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Systemic Blood Pressure After Stent Management for Arch Coarctation Implications for Clinical Care

Gareth J. Morgan, MB, BAO, BCH, MPHIL, Kyong Jin Lee, MD, Rajiv Chaturvedi, MD, PHD, Timothy J. Bradley, MB, CHB, Luc Mertens, MD, Lee Benson, MD

Toronto, Ontario, Canada

Objectives The goal of this study was to prospectively assess blood pressure (BP) and echocardiographic parameters to delineate the incidence and nature of the hypertension burden in this cohort.

Background Few data are available on the long-term outcomes of aortic stenting.

Methods Thirty-one patients with successfully stented coarctation during childhood (mean age 12.4 years) underwent 24-h ambulatory BP monitoring (ABPM), exercise BP measurement, and echocardiographic assessment.

Results Mean time after stent implantation was 5.3 ± 4 years. Hypertension was noted on one-off right-arm BP assessment in 3 patients (10%), but on the basis of the 24-h ABPM assessment in 14 patients (45%). Twenty-four of 31 patients (80%) had an abnormally elevated exercise BP response. Peak exercise BP correlated with left ventricular mass index ($r = 0.51$; $p < 0.05$), which was also significantly increased in the entire cohort (mean = 91.3 g/m^2; $p < 0.05$). In patients with significant somatic growth since implantation, the indexed diameter of the stent (to aortic diameter) had significantly decreased from the 48th percentile at the implantation to the 4th percentile during the study ($p < 0.05$). There was no difference in any parameter between patients with native or those with recurrent coarctation.

Conclusions Hypertension is endemic in patients with stented coarctation, irrespective of the absence of residual obstruction. Due to abnormal BP homeostasis, hypertension should be aggressively pursued by ABPM assessment and exercise stress testing in this population. Relative hypoplasia of the stented arch after somatic growth may contribute to this tendency and should provoke consideration of elective serial redilation of coarctation stents. (J Am Coll Cardiol Intv 2013;6:192–201) © 2013 by the American College of Cardiology Foundation

From the Department of Pediatrics, Division of Cardiology, the Labatt Family Heart Center, the Hospital for Sick Children, the University of Toronto School of Medicine, Toronto, Ontario, Canada. Dr. Lee is a consultant for Abbott Canada. All other authors have reported that they have no relationships relevant to the contents of this paper to disclose.

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Coarctation of the aorta (CoA) accounts for 5% to 8% of all congenital heart lesions presenting in infancy (1). Since the first surgical correction in 1944, numerous treatment strategies have been described and tested to relieve the arch obstruction (2,3). In the last 2 decades, percutaneous approaches have attained clinical prominence with excellent short-term clinical outcomes (3–6). A comprehensive understanding of the pathophysiology after arch repair, in regard to intrinsic systemic vascular abnormalities and blood pressure (BP) homeostasis is in its infancy. Multiple studies have shown abnormal responses to exercise in all age groups whether addressed surgically or by stent or balloon dilation. However, the clinical significance of these abnormal responses has not been fully characterized (7–12).

Although several authors have assessed resting, ambulatory, and exercise BP response, few studies have prospectively assessed a cohort to determine the longer-term impact on cardiovascular physiology (13,14). Thus, the goals of this study were first to delineate the incidence of hypertension through analysis of multiple BP parameters at medium- to long-term follow-up after successful stent implantation, and second, to identify patient and treatment characteristics that may be associated with an increased hypertensive burden.

Methods

Study design. One hundred ten children were identified from the cardiac interventional database that had stent implantation for CoA at age <18 years, between September 1995 and November 2009. Indications for stent implantation were a cuff systolic upper-to-lower limb BP gradient of >20 mm Hg with angiographic confirmation of the lesion, either a recurrent (reCoA) or so-called native (naCoA) obstruction in the isthmus region of the aorta. From this population, 41 children had a previous surgical repair with reCoA and 69 had an naCoA. Sixteen patients were excluded; 4 who were <8 years of age and not felt to be able to cooperate with the exercise protocol; 8 due to complex intracardiac anatomy; and 4 due to a physical disability that disallowed formal exercise testing (ET). Of the remaining 94, 11 patients were not contacted because they lived outside of Ontario, 18 could not be contacted, and 28 patients did not wish to participate in the study. Two patients had hemodynamically insignificant intracardiac abnormalities considered not to influence the study, along with 15 patients with bicuspid aortic nonstenotic valves. Thirty-seven patients agreed to participate in the study. Of these, 6 patients failed to attend their appointments. As such, 31 patients were recruited to participate in the study, which included clinical and echocardiographic assessment, ET and BP assessment, and 24-h ambulatory blood pressure monitoring (ABPM). One patient who had ABPM monitoring failed to attend the exercise component of the protocol. Surgical and interventional details, including angiography, were reviewed to define arch measurements following the most recent intervention, specifically the minimum stent diameter and compared with published normative data (15). Invasive gradients and follow-up arm and leg BPs were documented to determine procedural success. The study was approved by the institutional review board and the research ethics committee, and informed, written consent was obtained from all subjects.

Resting and exercise BP measurement and echocardiographic assessment. Resting BPs were measured with a GE Dinamap ProCare system (Critikon, Tampa, Florida), immediately before a standardized recumbent bicycle staged exercise study. Resting BP was recorded as an average of 2 readings taken from the right arm sitting, over a 5- to 10-min period immediately before exercise, and from the noncatheterized leg. All femoral pulses were easily palpable. Echocardiographic examinations were performed by 2 experienced cardiac sonographers, using a Vivid 7 echocardiographic system (GE Corp., Wauwatosa, Wisconsin) with probe frequencies selected as appropriate for patient size. A full baseline echocardiographic study was performed before exercise according to our clinical standard coarctation protocol, which includes apical 4-chamber, parasternal short-axis, and parasternal long-axis views, acquired according to published guidelines. Left ventricular mass was calculated according to the Devereux formula and indexed to body surface area. After the baseline echocardiographic study, an exercise study was performed on a reclining bike (Lode, Groningen, the Netherlands). During exercise, peak gradients were recorded through the stented aorta using continuous-wave Doppler techniques.

Abbreviations and Acronyms

ABPM = ambulatory blood pressure monitoring
BP = blood pressure
BSA = body surface area
CoA = coarctation of the aorta
ECG = electrocardiography
EIH = exercise-induced hypertension
ET = exercise testing
LVMI = indexed left ventricular mass
MASBP = mean ambulatory systolic blood pressure
naCoA = native coarctation
reCoA = recurrent coarctation

BP measurement, electrocardiography (ECG), and stress echocardiographic assessment was then performed on a semirecumbent cycle ergometer during progressive exercise in incremental stages. Bicycle pedaling was begun at 25 W and increased by 25 W every 2 min with the right arm BP taken every 2 min during exercise using the Dinamap system. The test was either symptom-limited (fatigue, chest pain, ECG changes) or when the target heart rate (defined as 80% of the maximal heart rate for age) was reached.

An abnormal systolic BP response to exercise (exaggerated absolute rise) or exercise-induced hypertension (EIH), was defined using published normal adult and pediatric values as appropriate (see Results) (16–22). During exercise,

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echocardiographic imaging was performed at each incremental stage, in the transthoracic parasternal long- and short-axis and apical views. Just before volitional fatigue as indicated by the subject, the peak instantaneous pressure Doppler gradient through the stent was reassessed in the long-axis suprasternal view.

Ambulatory BP assessment. Spacelabs Ultralight or Spacelabs 90207 (Spacelabs, Issaquah, Washington) ABPM monitors were used for 24-h BP assessment. Twenty-four–hour circadian variability (normal variability >10% between daytime and nighttime values, so-called "dipping"), as well as night and daytime mean systolic and diastolic BPs, were recorded. An appropriately sized cuff was placed on the right arm (no patient had an aberrant right subclavian artery), and the investigation was repeated if <85% of attempted readings were successful. Hypertension was defined as either a 24-h mean ambulatory systolic BP (MASBP) of >95th percentile for sex and height or a systolic BP load (percentage of the 24-h period at >95th percentile) of >40% (18–22).

Statistical analysis. Data are presented as medians with ranges, or means with standard deviations, as appropriate. Comparison with published normal morphological data was performed for the study group as indicated using a 1-sample *t* test to assess the difference in means. Paired *t* tests were used to assess changes in measured parameters in an individual after an intervention and over time (e.g., between stent intervention and study enrollment). For nonparametric data, the Mann–Whitney *U* test was used for unpaired samples. and the Wilcoxon signed rank test for paired samples. Correlation (Pearson coefficient) plots were performed to assess correlation statistics in the datasets. Fisher contingency tables were used to assess significant relationships within categorical data. A $p < 0.05$ was considered statistically significant.

Results

Patient characteristics. Relevant demographics and clinical details for each subject are listed in Table 1, and parameters referring to the acute efficacy of the stent intervention are presented in Table 2. Thirty-one patients with stented reCoA (n = 11) or naCoA (n = 20) participated in the study. Nine patients had balloon dilation or an additional stent implantation to their lesion following the initial stent procedure. The median age at initial stent implantation was 13.1 years (range 4.5 to 17.8). The median follow-up (time since initial stent implantation) was 5.8 years (range 0.2 to 14.1), and median time from the last percutaneous procedure to the study follow-up was 2.7 years (range 0.2 to 14.1). All stent procedures were clinically successful, with a median *z*-score for the minimum diameter of the stented lesion of −0.1 (−3.0 to 3.2) (15). Acute invasive pull-back gradients following implantation were a mean 2.8 ± 3.7 mm Hg. Initial follow-up data (between 6 weeks and 6 months of intervention) were retrospectively available in 24 of the 31 patients, with the documented resting BP being >95th percentile for sex- and height-matched controls in 10 of 24 cases (42%). There was no significant difference in demographics or clinical characteristics between those with an naCoA or reCoA.

Resting and ambulatory BP monitoring. Resting BP obtained before exercise identified 3 patients (9.7%) as hypertensive (resting systolic BP >95th percentile for height), 2 of which were being treated for hypertension. The median resting BP for the study group was at the 70.5 percentile (range 0.1 to 99th percentile). The median right arm-to-leg resting BP gradient was 1 mm Hg (range: 0 to 34 mm Hg). Three patients were found to have a right arm-to-leg BP gradient of >10 but <20 mm Hg; and 4 a gradient of ≥20 mm Hg.

Hypertension was identified on ABPM in 14 patients (45%), by both a MASBP >95th percentile and increased BP load of >40% (18,19,23–25). Masked hypertension (hypertension found on ABPM analysis not recognized on one-off office readings) was detected in 7 (26%) of the cohort. Loss of BP circadian rhythm (dipping) was noted in 7 (23%) (Patients #18, #22, #23). The study groups' MASBPs were clustered around the 78th percentile, the level of divergence from the normal percentile spread being significant ($p < 0.05$). MASBP values and percentiles were significantly higher than the corresponding resting one-off systolic BP (mean difference 8.1 mm Hg; $p < 0.01$, and difference in paired means 5.6 percentile points, $p < 0.05$); (Fig. 1).

Effect of somatic growth on effective arch diameter. The median time from the most recent intervention on the CoA stent, to the study date, was 2.7 years (range 0.2 to 14.1 years). In most patients, significant somatic growth had occurred. The potential mismatch in stent size was assessed by comparing reference values for growth of the aortic isthmus related to height to stent diameter (15). For patients who underwent significant somatic growth (≥10-cm height increase) from the time of the intervention to the date of enrollment, the median stented arch diameter decreased from the 48th percentile to the 4th percentile ($p < 0.05$) (Fig. 2). The mean individual decrease in minimum effective diameter was 21.4 percentile points ($p < 0.05$) from the time of the last stent intervention. The relationship between a minimum aortic diameter ≤5th percentile, and mean ABPM percentile is depicted in Figure 3. Patients with a smaller aortic stent diameter had a higher mean ABPM pressure, with a median difference of 4.2 percentile points, and a mean difference of 11.6 percentile points; however, this difference was not statistically significant.

Exercise BP analysis. Of the 4 patients with a resting systolic arm-to-leg BP gradient of >20 mm Hg, none had an adequate heart rate response to exercise, and 3 had EIH.

Table 1. Patient Characteristics

Patient #	naCoA or reCoA	Sex	Age at Study (yrs)	Height (cm)	Weight (kg)	Time From Implant to Study (yrs)	Arm-Leg BP Gradient at Study (mm Hg)	Resting RA BP in mm Hg (Percentile)	24-h Mean ABPM Systolic BP (Percentile)	Hypertensive BP Load (%)
1	reCoA	M	23.1	172	76.7	8.1	0.0	133 (84.3)	149 (99.9)	94
2	naCoA	M	19.3	176	79.2	5.7	3.0	133 (84.5)	147 (99.9)	73.5
3	naCoA	M	19.8	179	62.6	5.9	30.0	128 (70.5)	136 (97.1)	66.6
4	naCoA	M	14.1	162	52.9	5.4	15.0	119 (75.5)	122 (83.8)	32.8
5	reCoA	M	24.1	173	92.4	6.3	0.0	135 (88.4)	136 (98.1)	59.7
6	naCoA	M	8.1	135	33.8	2.8	7.0	111 (87.4)	124 (98.2)	61.1
7	naCoA	M	19.8	170	83.2	11.5	0.0	118 (35.1)	133 (96.8)	45.8
8	naCoA	M	10.3	140	33	5.8	1.8	106 (62)	119 (91.8)	31.5
9	naCoA	M	9.9	136	37.7	0.2	6.0	111 (80.4)	115 (85.4)	26.7
10	naCoA	F	26.7	159	82.6	12.8	0.0	113 (15.2)	130 (97.3)	64.1
11	naCoA	M	14.2	159	71.6	1.1	9.0	130 (95.7)	133 (98.8)	69.9
12	naCoA	M	17.0	173	58.8	7.0	0.0	118 (46)	138 (99.0)	66.3
13	reCoA	M	16.7	180	73.7	0.2	0.0	82 (0.1)	103 (0.8)	0
14	naCoA	M	15.6	176	75	0.2	7.0	115 (48.1)	129 (88.5)	29.2
15	reCoA	M	15.2	171	71.4	5.8	1.0	110 (33.6)	122 (69.4)	19.6
16	naCoA	M	15.6	177	61.5	6.3	18.0	122 (72.8)	122 (61.7)	10.4
17	reCoA	F	13.3	159	60.1	0.5	0.0	104 (33.4)	109 (30.8)	0
18	reCoA	M	11.7	138	41.1	1.5	1.0	107 (55)	132 (99.8)	82.5
19	naCoA	F	18.3	160	58.6	6.7	0.0	88 (0.11)	104 (11.1)	0
20	naCoA	M	20.7	182	81.3	7.0	29.0	143 (97.5)	138 (98.4)	62
21	reCoA	M	28.3	178	86.8	14.1	0.0	133 (87.6)	125 (67.6)	24.9
22	naCoA	M	16.3	179	90.8	8.0	33.8	131 (90.2)	123 (58.8)	29.6
23	naCoA	M	17.5	176	71.1	2.3	7.3	115 (32.3)	129 (88.5)	33.1
24	reCoA	M	21.4	186	80.5	11.3	22.0	147 (99.1)	143 (99.6)	74.1
25	reCoA	M	16.7	168	58.6	1.7	0.0	111 (25.4)	119 (55.1)	17.1
26	naCoA	M	19.1	169	72.3	6.7	0.0	100 (2)	110 (14.7)	2
27	reCoA	M	17.6	180	95.4	0.2	10.0	136 (93.2)	130 (86.6)	30
28	naCoA	F	27.4	167	89.4	10.8	2.0	126 (80)	117 (69.4)	17.5
29	reCoA	M	15.2	166	62	0.2	0.0	119 (66.4)	132 (97.5)	48.3
30	naCoA	M	22.0	176	72.5	6.0	0.0	113 (19.5)	127 (82.7)	6.3
31	naCoA	F	13.9	152	48	2.0	0.0	120 (82.9)	130 (99.8)	86.3
Mean ±SD	reCoA = 11	M = 26	17.7 ± 5.0	167.4 ± 14.1	68.2 ± 17.2	5.3 ± 4	6.5 ± 10	118.6 ± 14.7	127 ± 11.3	40.8 ± 28.3
Median (# range)	naCoA = 20	F = 5	17.0 (8–28)	171 (135–186)	71.6 (33–95.4)	5.8 (0.2–14.1)	1.0 (0–34)	118 (88–147)	129 (104–149)	32.8 (0–94)

ABPM = ambulatory blood pressure monitoring; BP = blood pressure; naCoA=native coarctation; RA = right arm; reCoA = recurrent coarctation.

However, analysis of the resting BP gradient as a continuous or a categorical variable did not correlate with the presence of EIH. Subanalysis of those patients with ABPM hypertension did not show a correlation with the exercise response (Fig. 4), with the difference in the median systolic pressure increase of 6 mm Hg ($p > 0.05$). Similarly, there was no relationship between those with a small stent diameter and the presence of EIH.

Because this patient cohort spanned an adolescent to young adult age range, adult and pediatric normative data were applied to compare BP results (16,17,21,22).

ADULT DATA. In adults, EIH is defined as a peak systolic BP of >220 mm Hg (which occurred in 9 of 31 patients [30%]) or an increase in systolic BP of >60 mm Hg in men and >50 mm Hg in women (which occurred in 24 patients [80%]) (21,22). All those who had a peak exercise BP of >220 mm Hg also had an abnormally increased systolic response. Of the 6 patients whose BP response was not exaggerated, 5 had an inadequate exercise heart rate response (1 on a beta-blocker), suggesting a suboptimal nondiscriminatory exercise test. Thus, on the basis of adult guidelines, all but 1 patient (who had a satisfactory exercise test) had EIH.

PEDIATRIC DATA. Using published percentile data on normal bicycle exercise BP response in children (16,17), 11 patients (37%) had an exaggerated hypertensive exercise response at >95th percentile ($p < 0.05$).

Echocardiographic–BP correlations. Baseline echocardiographic data are detailed in Table 3. Measurements of systolic cardiac function were all within normal limits, with

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Table 2. Acute Results of Stent Intervention

Patient #	Age at Implant (yrs)	Stent Manufacturer and Model	Invasive Gradient After Last Intervention (mm Hg)	*z*-Score of Coarctation Diameter Before Stent Implant	*z*-Score of Minimum Stent Diameter at Time of Implant	Arm-Leg BP Gradient (mm Hg) at First Follow-Up After Implant
1	15.0	J&J P5014	8	−4.5	−2.4	0.0
2	13.6	J&J P5014	0	−1.2	1.3	0.0
3	13.9	NuMed CP 45 mm	0	−6.6	−1.1	*
4	8.6	J&J P3110	4	−5.5	−0.7	4.0
5	17.8	J&J PG5910	14	−2.2	−0.2	16.0
6	5.3	NuMed CP 28 mm	0	−12.8	−1.5	0.0
7	8.2	J&J PG5910	0	−0.7	3.2	0.0
8	4.5	J&J PG3910	7	−4.4	−1.1	*
9	9.7	NuMed CP 34 mm	0	−4.8	−0.8	10.0
10	13.9	J&J P5014	0	−3.6	0.1	0.0
11	13.1	NuMed CP 39 mm	10	−4.4	0.1	8.0
12	10.0	J&J PG2910	0	−2.9	0.0	*
13	16.4	J&J 4,014 XL	7	−4.0	0.1	*
14	15.5	Atrium V12	3	−4.6	0.3	*
15	9.4	J&J PG2910	8	−7.1	−1.5	2.0
16	9.3	J&J PG3910	4	−9.8	−0.1	0.0
17	12.8	J&J P4014	0	−3.8	1.1	*
18	10.2	J&J P3110	1	−7.2	−2.6	9.0
19	11.6	J&J PG2910	5	−3.0	−0.8	*
20	13.7	J&J PG5910	0	−3.1	−1.1	10.0
21	14.2	J&J P4014	4	−2.7	−0.2	2.0
22	8.3	J&J P308	0	−3.9	−1.5	0.0
23	15.2	J&J P4014	1	−3.8	−0.1	0.0
24	10.1	J&J P5014	0	−1.7	1.9	0.0
25	15.0	J&J P3110	1	−2.7	0.2	0.0
26	12.4	J&J P5014	0	−3.6	1.2	*
27	17.4	Atrium V12	0	−1.9	−0.1	10.0
28	16.6	J&J P5014	0	−5.2	0.5	*
29	15.0	NuMed CP 45 mm	0	−3.4	0.8	0.0
30	16.0	J&J P5014	4	−3.2	0.9	0.0
31	11.9	NuMed CP 34 mm	7	−19.2	−3.0	*
Mean ±SD	12.4 ± 3.3		2.8 ± 3.7	−4.8 ± 3.6	−0.2 ± 1.3	3.4 ± 4.9
Median (range)	13.1 (4.5 to 18.8)		1 (0 to 14)	−3.8 (−19.2 to −0.7)	−0.1 (−3.0 to 3.2)	0 (0 to 16)

NuMed CP were covered stents. *Data points that were unavailable or of uncertain accuracy.
BP = blood pressure; J&J = Johnson and Johnson.

a mean fractional shortening of 42.2 ± 6% and mean left ventricular ejection fraction of 72.4 ± 7% (biplane Simpson's calculation). There was a correlation ($r = 0.32$; $p < 0.05$) between resting continuous-wave Doppler flow gradients through the stent (mean 31.2 ± 9.4 mm Hg) and the resting arm-to-leg BP gradient (mean 1.1 ± 15 mm Hg). The gradient also correlated with simultaneously recorded resting right arm BP ($r = 0.39$; $p < 0.05$). Although there was positive correlation between exercise arm-to-leg gradient, exercise BP, and ABPM percentile, none reached statistical significance.

Indexed left ventricular mass (LVMI) was calculated from both body surface area (BSA) and height (26–30). In this cohort, the LVMI values correlated almost perfectly using either normalization ($r = 0.96$; $p < 0.001$), and therefore, given the young adult age range at exercise testing, we elected to use the more recognized BSA normalization for adults in our calculations (28,29). As such, LVMI was increased with a mean of 91.3 ± 24.5 g/m^2 compared with the normal mean value for men of 61 ± 10 g/m^2 or 47 ± 7 g/m^2 for women ($p < 0.05$). LVMI positively correlated with the peak exercise BP ($r = 0.51$; $p < 0.05$) (Fig. 5), whereas the MASBP percentiles trended with LVMI, but without statistical significance. From the LVMI data, 5 patients were classified as having left ventricular hypertrophy, and of those, only 1 had an increased relative wall thickness, the remainder of the cohort (hypertrophied and nonhypertrophied) having normal ratios (27).

Recurrent versus native coarctation. The average age at stent implantation and the interval between stent interven-

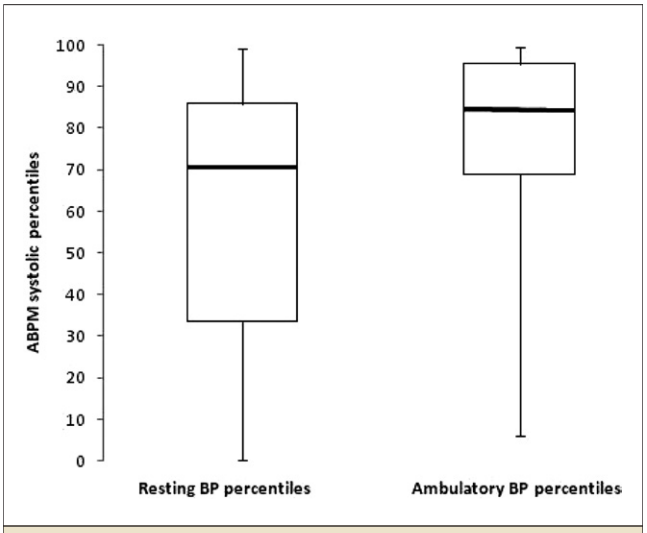

Figure 1. Comparison of "One-Off" BP With ABPM Mean Systolic Percentiles

Comparison of "one-off" resting systolic blood pressure (BP) percentiles (median 70.5; range 0.1 to 99) with ambulatory blood pressure monitoring (ABPM) mean systolic percentiles (median 84.5; range 6 to 99). Difference in paired means, 15.6 percentile points ($p < 0.05$).

tion and the study protocol were similar for both reCoA and naCoA patients. The invasive pull-back gradients before intervention were statistically different between the 2 subgroups (mean 22.8 mm Hg [reCoA] vs. 12.3 mm Hg [naCoA]; $p < 0.05$). However, there was no difference in residual pull-back gradients (3.6 mm Hg [naCoA]) vs. 2.6 mm Hg [reCoA]) after the intervention. Similarly, there was no significant difference in peak exercise BP response or mean ABPM percentiles between the 2 groups, or the proportion of those meeting criteria for hypertension on ABPM, which was approximately 45% in either group.

Discussion

Over the last decade, the literature on repaired coarctation has shown that freedom from residual hypertension is not related to freedom from residual obstruction. The cause of this tendency to hypertension is still under debate, with hypotheses involving the presence of an inherent arteriopathy, arterial stiffness induced by chronic shear stress, and abnormal flow or abnormal renal homeostasis as potential contributions (11,14–20,31).

Our data show that in a dichotomous pediatric population containing both patients with stented native and recurrent coarctation after surgical repair, ambulatory and exercise hypertension are detectable sequelae despite the lack of early or long-term residual or recurrent obstruction. The presence of hypertension was not predictable from baseline procedural characteristics, such as duration of coarctation before definitive treatment, length of follow-up after intervention, or degree of pre-procedural isthmal hypoplasia. Pre-existent arch hypoplasia has been implicated as a substrate for persistent ambulatory and exercise-induced hypertension, but this was not observed in this cohort, with no correlation between BSA-indexed transverse arch caliber, ABPM percentile or exercise BP (14,32). Indeed, the prevalence of significant hypertension throughout the cohort made the statistical identification of predisposing factors difficult.

Placing a nondistensible metal stent into a growing aorta is an understandable cause for concern. These data underscore that following successful stenting in childhood, growth into adulthood may occur without signs of residual or progressive arch obstruction at rest. As such, body size may more than double from the time of initial stent placement to adulthood, leaving the aortic stent an area of fixed hypoplasia. For those patients who had undergone significant somatic growth since the intervention, there was a significant decrease in the corrected minimum stent diameter ($p < 0.05$). There was also a trend between the indexed stent diameter and the presence of hypertension on ABPM between the group with a small aortic arch (<5th percentile) and those with normal arch diameters.

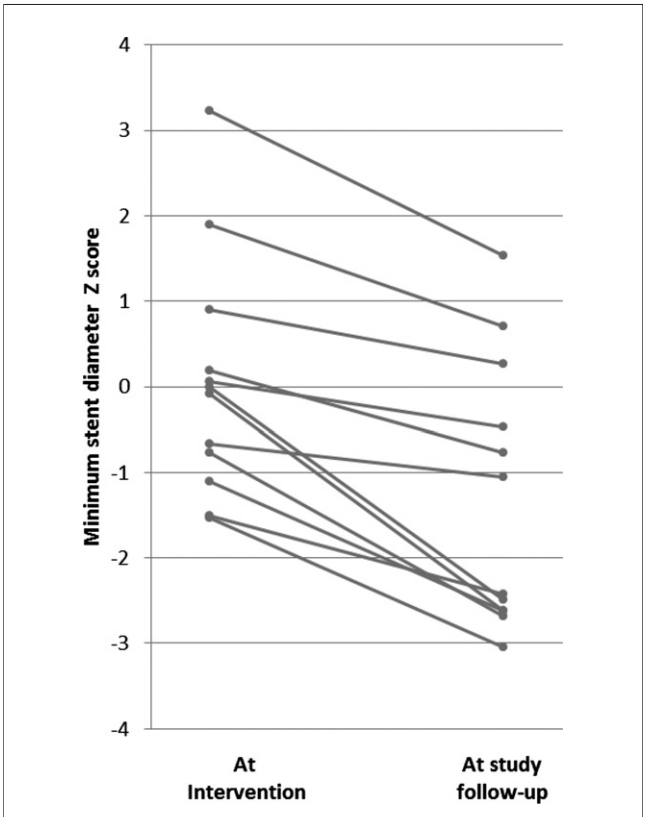

Figure 2. *z*-Score of the Minimum Stent Diameter in Patients With Significant Somatic Growth

Decrease in *z*-score of the minimum stent diameter in patients with significant somatic growth since intervention (>10-cm increase in height). The *z*-score decreased by a mean of 1.36 ($p < 0.05$).

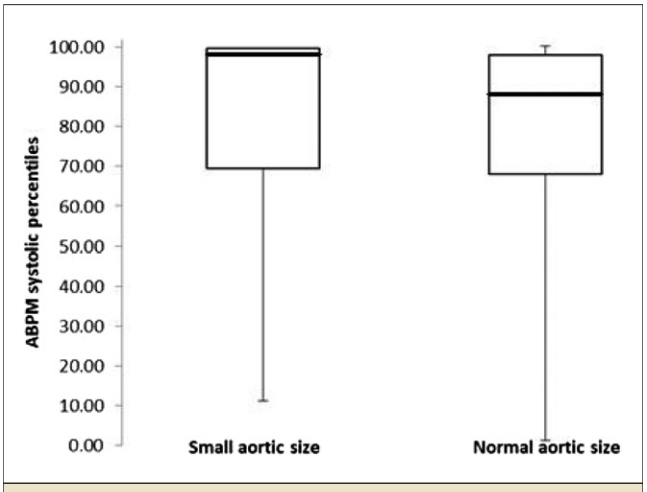

Figure 3. Comparison of ABPM Percentiles by Stent Diameter

Comparison of ambulatory blood pressure monitoring (ABPM) percentiles for patients with a minimum stent diameter >5th percentile (median 82.5; range 8 to 99) versus those with diameters ≤5th percentile (median 96.1; range 6 to 99.6). Mean difference 11.6 percentile points.

This finding suggests that once implanted, the stent should be carefully monitored and electively dilated according to the patient's growth, despite the absence of a resting gradient, to avoid the development or progression of hypertension.

The presence of EIH (24 of 25 adequate studies) did not correlate with resting systolic BP, stent diameter, or the presence of ABPM hypertension. These observations are consistent with the postulate that an abnormal exercise response represents a combination of abnormal BP homeostasis due to an inherent vasculopathy, sympathetic overactivity, and the presence of an abnormal arch segment, that is, the stent. There is no evidence that the incidence of EIH is higher in stented patients versus those with surgical repair as discussed in other studies; however, these 2 populations are often so distinct with respect to age, clinical history, and management pathways that a comparison on this point is almost impossible (33).

What is clear from our data and that of others is that systemic hypertension is underinvestigated, underdiagnosed, and undertreated in this at-risk population (34). Indeed, many of our patients had significant hypertension on ABPM as opposed to one-off office BP checks. We would recommend that periodic ABPM monitoring be a routine practice in the long-term follow-up of all patients with "corrected" coarctation.

Echocardiographic data also noted that continuous-wave Doppler velocities through the stented area could be useful in predicting the presence of EIH or ABPM hypertension. A longitudinal study of continuous-wave Doppler velocities and their correlation with ABPM was beyond the scope of this study; we would suggest that a high continuous-wave Doppler velocity or a velocity that is serially increasing should trigger a more thorough investigation of the possible presence of systemic hypertension. The actual cutoff point at which the stent velocity becomes significant is not clear.

Blood pressure load on ABPM assessment is independently associated with an increased LVMI (35,36), and may therefore be a more relevant clinical parameter than the standard mean BP calculation (19,37). In this study, all patients whose mean ambulatory BPs were >95th percentile had a hypertensive BP load >40%, and 5 solely had a high BP load. As such, the incidence of systemic hypertension may be higher than compared to historical data, which may not have assessed BP load.

The clinical relevance of EIH in the coarctation population has been questioned in the literature, but without comprehensive normal data, it is difficult to base clinical and/or interventional decisions solely on this finding. A significant proportion of this cohort had EIH on the basis of both adult and pediatric criteria, further supporting the theory that patients with an adequate anatomic correction still have abnormal BP homeostasis. We also found a positive correlation between exercise BP and LVMI, which additionally underscores the detrimental effects of exercise hypertension on the cardiovascular system.

Previous studies addressing stenting of reCoA or naCoA have focused on adult populations, with little data available on the fate of those who have the procedure done in the pediatric age group. Some authors suggest that the propensity to hypertension may be related to the chronicity of an uncorrected obstruction, and therefore, patients who have their obstructive gradient abolished in childhood are more likely to remain normotensive. Our data do not give

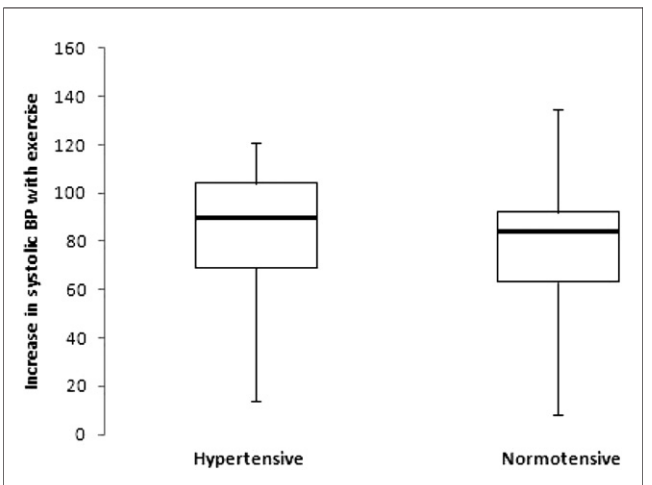

Figure 4. Comparison of Systolic BP Response to Exercise

Comparison of systolic BP response to exercise in those hypertensive on ABPM (median 90; range 14 to 121) versus those normotensive (median 84; range 8 to 135). Median difference in systolic response 6 mm Hg ($p > 0.05$). Abbreviations as in Figure 1.

Table 3. Echocardiographic Variables

Patient #	Fractional Shortening (%)	Ejection Fraction (%)	LVPWd (mm) (*z*-Score)	IVSd (mm) (*z*-Score)	LVEDD (mm) (*z*-Score)	RWT	LVMi (g/m^2)	Hypertension	LVH
1	37	67	0.83 (0.5)	0.78 (0)	5.07 (−0.1)	0.32	73.87	Yes	No
2	55	85	0.78 (0)	1.02 (2.1)	5.32 (0.4)	0.34	89.80	Yes	No
3	46	77	0.91 (1.3)	1.18 (3.55)	5.66 (1.8)	0.37	132.30	Yes	Yes
4	48	79	0.81 (1)	0.64 (−0.9)	5.09 (1.2)	0.28	79.68	No	No
5	46	77	1 (1.5)	1.43 (4.6)	5.54 (0.6)	0.44	135.93	Yes	Yes
6	50	81	0.63 (0.3)	0.74 (1.33)	4.84 (2.1)	0.28	93.90	Yes	No
7	33	61	0.88 (0.82)	0.95 (1.5)	5.69 (1.36)	0.32	103.28	Yes	No
8	39	69	0.5 (−1.3)	0.4 (−3.6)	4.8 (2.2)	0.19	54.87	No	No
9	56	87	0.62 (0)	0.73 (1)	3.96 (−0.8)	0.34	62.11	No	No
10	43	74	0.6 (−1.5)	0.92 (1.45)	5.12 (0.2)	0.30	71.64	Yes	No
11	51	82	0.68 (−0.5)	0.94 (1.82)	5.92 (2.6)	0.27	106.07	Yes	No
12	—	—	—	—	—	—		Yes	
13	43	74	0.85 (0.6)	0.64 (−1.58)	5.87 (1.9)	0.25	85.07	No	No
14	43	73	0.93 (1.3)	0.81 (0.8)	5.41 (0.3)	0.32	90.52	No	No
15	38	68	0.74 (−0.1)	0.71 (−0.6)	5.29 (0.7)	0.27	72.12	No	No
16	38	68	0.72 (−0.2)	0.75 (0)	4.67 (−0.8)	0.31	61.49	No	No
17	—	—	—	—	—	—		No	
18	38	68	0.78 (1.4)	0.74 (1)	3.69 (−2.1)	0.41	61.63	Yes	No
19	32	59	0.63 (−0.8)	0.74 (0.2)	4.54 (−0.7)	0.30	58.84	No	No
20	46	76	1.09 (2.1)	1.18 (3.1)	6.09 (2.1)	0.37	147.46	Yes	Yes
21	38	67	1 (1.5)	0.93 (1.2)	6.13 (2.1)	0.31	119.30	No	Yes
22	44	74	1.05 (1.8)	0.83 (0.2)	5.7 (0.9)	0.33	99.54	No	No
23	37	66	0.85 (0.7)	1.07 (2.6)	5.54 (1.2)	0.35	109.49	No	No
24	36	65	0.78 (−0.1)	0.74 (0.6)	6.14 (2.1)	0.25	88.77	Yes	No
25	44	75	0.78 (0.5)	1.07 (3.1)	5.22 (1.1)	0.35	105.96	No	No
26	35	64	0.68 (−0.7)	0.78 (0.2)	5.28 (0.7)	0.28	72.73	No	No
27	41	71	0.84 (0.2)	0.7 (−1.2)	6.06 (1.7)	0.25	83.97	No	No
28	48	80	1.03 (1.8)	0.84 (0.5)	5.09 (−0.3)	0.37	86.47	No	No
29	37	66	0.81 (0.7)	0.97 (2.2)	5.91 (2.8)	0.30	122.66	Yes	Yes
30	37	67	0.93 (1.3)	0.99 (2)	4.9 (−0.6)	0.39	88.46	No	No
31	—	—	—	—	—	—	—	—	—
Mean ±SD	42.2 ± 6.1	72.4 ± 7	0.81 ± 0.14	0.86 ± 0.2	5.3 ± 0.6	0.32 ± 0.05	91.3 ± 24.5		
Median (# range)	42 (32–56)	72 (59–87)	0.81 (0.5–1.09)	0.82 (0.4–1.4)	5.3 (3.7–6.1)	0.32 (0.19–0.44)	88.6 (54.9–147.5)		

IVSd = diastolic interventricular septal thickness; LVEDD = left ventricular end-diastolic dimension; LVH = left ventricular hypertrophy; LVMi = left ventricular mass index (see text); LVPWd = diastolic left ventricular posterior wall thickness; RWT = relative wall thickness [(2 × LVPWd)/LVEDd]. *One patient failed to attend for the complete echo protocol and in 2 patients the echo data was deemed inadequate for detailed analysis.

credence to this assertion and support the hypotheses identifying persistent hypertension as a pre-programmed disorder related to an intrinsic vasculopathy and/or associated renal dysfunction.

Study limitations. The main limitations of this study are related to the sample size and heterogeneity of the sample. The duration since stent implantation was widely variable within the sample, limiting the ability to fully assess the long-term effects of stents on the presence, degree, and management of hypertension. The study also highlights the difficulty in statistical analysis of patients moving from childhood to adulthood (38). There was a relative lack of normal data covering this period, making longitudinal analysis challenging.

Conclusions

The risk of hypertension is not relieved by the removal of a measurable gradient in CoA. The chronic burden of hypertension in coarctation patients is likely significantly higher than in other at-risk populations due to the early onset of the illness. This population needs to be treated as particularly high risk in this respect, and hypertension should be aggressively sought and treated. The study emphasizes the need for close follow-up of patients who have had angiographically successful correction of CoA. As yet, no satisfactory theory explaining the origin of hypertension in coarctation exists, but whatever the mechanism, it remains a major issue requiring careful lifelong review, regardless of the age of repair.

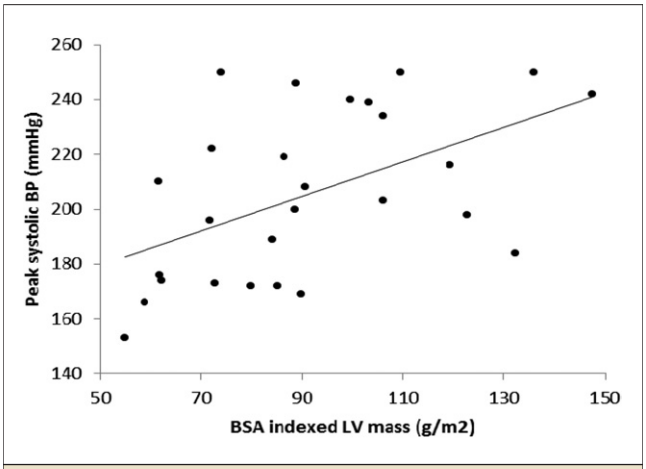

Figure 5. Scatter Plot of Peak Systolic Exercise BP Versus LVMI

Pearson coefficient r = 0.52 ($p < 0.05$). BP = blood pressure; BSA = body surface area; LV = left ventricular; LVMI = left ventricular mass index.

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Reprint requests and correspondence: Dr. Lee Benson, The Hospital for Sick Children, 555 University Avenue, Toronto, Ontario, M5G1X8, Canada. E-mail: lee.benson@sickkids.ca.

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Key Words: coarctation of the aorta ■ endovascular stent ■ interventional cardiology ■ systemic hypertension.