Magnetic Resonance Imaging Predictors of Coarctation Severity

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Background—MRI is increasingly used for anatomic assessment of aortic coarctation (CoA), but its ability to predict the transcatheter pressure gradient, considered the reference standard for hemodynamic severity, has not been studied in detail. This study evaluated the ability of MRI to distinguish between mild versus moderate and severe CoA as determined by cardiac catheterization.

Methods and Results—The clinical, MRI, and catheterization data of 31 subjects referred for assessment of native or recurrent CoA were reviewed retrospectively. Patients were divided into 2 groups on the basis of peak coarctation gradient by catheterization: <20 mm Hg (n=12) and ≥20 mm Hg (n=19). Patients with cardiac index <2.2 L·min⁻¹·m⁻² by catheterization were excluded. By logistic regression analysis, the following variables simultaneously predicted coarctation gradient ≥20 mm Hg: (1) smallest aortic cross-sectional area (adjusted for body surface area) measured by planimetry from gadolinium-enhanced 3D magnetic resonance angiography (OR 1.71 for 10 mm²/m² decrease, \(P=0.005\)) and (2) heart rate–corrected mean flow deceleration in the descending aorta measured by phase-velocity cine MRI (OR 1.68 for 100 mL/s⁻¹·m⁻² increase, \(P=0.018\)). For the combination of these variables, a predicted probability >0.38 had 95% sensitivity, 82% specificity, 90% positive and negative predictive values, and an area under the receiver-operator characteristics curve of 0.938. In a subsequent validation study, the prediction model correctly classified 9 of 10 patients, with no false-negatives.

Conclusions—the combination of anatomic and flow data obtained by MRI provides a sensitive and specific test for predicting catheterization gradient ≥20 mm Hg. (Circulation. 2005;111:622-628.)

Key Words: heart defects, congenital | heart diseases | magnetic resonance imaging | hemodynamics

The hemodynamic severity and clinical manifestations of coarctation of the aorta (CoA) vary from asymptomatic mild narrowing or tortuosity of the aortic isthmus to severe obstruction associated with shock. In addition to clinical symptoms, a number of methods have been used to assess the severity of CoA. Cardiac catheterization with angiography and hemodynamic evaluation is considered the reference standard, and many published reports regard a transcatheter peak-to-peak pressure gradient ≥20 mm Hg as an important criterion for the diagnosis of hemodynamically significant CoA in the setting of normal cardiac index.¹⁻⁸

Several noninvasive methods have been used to assess the severity of CoA. Arm-to-leg blood pressure difference measured by sphygmomanometry can provide helpful information, but several reports have shown that it may not accurately represent the hemodynamic severity of the stenosis.⁶⁻⁹,¹⁰ Echocardiography has been used successfully to assess the morphology and hemodynamic severity of CoA,¹¹ but it has known limitations related to acoustic barriers and violation of the assumptions that underlie the simplified Bernoulli equation.¹² Cardiac magnetic resonance imaging (CMRI) provides an accurate assessment of the anatomic characteristics of CoA and collateral blood vessels.⁵¹¹⁻¹⁵ Prior investigations on CMRI assessment of CoA severity compared the anatomic features and the extent of collateral blood flow with catheterization diameter measured by x-ray angiography,¹⁰¹⁵ blood pressure measurements by sphygmomanometry,⁹ and Doppler assessment of flow velocity.¹⁶ The ability of CMRI to predict the hemodynamic severity of CoA as measured by cardiac catheterization remains unclear. The aim of the present study, therefore, is to determine whether CMRI can distinguish between mild (<20 mm Hg) and moderate or severe (≥20 mm Hg) CoA using the pressure gradient at catheterization as the reference standard.

Methods

Candidates for this study were identified by a retrospective review of the electronic database of the Department of Cardiology at Children’s Hospital Boston. Patients who fulfilled the following criteria were included: (1) underwent CMRI assessment of CoA from February 1997 through January 2003, including contrast-enhanced...
3D MR angiography (3D MRA) and phase-velocity cine MRI (PVC-MRI) flow measurements in the ascending aorta and descending thoracic aorta; (2) underwent cardiac catheterization with recording of the peak-to-peak pressure gradient across the coarctation (CoA) within 1 year from the time of CMRI; and (3) had no intervention between the CMRI and the catheterization procedure. Patients with cardiac index $<2.2 \text{ L} \cdot \text{min}^{-1} \cdot \text{m}^{-2}$ at catheterization (Fick method) and those with incomplete CMRI flow data were excluded. To determine normal dimensions of the thoracic aorta based on contrast-enhanced 3D MRA, 20 consecutive patients with a similar age distribution and normal aortas were studied (age 15.8 ± 1.4 years [range 8 days to 48 years]; body surface area 1.2 ± 0.63 m$^2$ [range 0.18 to 2.16 m$^2$]). After conclusion of the retrospective part of the study, the prediction model was tested in 10 consecutive patients (median age 2.5 years [range 0.3 to 17.4 years]) who met the same inclusion criteria and underwent CMRI and catheterization studies from February 2003 through February 2004. The Children’s Hospital Committee on Clinical Investigations approved review of the medical records and computer databases.

**Figure 1.** Assessment of flow profiles in ascending (AAo) and descending (DAo) aorta by PVC-MRI. A, Image-acquisition plane is positioned perpendicular to proximal AAo and mid-DAo. B, Flow measurements in AAo and DAo: (a) flow onset; (b) peak acceleration; (c) peak flow; (d) peak deceleration; (e) cessation of flow; (f) time to peak acceleration; (g) rise time; (h) time from peak flow to peak deceleration; (i) fall time; and (j) duration of flow. Mean acceleration, mean deceleration, and time delay between onset of AAo and DAo flow were calculated (not shown graphically).

Magnetic Resonance Imaging

CMRI studies were performed on a 1.5-T whole-body scanner (Signa Horizon LX with EchoSpeed or TwinSpeed Gradients, General Electric). The imaging protocol used in our laboratory in patients with CoA has been published previously. Aortic arch morphology was assessed by gadolinium-enhanced 3D MRA performed in the sagittal plane with the following imaging parameters: field of view = 180 to 440 mm; matrix = 160 to 192 (phase)×256 (frequency); slice thickness = 1.8 to 3.6 mm; echo time $[\text{TE}] = 1$ to $3$ ms; repetition time $[\text{TR}] = 2$ to $6$ ms; flip angle = 45°; number of signal averages = 0.5 to 1. Gadopentetate dimeglumine (0.2 to 0.3 mmol/kg; Magnevist, Berlex Laboratories) was injected through an intravenous cannula at a rate of 1.5 to 2 mL/s. The time delay between start of contrast injection and data acquisition was determined by the “best estimate” method when manual injection was performed (≈5 to 10 seconds)$^{18,19}$ or by fluoroscopic triggering when a power injector was used. Two sequential acquisitions were performed with breath holding, each lasting 20 to 30 seconds.

Flow measurements were performed in the ascending and descending aorta with commercially available PVC-MRI sequences during free breathing. The imaging plane was positioned perpendicular to the ascending and descending aorta at the level of the right pulmonary artery (Figure 1A). When the flow signal in the descending aorta was incoherent because of the coarctation flow jet, the...
acquisition was repeated perpendicular to the descending aorta at the level of the mid left atrium. A standard PVC-MRI sequence (TE=6 to 7 ms; TR=18 to 25 ms; matrix=128×160×256; field of view=140 to 360 mm; slice thickness=5 to 6 mm; velocity encoding=150 to 400 cm/s; sampling interval=43.4±9.8 ms; number of samples per RR interval=20.4±6.3) was used in 23 patients, and a segmented k-space PVC-MRI sequence (TE=3 to 4 ms; TR=8 to 10 ms; matrix=128×160×256; views per segment=2 to 4; field of view=140 to 320 mm; slice thickness=4 to 6 mm; velocity encoding=150 to 300 cm/s; sampling interval=32.3±8.7 ms; number of samples per RR interval=23.8±5.8) was used in 8 patients.

Data Analysis

MRI data were analyzed with a commercially available computer workstation (Advantage Windows version 4.0, GE Medical Systems). Aortic arch anatomy was evaluated by constructing user-defined subvolume maximal-intensity projections and multiplanar reformatted images. Image contrast and brightness were adjusted to a level at which the chest wall was just visible and the peripheral lung tissue remained dark. The morphometry of the aorta was analyzed as outlined in Figure 2. Using electronic calipers, 2 orthogonal diameters and the cross-sectional area (by planimetry) of the aorta were measured in the ascending aorta at the level of the right pulmonary artery, proximal transverse arch, distal transverse arch, aortic isthmus, and proximal and distal descending thoracic aorta. To adjust for body size, aortic diameters were indexed to the body surface area.20

PVC-MRI flow data were analyzed on the same computer workstation with commercially available software (FLOW 2.0, Medis). The underlying principles and analysis techniques for PVC-MRI have been described previously.21 To further analyze the velocity and flow profiles in the ascending and descending aorta, the PVC-MRI data were exported to a software program developed by one of the investigators (ENM). With that software, the following variables were calculated (Figure 1B): peak and mean acceleration; peak flow velocity and rate; peak and mean deceleration; time to peak acceleration; rise time; time from peak flow to peak deceleration; fall time; duration of flow; and the time delay between onset of flow in the ascending and descending aorta. Time-based variables were corrected for heart rate with Bazett’s formula: 1/(RR interval)^0.5.

Statistical Analysis

Patient characteristics and MRI data were compared for study subjects with no or mild obstruction by catheterization (<20 mm Hg) and those with moderate and severe obstruction (≥20 mm Hg) with either the 2-sample t test or Wilcoxon rank sum test for continuous variables and Fisher’s exact test for categorical variables. For catheterization and morphometric data, continuous variables were compared for study subjects and the normal aorta group by 1-way ANOVA or the Kruskal Wallis test. z Scores for indexed dimensions of the aorta were derived from the normal aorta group. Logistic regression analysis was used to explore the relationships between the outcome of moderate or severe obstruction and potential predictor variables.22 Odds ratios (ORs) and areas under the receiver-operator characteristic (ROC) curve were calculated for each variable. Multivariable logistic regression was used to develop a rule for predicting the probability of moderate or severe obstruction. The likelihood ratio test was used to assess which variables should be included in the model, with P<0.05 required for entry. After conclusion of the retrospective study, the prediction rule was tested in 10 consecutive patients. All analyses were performed with stata version 8.

Results

Demographic characteristics were similar between patient groups (Table 1). The prevalence of single or complex
biventricular anatomy was higher among patients with coarctation gradient <20 mm Hg. All 19 patients with coarctation gradient ≥20 mm Hg underwent transcatheter interventions, either balloon angioplasty alone (n=5) or with stent placement (n=14). Except for a higher prevalence of collateral vessels seen on 3D MRA (26% versus 0%, P=0.01), the groups did not differ significantly in terms of left ventricular mass, ejection fraction, or cardiac index (Table 1). The morphometric findings in patients and the normal aorta group are summarized in Table 2. Compared with the normal aorta, the ascending aorta was dilated in both patient groups, and the distal transverse arch and isthmus were hypoplastic and elongated. Compared with patients with coarctation gradient <20 mm Hg, both aortic arch and isthmus hypoplasia were more severe in those with gradient ≥20 mm Hg.

**Predictors of Coarctation Severity**

Table 3 summarizes the variables found to be predictive of coarctation gradient ≥20 mm Hg by logistic regression analysis. The variables generating the highest area under the ROC curve were the smallest aortic cross-sectional area indexed to body surface area (Figure 3), followed by several flow variables measured in the descending thoracic aorta (Figure 4). In general, variables based on measurements of flow rate were more predictive of coarctation severity than variables based on measurements of flow velocity. None of the flow variables measured in the ascending aorta were predictive of coarctation gradient by catheterization. Similarly, the time delay between either the onset or the peak flow between the ascending and descending aorta did not differentiate between patient groups.

Among the flow variables measured in the descending aorta, heart rate–corrected mean deceleration provided the most additional predictive value over what was available by the indexed smallest cross-sectional area (P=0.014 by the likelihood ratio test). By multivariable logistic regression analysis, the following predictive rule was developed on the basis of these 2 independent variables: log [p/(1−p)] = 6.69−(0.0485×smallest indexed aortic cross-sectional area)+(0.00506×heart rate–corrected mean deceleration), where p = probability of coarctation gradient ≥20 mm Hg. The area under the ROC curve for this model is 0.938 (Figure 5). A predicted probability >0.38 was 95% sensitive and 82% specific and had 90% positive and negative predictive values (Table 4). With this probability value, 28 of 31 subjects were classified correctly, and, importantly, only 1 of 19 patients with coarctation gradient ≥20 mm Hg was misclassified (false-negative). Among the 10 patients in whom the prediction

<table>
<thead>
<tr>
<th>TABLE 2. Morphometric Data</th>
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<tbody>
<tr>
<td>Normal Aorta (z Score)</td>
</tr>
<tr>
<td>(n=20)</td>
</tr>
<tr>
<td>Indexed diameter, mm/m^{1.5}</td>
</tr>
<tr>
<td>Ascending aorta</td>
</tr>
<tr>
<td>Distal arch</td>
</tr>
<tr>
<td>Isthmus</td>
</tr>
<tr>
<td>Indexed cross-sectional area, mm^{2/3}</td>
</tr>
<tr>
<td>Ascending aorta</td>
</tr>
<tr>
<td>Distal arch</td>
</tr>
<tr>
<td>Isthmus</td>
</tr>
<tr>
<td>Minimum</td>
</tr>
<tr>
<td>Indexed distal arch length, mm/m^{2/3}</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

*P values are for comparison between measurements of indexed dimensions. z Scores are shown for descriptive purposes.

<table>
<thead>
<tr>
<th>TABLE 3. Predictors of Coarctation Gradient ≥20 mm Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predictor Variable</td>
</tr>
<tr>
<td>Indexed smallest aortic cross-sectional area</td>
</tr>
<tr>
<td>(10 mm²/m² increase)</td>
</tr>
<tr>
<td>Rate-corrected DAo flow duration (0.01 s^{1.5}</td>
</tr>
<tr>
<td>increase)</td>
</tr>
<tr>
<td>Rate-corrected DAo flow fall time (0.01 s^{1.5}</td>
</tr>
<tr>
<td>increase)</td>
</tr>
<tr>
<td>Rate-corrected DAo mean flow deceleration (100 mL/s^{1.5}</td>
</tr>
<tr>
<td>increase)</td>
</tr>
<tr>
<td>DAo mean flow deceleration (100 mL/s² increase)</td>
</tr>
<tr>
<td>DAo peak flow deceleration (100 mL/s² increase)</td>
</tr>
<tr>
<td>Rate-corrected DAo mean flow acceleration (100</td>
</tr>
<tr>
<td>mL/s^{1.5} increase)</td>
</tr>
</tbody>
</table>

CL indicates confidence limits; DAo, descending aorta.
rule was applied prospectively, 9 patients were classified correctly, with no false-negatives. Among the 5 patients with a transcatheter gradient ≥20 mm Hg, the probability values were 0.96, 0.98, and 0.99 in 3 patients. Among the 4 patients with a transcatheter gradient <20 mm Hg, the probability values were 0.01, 0.06, and 0.29. In the patient with a false-positive prediction, the value was 0.81.

Discussion

This study shows that in patients with CoA, the cross-sectional area of the narrowest aortic segment and the mean deceleration of flow in the descending aorta distinguish between those who have transcatheter pressure gradients above and below 20 mm Hg. This combination of morphological and flow variables had an excellent sensitivity (95%), good specificity (82%), and an area under the ROC curve of 0.94. A practical advantage of these findings is that both 3D MRA of the thoracic aorta and PVC-MRI flow analysis are established MRI techniques, are commonly used in clinical practice, and require relatively short acquisition and image-processing times.\(^9,13–16,23–26\) Moreover, both techniques have been evaluated in patients with CoA and were found to reliably assess aortic morphology and collateral vessels and to accurately quantify flow in the descending aorta.\(^9,13\)

Assessment of coarctation severity presents a clinical challenge. There is clear evidence that “significant” CoA is associated with premature death and substantial late morbidity, including hypertension, cerebral aneurysms, heart failure, and premature coronary artery disease.\(^5–27\) The threshold at which CoA becomes significant is less well established. The hemodynamic burden imposed by CoA involves a complex interplay between anatomic (eg, effective flow orifice, geometry, length), mechanical (eg, aortic compliance), flow rate, and ventricular variables (eg, ventricular function and ventriculo-arterial coupling). In this study, a peak-to-peak pressure gradient of 20 mm Hg was chosen as a threshold value to distinguish mild from moderate and severe CoA on the basis of the preponderance of its use in the literature. A pressure gradient >20 mm Hg by catheterization has been proposed in numerous studies as an indication for surgical or balloon dilation of CoA and for the definition of procedural success.\(^1–4,6,7,27,28\) The limitations inherent to relying on only one measurement of CoA severity, however, are recognized.
TABLE 4. Test Characteristics of Variables Predictive of Peak Pressure Gradient ≥20 mm Hg

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sensitivity, %</th>
<th>Specificity, %</th>
<th>PPV, %</th>
<th>NPV, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indexed smallest aortic cross-sectional area &lt;56 mm²/m²</td>
<td>79</td>
<td>83</td>
<td>88</td>
<td>71</td>
</tr>
<tr>
<td>Rate-corrected DAo mean flow deceleration more than −340 mL/s¹.⁵</td>
<td>63</td>
<td>91</td>
<td>92</td>
<td>59</td>
</tr>
<tr>
<td>Probability level &gt;0.38 by the prediction rule*</td>
<td>95</td>
<td>82</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

PPV indicates positive predictive value; NPV, negative predictive value; and DAo, descending aorta.

*The prediction rule combines heart rate–corrected mean deceleration and indexed smallest aortic cross-sectional area (see text for details).

In clinical practice, additional variables are often considered when deciding how to manage CoA in individual patients.

Previous studies on the use of CMRI to assess coarctation severity have concentrated on 2 methods: the diameter of the coarctation segment and the percent increase in flow between the proximal and distal descending thoracic aorta as a measure of collateral flow. Several studies found good correlations between coarctation diameter by MRI and x-ray angiography.¹⁰,¹⁴,¹⁸ For example, Riquelme and colleagues¹⁴ showed a correlation coefficient of 0.99 between gradient echo cine MRI and angiography, whereas Simpson et al.¹⁵ and Mendelsohn et al.¹⁰ reported correlation coefficients of 0.9 and 0.91, respectively. Other groups have focused on the percent increase in descending aorta flow from collateral vessels to assess coarctation severity.²⁹ Steffens et al.³⁰ reported that the percent increase in flow correlated with the diameter of the coarctation segment (r=0.94), with arm-to-leg blood pressure difference (r=0.84), and with Doppler gradient (r=0.76). More recently, Araoz and colleagues⁸ demonstrated that the percent increase in descending aorta flow in 19 patients with repaired CoA more accurately reflected the degree of narrowing than arm-to-leg blood pressure measurements. The present study did not evaluate the test characteristics of percent increase in descending aorta flow attributable to collateral vessels because we noted that in patients with severe CoA, the flow signal immediately distal to the stenotic segment was often incomplete because of dephasing. This known limitation of current PVC-MRI techniques can potentially lead to underestimation of flow in the proximal descending aorta, which in turn may lead to overestimation of the relative increase in aortic flow at the level of the diaphragm. On the other hand, the present findings agree with previous reports that the presence of significant collateral vessels to the descending thoracic aorta on 3D MRA is a specific marker of severe coarctation.²⁹

Study Limitations
Sample size is a limitation of the present study. A larger sample size would have allowed the inclusion of additional variables in the prediction model. Moreover, the validation group included only 10 patients, whose age at MRI and catheterization was younger than that of the main study group. The results of the present study may not apply to patients with CoA and an aortopulmonary shunt, such as infants who have undergone stage I Norwood operation. In these patients, the diastolic runoff from the aorta to the pulmonary arteries may alter the flow profile in the descending aorta. It is also recognized that the sampling rate of the PVC-MRI sequence may be insufficient to detect small differences between groups in some flow variables. Finally, the nonsimultaneous MRI and catheterization and the lack of standardization of physiological conditions may confound direct comparison of CoA gradient between the 2 techniques; however, such comparison was not the primary aim of this report. Instead, the prediction model was developed on the basis of conditions typically present during the course of routine clinical MRI examinations and proved valid in the prospective arm of the study.

Conclusions
In patients with CoA, the combination of narrowest aortic cross-sectional area and heart rate–corrected mean flow deceleration in the descending aorta obtained by MRI provides a sensitive and specific test for predicting a catheterization gradient ≥20 mm Hg. This information can be used together with clinical and other noninvasive data to determine the need for transcatheter or surgical intervention.

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References


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