIALS AND METHODS

Study Design and Patient Population

A database search identified 22 adolescents and adults who underwent balloon angioplasty for unoperated CoA at our institution between December 1988 and September 1997. From then on, all adolescents and adults with unoperated CoA were offered primary stenting as an alternative to surgery. For the sake of this open observational nonrandomized study, inclusion criteria included diagnosis of a discrete CoA by angiography or magnetic resonance imaging (MRI) with a systolic arm-to-leg blood pressure gradient of $>20$ mm Hg and age and weight over 10 years and 30 kg, respectively. Exclusion criteria included the presence of a long and tubular CoA; significant isthmus or transverse aortic arch hypoplasia defined as a ratio of the diameter of these structures to the descending aorta at the level of the diaphragm of $<0.6$ (25); blind CoA (or acquired aortic atresia); presence of aortic aneurysms before the intervention (adjacent ductal ampulla was not considered a contraindication); associated cardiac malformations requiring surgery; severe comorbid diseases; contraindications for a femoral intervention; and failure to comply with follow-up. According to these criteria, 21 consecutive patients agreed to be followed under a strict prospective protocol and underwent stent implantation (group 1, or G1). Out of the historical cohort of 22 patients who underwent balloon angioplasty, 7 were excluded due to mixed reasons (hypoplasia of the aortic arch/isthmus: $n = 4$; mild stenosis: $n = 1$; no follow-up after the intervention: $n = 2$), leaving 15 patients for a retrospective analysis (group 2, or G2).

This study was performed in compliance with the regulations of the Human Investigation Committee of our institution. Informed consent was obtained from patients or parents for the procedure.

Catheterization and Intervention Techniques

Oral intake was ceased a minimum of 6 hr before the scheduled procedure, which was performed under general endotracheal anesthesia or heavy sedation. After establishment of venous and arterial accesses, heparin sulfate was given (50–150 IU/kg; maximum 10,000 IU). Standard left catheterization was performed crossing the CoA site in a retrograde manner followed by aortic angiograms in left lateral, mid left anterior oblique, and shallow right anterior oblique (with caudal angulation if needed) views. Measurements of structures were made with correction for magnification. Generally, an angiographic catheter was left in the transverse arch from either a transseptal or a right brachial approach for test injections and simultaneous pressure measurements during the stenting procedure. A long and stiff guidewire was passed across the lesion and left in the ascending aorta, right or left subclavian artery depending on the straightest wire course.

The techniques of angioplasty and stent implantation were similar to those described previously [6–12,30]. The diameter of the balloon for either procedure was chosen to equal that of the proximal isthmus at the level of the takeoff of the left subclavian artery, not exceeding the diameter of the descending aorta at the level of the diaphragm. The isthmus diameter was also used to quantify the degree of stenosis. Balloon inflation was slowly performed by hand until the waist caused by the coarctation was eliminated. Inflation was repeated once or twice and the next larger balloon was inserted if the residual gradient remained $\geq 20$ mm Hg for the angioplasty procedure.

Three types of stents were used for primary stenting: the extra large 40 mm long Palmaz stent ($P$ 4014; Cordis, Miami, FL); the 34–45 mm long CP stent (NuMED, Hopkinton, NY) with eight zigs [27,31], and the 39–45 mm long covered CP stent (NuMED) with eight zigs [27,31]. The latter has become available at our institution since December 2001 and has been used for critical lesions ($<2–3$ mm), CoA in an older patient ($>30$ years of age), and those associated with a patent ductus arteriosus (PDA) or an aneurismatic ascending aorta. The stents were crimped onto a BIB balloon (NuMED) with the outer balloon being 0.5–1.0 cm longer than the stent. The CoA site was predilated.
follow-up. Hemodynamic success was arbitrarily defined as a residual gradient lower than 10 mm Hg immediately after the procedure. Line of dissection is the presence of a double-contour line in the aortic wall as demonstrated by angiography. Irregularity of the aortic wall is the presence of a minor external bulge measuring less than 3 mm by angiography. A small aneurysm was defined as an external bulge > 3 mm with no more than 50% of the diameter of the descending aorta at the level of the diaphragm by angiography or MRI. An external bulge measuring > 50% of the diameter of the aorta was considered a moderate aneurysm and ≥ 50 mm as a large aneurysm. Major complications include death, aortic rupture, cerebral vascular accidents, paraplegia, aneurysms ≥ moderate, and vascular lesions requiring surgery.

Statistical Analysis
Quantitative data are presented as mean and standard deviation or median and range as applicable. Categorical variables are presented as numbers and frequencies and were compared using a chi-square or Fisher’s exact test as applicable. The presence of symptoms before and after the procedure was compared using a Wilcoxon test. Quantitative variables were compared between groups using a two-tailed unpaired t-test or a Mann-Whitney test. Quantitative variables before and after the procedure were compared in the same group using a Student’s paired t-test or a Wilcoxon rank-sum test. Quantitative variables with repeated measures over time were compared in both groups using a generalized linear model for analysis of variance. Statistical analysis was performed using SPSS 10.0 for Windows (SPSS Institute, Chicago, IL) and a SigmaStat 2.0 for Windows (Jandel) softwares. The level of significance was set at 0.05.

RESULTS
Patient Characteristics
Clinical and demographic data (Table I) were similar in both groups before the intervention except for the more frequent use of antihypertensives in G1. The distribution of associated conditions was also similar in both groups (Table I).
Acute Results

Technical aspects of procedures. All procedures were completed successfully in both groups. In G1, predilation of the lesion was employed in 6 patients (29%) and the BIB balloon in 19 patients (90%). In two patients, there was distal stent migration. In one of these, migration occurred during stent deployment using a conventional balloon with the same length of the stent. In the other patient with a critical lesion, a staged approach was used for stent deployment (isthmus diameter, 18 mm; balloon diameter, 12 mm) and migration occurred following attempts at flaring the ends of the stent with a 15 mm diameter balloon. In both cases, the uncovered stents were implanted in the descending aorta uneventfully followed by a second and successful stent implantation in the stenotic area. However, due to a small aneurysm formation in the second patient, a Braile stent was implanted with immediate exclusion of the aneurysm. In total, 23 stents were used, consisting of 12 regular CPs, 3 covered CPs, 7 Palmaz, and 1 Braile. The mean diameter of the balloon used for stent delivery and angioplasty was 17.7 \(\pm\) 3.3 mm (12–25) and 16.3 \(\pm\) 3.0 mm (12–20), respectively (\(P = 0.214\)). In both groups, the balloon/isthmus diameter ratio was 1.0 \(\pm\) 0.1 (\(P = 0.688\)). One patient with severe aortic stenosis in G1 was submitted to balloon dilation before stent implantation. The procedure time was 2.5 \(\pm\) 0.6 hr (1.5–4.0) for G1 and 1.9 \(\pm\) 0.6 hr (1.0–2.5) for G2 (\(P = 0.003\)).

Angiographic analysis before and after procedure. Although the CoA diameter and the degree of stenosis were similar in both groups before the intervention and were significantly improved afterward, the post-CoA diameter was larger, the immediate gain in the dilated area was higher, and the degree of residual stenosis was lower in G1 (Table II). Aortic wall abnormalities were observed in one patient in G1 (5%; a small aneurysm as mentioned before) and in eight patients in G2 (53%; \(P < 0.001\)), including dissections (n = 2), irregularities of the aortic wall (n = 4), and small aneurysms (n = 2). There was no difference between various variables in patients with and without aortic wall abnormalities in G2, as seen in Table III.

Hemodynamics before and after procedure. The hemodynamic variables were similar in both groups before the intervention as shown in Table IV. After the intervention, success was achieved in all patients in G1 (100%) and in 11 patients in G2 (73%; \(P = 0.023\)). Although gradient reduction was statistically

<table>
<thead>
<tr>
<th>Variables</th>
<th>Group 1 (n = 21) mean (SD)</th>
<th>Group 2 (n = 15) mean (SD)</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CoA, mm</td>
<td>4.6 (2.1)</td>
<td>5.0 (2.2)</td>
<td>0.553</td>
</tr>
<tr>
<td>Isthmus, mm</td>
<td>18.1 (2.6)</td>
<td>16.5 (3.1)</td>
<td>0.113</td>
</tr>
<tr>
<td>% stenosis</td>
<td>74.8 (11.3)</td>
<td>70.1 (10.4)</td>
<td>0.210</td>
</tr>
<tr>
<td>Post</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CoA, mm</td>
<td>16.9 (2.9)</td>
<td>12.9 (3.2)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>% stenosis</td>
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<td>23.5 (10.0)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>% immediate gain</td>
<td>332.8 (171.9)</td>
<td>189.6 (104.3)</td>
<td>0.007</td>
</tr>
</tbody>
</table>

TABLE II. Quantitative Analysis of the Aorta Pre- and Postintervention

<table>
<thead>
<tr>
<th>Variables</th>
<th>Group 1 (n = 21) mean (SD)</th>
<th>Group 2 (n = 15) mean (SD)</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td></td>
<td></td>
<td></td>
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<tr>
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</tr>
<tr>
<td>Post</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CoA, mm</td>
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<td>12.9 (3.2)</td>
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</tr>
<tr>
<td>% stenosis</td>
<td>5.4 (6.5)</td>
<td>23.5 (10.0)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>% immediate gain</td>
<td>332.8 (171.9)</td>
<td>189.6 (104.3)</td>
<td>0.007</td>
</tr>
</tbody>
</table>
significant in both groups ($P$ for both $< 0.001$), the residual gradient was lower and the degree of gradient reduction was higher in G1 (Table V). In addition, pressure changes behaved differently in each group. In G1, there was no significant change in systolic pressure in the ascending aorta ($P = 0.910$), and an increase in systolic pressure in the descending aorta ($P < 0.001$), in diastolic pressure in the ascending aorta ($P = 0.028$), and in the descending aorta ($P < 0.001$). In G2, there was a decrease in systolic pressure in the ascending aorta ($P = 0.004$), an increase in systolic pressure in the descending aorta ($P = 0.003$), and no significant change in diastolic pressure in the ascending ($P = 0.400$) and in the descending aorta ($P = 0.546$).

In-hospital course. No major complication occurred in either group. Nitroprusside was used for less than 18 hr in three patients in G1 and one patient in G2 to control systemic hypertension. Blood transfusion was required in one patient in each group. Two patients from G1 complained of diffuse thoracic pain requiring the use of opioids. Mildly diminished right femoral pulse at the site of balloon insertion was observed in one patient from G2, not requiring surgery. A hematoma at the right brachial crease was detected in one patient in G1, subsequently requiring antibiotics due to local infection. In-hospital stay was a mean of 1.4 ± 0.7 days for G1 and 1.7 ± 0.7 for G2 ($P = 0.334$).

Follow-Up

Hemodynamic and angiographic evaluation. Repeat catheterization was performed in 19 patients in G1 and in all patients in G2. Two patients in G1 had an angio MRI done. The time elapsed for these investigations was a median of 1.0 year (0.5–2.5) for G1 and 1.5 (0.9–14.5) for G2 ($P = 0.005$). The mean age

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**TABLE III. Comparison of Variables Between Patients With and Without Aortic Wall Abnormalities After Balloon Angioplasty**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Without abnormalities (n = 7)</th>
<th>With abnormalities (n = 8)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demographic, mean (SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age, years</td>
<td>20.4 (14.0)</td>
<td>16.2 (5.6)</td>
<td>0.779</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>49.4 (14.2)</td>
<td>53.9 (5.6)</td>
<td>0.608</td>
</tr>
<tr>
<td>Height, cm</td>
<td>158.4 (9.8)</td>
<td>158.0 (17.6)</td>
<td>0.867</td>
</tr>
<tr>
<td>Hemodynamic, mean (SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systolic gradient pre, mm Hg</td>
<td>56.7 (17.2)</td>
<td>44.4 (14.4)</td>
<td>0.154</td>
</tr>
<tr>
<td>Systolic gradient post, mm Hg</td>
<td>6.6 (8.7)</td>
<td>5.4 (7.8)</td>
<td>0.779</td>
</tr>
<tr>
<td>Angiographic, mean (SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CoA pre, mm</td>
<td>4.4 (2.6)</td>
<td>5.5 (1.9)</td>
<td>0.377</td>
</tr>
<tr>
<td>CoA post, mm</td>
<td>12.6 (4.0)</td>
<td>13.2 (2.6)</td>
<td>0.738</td>
</tr>
<tr>
<td>Gain, %</td>
<td>227.3 (128.4)</td>
<td>156.7 (70.4)</td>
<td>0.202</td>
</tr>
<tr>
<td>Isthmus, mm</td>
<td>17.0 (3.3)</td>
<td>16.0 (3.1)</td>
<td>0.565</td>
</tr>
<tr>
<td>Technical, mean (SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balloon diameter, mm</td>
<td>16.7 (3.3)</td>
<td>16.0 (3.0)</td>
<td>0.613</td>
</tr>
<tr>
<td>Associated conditions, n (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bicuspid aortic valve</td>
<td>5 (71)</td>
<td>4 (50)</td>
<td>0.608</td>
</tr>
</tbody>
</table>

**TABLE IV. Analysis of the Hemodynamic Variables According to the Technique Employed**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group 1 (n = 2), mean (SD)</th>
<th>Group 2 (n = 15), mean (SD)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre intervention, mm Hg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systolic pressure in ascending aorta</td>
<td>141.9 (27.3)</td>
<td>146.9 (22.0)</td>
<td>0.559</td>
</tr>
<tr>
<td>Systolic pressure in descending aorta</td>
<td>94.7 (19.4)</td>
<td>96.8 (15.4)</td>
<td>0.726</td>
</tr>
<tr>
<td>Systolic gradient</td>
<td>47.3 (19.7)</td>
<td>50.1 (16.5)</td>
<td>0.651</td>
</tr>
<tr>
<td>Diastolic pressure in the ascending aorta</td>
<td>78.0 (14.9)</td>
<td>83.4 (18.2)</td>
<td>0.339</td>
</tr>
<tr>
<td>Diastolic pressure in the descending aorta</td>
<td>67.9 (17.1)</td>
<td>74.7 (14.2)</td>
<td>0.220</td>
</tr>
<tr>
<td>Post intervention, mm Hg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systolic pressure in ascending aorta</td>
<td>141.2 (20.8)</td>
<td>124.5 (22.7)</td>
<td>0.028</td>
</tr>
<tr>
<td>Systolic pressure in descending aorta</td>
<td>140.8 (21.1)</td>
<td>118.5 (21.6)</td>
<td>0.004</td>
</tr>
<tr>
<td>Systolic gradient</td>
<td>0.4 (1.4)</td>
<td>5.9 (7.9)</td>
<td>0.019</td>
</tr>
<tr>
<td>% decrease in Systolic gradient</td>
<td>99.5 (1.8)</td>
<td>87.3 (17.0)</td>
<td>0.015</td>
</tr>
<tr>
<td>Diastolic pressure in the ascending aorta</td>
<td>86.2 (13.0)</td>
<td>78.8 (15.0)</td>
<td>0.122</td>
</tr>
<tr>
<td>Diastolic pressure in the descending aorta</td>
<td>86.8 (13.4)</td>
<td>77.7 (14.0)</td>
<td>0.056</td>
</tr>
</tbody>
</table>
of patients at the time of these investigations was a mean of 25.7 ± 10.4 years for G1 and 22.2 ± 13.1 for G2 (P = 0.783). The late residual gradient, the diameter at the CoA site, and the degree of residual stenosis at the time of these investigations are demonstrated in Table V. The time-related behavior of the systolic gradient and the CoA diameter are shown in Figures 1 and 2, respectively. Figure 3 demonstrates maintenance of the initial results in a patient from G1. Figure 4 shows late diameter gain at the site of CoA in a patient from G2. At follow-up, out of four patients from G2 in whom there was an immediate residual gradient between 14 and 22 mm Hg, in one patient the gradient decreased to 3 mm Hg, in two to 10 mm Hg, and in the remaining patient the gradient has not changed (14 mm Hg). A residual gradient of 30 mm Hg was detected in another patient who had initial hemodynamic success.

Although stent fractures were observed in four patients in whom the CP stent was used (27%) and in none having the Palmaz stent, this difference did not reach statistical significance (P = 0.263). A single and localized fracture between two rows was seen in three patients and a circumferential fracture all along the wire mesh was seen in the other. Mild intrastent neointimal proliferation of 1–2 mm was observed in four patients in whom the Palmaz stent was employed (57%) and in one patient having the CP stent (7%; P = 0.021).

A moderate aneurysm measuring 20 mm was observed in a 51-year-old patient in G1 at repeat catheterization 1 year after a covered CP stent implantation. He had an aneurysmal ascending aorta and had previously undergone two aortic valve replacements due to a dysfunctional bicuspid aortic valve. Regarding the aortic wall abnormalities seen initially in G2, the line of dissection disappeared in two patients and there was no progression in size of the mild irregularities seen in four patients and the small aneurysm in the other two.

Clinical and echocardiographic findings. The follow-up duration was a median of 1.8 years (0.5–5.0) for G1 and 5.0 (1–16) for G2 (P = 0.037). The mean age of patients at the time of the last follow-up visit was a mean of 26.4 ± 10.6 years for G1 and 23.6 ± 12.7 for G2 (P = 0.876). Systolic and diastolic pressures taken in the upper limbs was a mean of 126.2 ± 11.6 and 80.5 ± 10.7 mm Hg, respectively, for G1, and a mean of 119.7 ± 14.9 and 80.2 ± 10.1 for G2. There was no difference in systolic and diastolic pressures between the groups (P = 0.149 and 0.975, respectively). The systolic gradient between the upper and lower limbs was lower in G1 (−6.2 ± 6.5 for G1 vs. 1.3 ± 11.7 mm Hg for G2; P = 0.036). One patient in G2 had a gradient of 30 mm Hg and was diagnosed with recoarctation. It was possible to discontinue

<table>
<thead>
<tr>
<th>Variables</th>
<th>Group 1</th>
<th>Group 2</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systolic gradient, mm Hg</td>
<td>Median</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>0–7</td>
<td>0–30</td>
</tr>
<tr>
<td>CoA, mm</td>
<td>Mean (SD)</td>
<td>16.7 (2.9)</td>
<td>14.6 (3.9)</td>
</tr>
<tr>
<td>Isthmus, mm</td>
<td>Mean (SD)</td>
<td>17.8 (2.5)</td>
<td>17.2 (3.4)</td>
</tr>
<tr>
<td>% residual stenosis</td>
<td>Mean (SD)</td>
<td>6.1 (8.7)</td>
<td>15.6 (12.8)</td>
</tr>
</tbody>
</table>

aP = 0.142.
bP = 0.065 (when compared to values before the intervention).

Fig. 1. Time-related systolic gradient behavior in the two groups. Both groups behaved in a similar fashion over time (no interaction) with a significant acute decrease followed by late stabilization. Intervals show 95% confidence limit.

Fig. 2. Time-related coarctation diameter behavior in the two groups. Each group behaved differently over time (interaction). In G1, there was an acute increase followed by late stabilization. In G2, there was a less marked acute increase followed by an additional late and significant increase. Intervals show 95% confidence limit. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]
the use of antihypertensives in 14 patients in G1 (66%) and 12 patients in G2 (80%; $P = 0.468$) and reduce dosages in the remaining patients in both groups. All patients were in functional class I at follow-up and there was a reduction in the prevalence of symptoms from 71% to 10% in G1 ($P < 0.001$) and from 53% to 13% in G2 ($P = 0.034$), with no difference between groups ($P > 0.999$). The patient with diminished pulses in the right leg did not have any limb shortening after 6.5 years. Maximal systolic gradient at the CoA site determined by transthoracic Doppler echocardiography was a mean of $15.8 \pm 10.8$ mm Hg in G1 and $23.8 \pm 13.9$ in G2 ($P = 0.088$).

**Reinterventions.** Two patients in G1 required reinterventions. The patient with late moderate aneurysm formation was successfully treated using a covered Braile stent with complete exclusion of the aneurysm. The other patient with a circumferential fracture in the

**Fig. 3.** Aortic angiograms in the lateral view. Left: Critical discrete coarctation of the aorta associated with a small patent ductus arteriosus and a normal-sized isthmus. Middle: There is significant diameter increase at the coarctation site after implantation of a covered CP stent (NuMED). The patent ductus arteriosus was immediately closed. Right: Repeat angiogram a year after the procedure. There is no stent recoil at the coarctation site and no significant neointimal proliferation within the stent. A slight indentation persists at the posterior aspect of the aortic wall.

**Fig. 4.** Aortic angiograms in right oblique view with slight caudal angulation. Left: Severe coarctation of the aorta associated with a normal sized isthmus. Middle: There is significant diameter increase at the coarctation site immediately after balloon angioplasty. A mild irregularity is observed at the medial aspect of the aortic wall. Right: Repeat angiogram 2 years after the procedure. There is an additional gain at the dilated site and normalization of the aortic contour.
CP stent with angulation of the vessel and protrusion of the stent struts into the aortic wall was treated using a covered Braile stent with straightening of the aortic contour. There was no need to redilate the stents during follow-up. One patient in G2 required reintervention due to recoarctation with a 30 mm Hg residual gradient treated successfully by a new angioplasty.

**DISCUSSION**

Both techniques were considered a safe and effective means for sustained gradient relief for adolescents and adults with a discrete and unoperated CoA. The rate and severity of complications were limited and both procedures yielded satisfactory and similar clinical outcomes at follow-up, allowing for better control of systemic hypertension. However, stenting was associated with more predictable and uniform results, which may have important implication in this patient population, as discussed below.

**Clinical and Demographic Features**

Even though these features were similar in both groups before intervention, which minimizes the risk of patient selection bias, the use of antihypertensives was more common in patients in G1. This probably reflects a physician’s more aggressive attitude when managing systemic hypertension in more recent times or might have been related to a trend to higher diastolic pressures seen in G1. Since similar aortic pressures measured invasively in the catheterization laboratory were observed in both groups before the interventions, it is unlikely that the more frequent use of these drugs in G1 played a role in the more significant gradient fall across the CoA site in this group.

**Technical Aspects**

Although this study encompasses the learning curve for both angioplasty and stenting, the higher procedural times observed in G1 reflects the more demanding technique required for stent implantation. We think that the two episodes of stent migration in this series were related to technical issues and could have been prevented. The use of a conventional single balloon with the same length of the stent for deployment as observed in a patient in this series, although advocated by some [21,29], may exacerbate the fluctuation phenomenon that commonly occurs during stent delivery [31], predisposing to stent slippage and migration. In our hands, the use of the BIB balloon allowed for a more controlled stent delivery, avoiding these problems. In the other patient, we speculate that, as a result of a staged approach, the underexpanded stent was not stable enough to allow for further manipulations for flaring the ends. A staged stent dilation has been recommended for patients with critical lesions [20,34], avoiding an abrupt increase in the CoA site, which may result in aortic wall dissection, rupture, or aneurysm formation. In this series, these complications were not observed after immediate full expansion of the stent in younger patients with noncritical lesions not associated with an aneurismal ascending aorta. On the other hand, it is generally accepted that the use of a covered stent may further minimize the above risks [35,36]. However, this was not the case in a patient in this series with markers of aortic wall weakness such as an advanced age, aneurismal ascending aorta, and a dysfunctional bicuspid valve requiring replacement [37–39]. Late aneurysm formation occurred unexpectedly and silently despite the use of a covered CP stent. This might have been related to tears or shrinkage in the ePTFE membrane [40]. Whether a staged approach is helpful to prevent this complication in such patients remains to be seen in further trials. Therefore, close follow-up using imaging techniques is mandatory in all patients with CoA submitted to percutaneous treatment [41]. Although some advocate flaring the ends of the stent to optimize endothelialization [25], it is unlikely that complete stent apposition in the poststenotic region is achieved in all patients using stents expandable up to 25 mm such as the Palmaz 4014 and the CP stent with eight zigs. If the main goal of stenting CoA is gradient relief, this is attained regardless of complete apposition of the stent in the poststenotic area and a more cosmetic angiographic result. As such, we do not recommend flaring routinely.

In this series, the use of stents was associated with a lower incidence of aortic wall abnormalities after the procedure. Because the stent works as a scaffold to the vessel wall and disperses the radial forces of the balloon in larger areas, it probably controls minor dissections and minimizes the risk of aneurysm formation [42]. The occurrence of an aneurysm formation immediately after stent migration in a patient herein corroborates with this affirmation. We were unable to detect risk factors for the development of such abnormalities following balloon angioplasty. This may be due to the limited number of patients in this series and a constant balloon/isthmus diameter ratio used for the entire cohort. Age and oversized balloons have been implicated as risk factors for the development of aneurysms following angioplasty in the literature [43].

**Acute Hemodynamics and Angiographic Findings**

Lower gradients and larger diameters at the CoA site were observed immediately after stenting. This results from neutralization of the elastic recoil of the vessel
commonly seen after balloon angioplasty. Theoretically, if the stent was more effective to reduce the gradient, lower pressures in the aorta should have been seen after the application of this technique. However, this did not occur and higher systolic and diastolic pressures were in fact observed in the ascending and descending aorta. We speculate that a more pronounced systemic adrenergic response occurs after stenting when compared to angioplasty. A sudden and sustained stretching of the aortic wall caused by stent implantation may induce a more intense vascular trauma in a similar way to what it is observed after surgical repair [44,45]. However, since paradoxical hypertension was not commonly observed in the postimplantation period, it is likely that this phenomenon is transient and self-limited.

**Hemodynamics and Angiographic Findings at Follow-Up**

Although both techniques were similarly effective to provide sustained gradient relief, stenting was associated with lower gradients at follow-up catheterizations. Although gradients ≤ 20 mm Hg have been considered as satisfactory endpoints for treated patients with CoA, there are no data demonstrating that gradient reduction below a predefined limit confers sustained benefit [42]. It has been speculated that even mild residual stenoses associated with low gradients may increase the risk of cardiovascular events such as persistent hypertension, cerebrovascular accidents, early coronary artery disease, and negative impact on ventricular function [42,46]. In this regard, increased left ventricular mass and hypertrophy and altered systolic and diastolic function have all been documented in patients with residual gradients operated on for CoA [47–51]. In our view, the older patients with unoperated CoA represent a small subgroup particularly at risk to develop such complications. It is under this context that the lower gradients observed late after stenting should be considered. In other words, we believe that it is of paramount importance to provide the best means for gradient relief, i.e., stenting, in these patients.

Repeated-measures analysis demonstrated that there was an additional late gain at the CoA region and a trend to a larger isthmus diameter in patients undergoing balloon angioplasty, equalizing the CoA diameter in both groups at follow-up. This probably results from remodeling of the dilated aorta, as already documented by some [52,53]. The trend toward a larger diameter at the CoA site seen in G1 at follow-up would probably have reached statistical significance with larger number of patients.

This study suggests that the abnormalities in the aortic wall more commonly observed after balloon angioplasty have a generally benign natural history, with involution or stabilization of the initial findings at late follow-up. The lack of unanimity of what constitutes an aneurysm is responsible for the variable incidence of this complication in the literature [3]. We take the approach that small aneurysms (less than 50% of the aortic diameter) should be followed clinically, with strict control of blood pressure levels and close surveillance using imaging techniques. In order to reduce the likelihood of rupture, larger aneurysms should undergo occlusion using coils as described before [54] or exclusion using self-expandable stents as seen in a patient in this series.

**Differences Between Stents**

Acknowledged in clinical practice but infrequently reported [27,31], the occurrence of fractures within the CP stent was well documented in this series. Although a localized fracture between two rows is probably benign with limited clinical implications, a circumferential fracture, such as seen in a patient herein, may result in distal embolization of the fragments and unpredictable consequences. Because there was no change in the stent position at late catheterization, we speculate that this type of fracture occurred after endothelialization of the intravascular implant. Refinement of the welding process using gold have been employed by the manufacturer to manage this problem (John Cheatham, personal communication). However, the efficacy of this modification remains to be documented in further trials. The large experience accumulated with the Palmaz stents has shown that longitudinal fractures within large stents implanted in the pulmonary arteries are exceedingly rare [55]. This complication has not been documented with extra large stents in the aorta, probably due to its somewhat thicker wire mesh. On the other hand, mild neointimal proliferation was more commonly observed with the Palmaz stent, likely because this stent is less radiopaque than the CP stent [31]. Since the vascular lumen is large in the adult aorta, a mild intrastent proliferation does not result in flow obstruction and local gradient generation.

**Clinical Outcomes**

Both techniques were similarly effective to normalize blood pressure levels in both cohorts of patients, which allowed either discontinuation or dosage reduction of antihypertensive agents as reported before [24,56,57]. In addition, symptoms were less prevalent in both groups at follow-up. However, lower gradients between upper and lower limbs at rest were seen in the stent group. Whether this observation represents an advantage in terms of cardiovascular risk reduction is speculative since this difference may not be clinically
relevant and hypertension was well controlled in both groups. Therefore, we acknowledge that the impact of primary stenting on achieving better clinical outcomes than primary angioplasty remains to be seen with longer follow-up and in further trials. We also acknowledge that primary angioplasty leaves open the possibility of future stenting if an adequate long-term result is not obtained [29]. Although exercise testing was not employed in this series to assess exercise-induced hypertension, the value of this test has been questioned recently [58]. Increased stiffness and altered relaxation vascular reserve in the upper body vessels have been implicated in the etiology of hypertension at rest and during exercise after repair [59–61]. Since the stent is a rigid metallic structure, it may theoretically increase the gradient across the CoA site at exercise, although preserved aortic compliance has been documented in animal models after stent implantation in the aorta [62].

The rate of reinterventions was similar in both groups at follow-up. Recoarctation was observed in a patient in G2 treated successfully by a second angioplasty and in none in G1. Due to neutralization of the elastic recoil and elimination of the deleterious effects of late local scarring with negative remodeling, it is unlikely that restenosis becomes an issue in patients managed by stenting. In addition, it is unlikely that increasing gradients due to progressive intimal proliferation within the stent will be encountered in mid- to long-term follow-up of these patients due to the size of the aorta. On the other hand, two patients in G1 required reinterventions, one for late aneurysm formation, as discussed above, and the other for stent fracture. Although the decision to implant a self-expandable covered stent was arbitrary in that patient, straightening of the stent inside the vessel along with intravascular coverage probably minimized the risk of aortic wall perforation due to protrusion of the stent struts.

Study Limitations

The noncontemporary time frame between the groups is one of the limitations of this study, although the technique of angioplasty has not changed significantly since its introduction. The small number of patients makes risk assessment less accurate, especially considering the low rate of complications encountered. Also, the follow-up period is still limited in patients managed by stenting. Other tools such as ambulatory monitoring of blood pressure could be explored in further trials to better assess late clinical outcomes. Echocardiographic and/or MRI evaluation of left ventricular mass and hypertrophy, as well as systolic and diastolic function, could also be helpful in this regard. Finally, a huge effort should be undertaken to set up a multicenter prospective randomized clinical trial, including a surgical arm, to define the best form of treatment for CoA in this age group.

Although stenting and angioplasty were similarly effective to control systemic hypertension in adolescents and adults with unoperated and discrete CoA, the former was associated with a lower incidence of aortic wall abnormalities, lower residual gradients, and less residual stenosis at the CoA site immediately after the procedure and at follow-up. In our view, these more predictable and uniform results may have important clinical implications in this patient population, justifying the continued use of primary stenting.

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