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Cardiac Ultrasound

Doppler Echocardiographic Profile and Indexes in the Evaluation of Aortic Coarctation in Patients Before and After Stenting

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OBJECTIVES We sought to assess the effect of successful stenting on the Doppler profile of aortic coarctation and to identify echocardiographic indexes that could be used for follow-up of such patients.

BACKGROUND Doppler echocardiography demonstrates characteristic flow patterns in significant aortic coarctation.

METHODS We undertook retrospective echocardiographic analyses before and at six to nine months after coarctation stenting in consecutive patients from 2002 to 2003. Peak systolic pressure gradient (SPG), diastolic velocity (DV), end-diastolic tail velocity (EDTV), systolic velocity half-time index (SVHTi) and diastolic velocity half-time index (DVHTi), and systolic pressure half-time index (SPHTi) and diastolic pressure half-time index (DPHTi) were measured. The severity of aortic coarctation was compared with cardiovascular magnetic resonance (CMR) imaging using the coarctation index (CoAi).

RESULTS The patient cohort was divided into two groups: group 1 (13 patients; age 30 ± 8 years), which consisted of patients with significant aortic coarctation treated with stenting, and group 2 (11 patients; age 39 ± 16 years), which consisted of patients with previous surgical repair of aortic coarctation without evidence of re-coarctation. After stenting, there was significant reduction in SPG ($p = 0.001$), DV ($p = 0.001$), EDTV ($p = 0.005$), DVHTi ($p = 0.001$), and DPHTi ($p = 0.001$) values. In the patient group as a whole, there was a significant correlation between SPG and DV ($r = 0.86$; $p < 0.001$), EDTV ($r = 0.80$; $p < 0.001$), DVHTi ($r = 0.56$; $p < 0.001$), and DPHTi ($r = 0.50$; $p = 0.002$). In addition, DV >193 cm/s (100% sensitivity, 100% specificity) and diastolic/systolic velocity ratio >0.53 (100% sensitivity, 96% specificity) had high predictive values for severe aortic coarctation (CoAi <0.25).

CONCLUSIONS After stenting, peak SPG, DV, and pressure half-time indexes (i.e., DVHTi and DPHTi) decreased significantly. These findings can confidently be used in the follow-up of coarctation patients after stenting, particularly in those with limited two-dimensional images. (J Am Coll Cardiol 2005;46:1045–53) © 2005 by the American College of Cardiology Foundation

Percutaneous stenting is an accepted form of treatment for isolated coarctation of the aorta. Numerous studies (1–5) have reported favorable outcomes in the early and intermediate follow-up periods. Although cardiovascular magnetic resonance (CMR) imaging is the procedure of choice (6) for the evaluation of coarctation of the aorta, its use may be limited because of a lack of availability or clinical contraindications. Echocardiography, because it is widely available, often is used in the initial assessment and follow-up after intervention of patients with coarctation. Two-dimensional and color Doppler echocardiographic techniques often are inadequate for a full assessment at the site of coarctation, especially in adults who have a limited suprasternal window.

Analysis of pulse-wave and continuous-wave Doppler across the coarctation site and at the abdominal aorta routinely are used for the indirect evaluation of coarctation. By using the Bernoulli equation, peak systolic pressure gradient (SPG) across the coarctation site can be measured (7,8). Pressure gradient alone as an index of aortic narrowing often is inadequate because Doppler velocities are affected by cardiac output (9), lesion length (10), the presence of collateral networks (9), and aortic compliance (11). Diastolic velocities (DVs) and diastolic pressure decays have been shown to provide clinicians with invaluable information for assessing coarctation severity (12–14).

The purpose of this study was to assess the effect of successful aortic stenting on the Doppler profile of aortic coarctation and to identify the best echocardiographic indexes that could be confidently used for the follow-up of such patients.

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Abbreviations and Definitions

CMR	= cardiovascular magnetic resonance
CoAi	= coarctation index
DPHTi	= diastolic pressure half-time index
DT	= diastolic tail
DV	= diastolic velocity
DVHTi	= diastolic velocity half-time index
EDTV	= end-diastolic tail velocity
SPG	= systolic pressure gradient
SPHTi	= systolic pressure half-time index
SV	= systolic velocity
SVHTi	= systolic velocity half-time index

PATIENTS AND METHODS

We retrospectively studied 24 consecutive patients with aortic coarctation in two groups as follows:

- Group 1: 13 patients who had percutaneous stenting for aortic coarctation between January 2002 and December 2003.
- Group 2: 11 surgically repaired aortic coarctation patients with no clinical or CMR evidence of re-coarctation.

Patients with other concomitant lesions, including aortic stenosis or regurgitation, patent ductus arteriosus, and long-segment aortic coarctation or hypoplastic arch, were excluded. Patients were studied by echocardiography and CMR before and at six to nine months after coarctation stenting. Availability of the echocardiographic studies was an essential inclusion criterion for patient selection. Right-arm systolic, diastolic, mean, and pulse pressure differences taken within three months from the echocardiogram date also were analyzed. Informed written consent was obtained from all patients. The study was approved by our local ethics committee.

Echocardiography. Transthoracic echocardiography was performed using a Phillips ultrasound imaging system (Sonos 5500, Hewlett-Packard Inc., Andover, Massachusetts) interfaced with a multifrequency transducer. Continuous-wave Doppler recordings were obtained from the standard suprasternal position to measure the maximum velocity across the coarctation site. Pulsed-wave Doppler from the standard subcostal view was performed to document the flow pattern of the abdominal aorta. Measurements made (Figs. 1A and 1B) included:

- Systolic velocity (SV) = peak systolic velocity (cm/s)
- Diastolic velocity (DV) = velocity measured at the end of "T" wave (cm/s)
- End-diastolic tail velocity (EDTV) = velocity measured at the beginning of "Q" wave (cm/s)
- Systolic velocity half-time index (SVHTi) = time taken for SV to fall to half its value (ms)
- Diastolic velocity half-time index (DVHTi) = time taken for DV to fall to half its value (ms)
- Systolic pressure half-time index (SPHTi) = time taken for the peak systolic pressure gradient ($4[SV]^2$) to fall to half its value (ms)
- Diastolic pressure half-time index (DPHTi) = time taken for the diastolic pressure gradient ($4[DV]^2$) to fall to half of its value (ms)

The instantaneous peak SPG (mm Hg) was calculated from the simplified Bernoulli equation (15) using the peak SV ($\Delta P = 4V^2$). Bazett's method (16) was used to index all time measurements to heart rate by dividing the values by the square root of the electrocardiographic R-R interval. All studies were performed with simultaneous electrocardiographic monitoring, and the onset of diastole was taken at the end of the electrocardiographic T-wave. Three measurements were taken from three consecutive cycles, and the averaged value was calculated. Rates of intraobserver and interobserver variability of selected echocardiographic indexes were calculated from 10 patients who were randomly selected from both groups.

CMR. Cardiovascular magnetic resonance was performed using a 1.5-T system (Siemens Sonata, Erlangen, Germany). The diameters of the aortic coarctation and the abdominal aorta were measured from CMR images when available or measured directly from the lateral cine angiograms taken before stenting and the ratio of their squares calculated. This ratio, the Fredriksen index or Coarctation index (CoAi) (17), measures the severity of the obstruction by comparing the ratio of the narrowest coarctation cross-sectional area to the area of the abdominal aorta at the diaphragm level (Fig. 2). Significant narrowing of the aortic coarctation is taken as having a CoAi of <0.25 (equivalent to a ratio of <0.5 of the CoA diameter to the diameter of the aorta at the diaphragm).

Reproducibility. In 10 patients, peak SPG and DV measurements were re-measured by the same observer and a second, blinded observer. The intraobserver and interobserver variability were calculated as mean percent error, defined as the difference between the two sets of measurements divided by the mean of the observations.

Statistical analysis. For each of the measured variables, values were expressed as mean ± SD or median and range according to the data distribution. All data initially were analyzed using the Kolmogorov-Smirnov test to assess for normality. Correlation was tested with Pearson's coefficient or Spearman's rho depending on normality. Paired *t*, Wilcoxon signed rank, and unpaired *t* tests were used as appropriate. Multivariate and receiver-operating characteristic analyses were performed to evaluate the best echocardiographic predictors of patients with severe aortic coarctation. The best predictive cutoff value was that which gave the highest product of sensitivity and specificity. A significant difference was defined as $p < 0.05$.

RESULTS

Demographics. Group 1 comprised 13 adult patients (7 men, age 30 ± 8 years) who had coarctation stenting for native coarctation (n = 7) or re-coarctation (n = 6). Group 2 comprised 11 patients (6 men, age 39 ± 16 years) who had

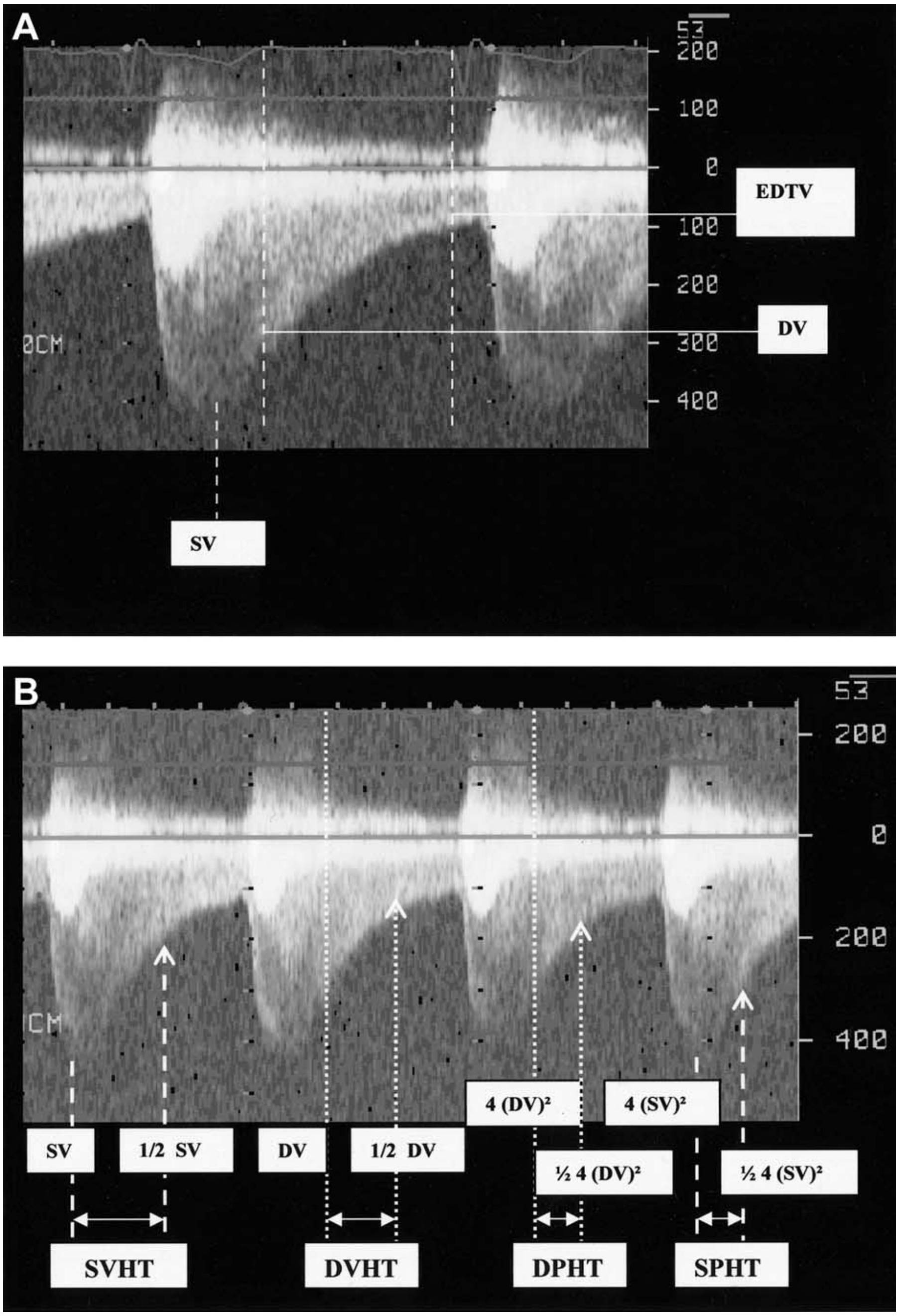

Figure 1. **(A)** Continuous-wave Doppler across aortic coarctation with prominent "diastolic tail," the peak systolic velocity (SV), diastolic velocity at the end of 'T' wave (DV), and end-diastolic tail velocity at beginning of 'Q' wave (EDTV). **(B)** Systolic velocity half-time (SVHT), systolic pressure half-time (SPHT), diastolic velocity half-time (DVHT), and diastolic pressure half-time (DPHT). SVHT (ms): time taken for the systolic velocity to fall to half of its peak value; DVHT (ms): time taken for the diastolic velocity to fall to half of its value at the end of T-wave; SPHT (ms): time taken for the peak systolic pressure gradient ($4[SV]^2$) to fall to half of its value; DPHT (ms): time taken for the diastolic pressure gradient ($4[DV]^2$) to fall to half of its value.

previously repaired aortic coarctation without any clinical or CMR evidence of re-coarctation. Coarctation severity index before and after stenting was calculated from CMR measurements (11 patients) or cine-angiograms (2 patients) during stenting and at nine-month follow-up. All patients had follow-up aortograms at nine months after stenting, and there was no angiographic or hemodynamic evidence of re-coarctation.

Blood pressure data. No significant differences were found in the systolic, diastolic, mean, and pulse pressure before and after stenting (group 1) or when compared with group 2. The strongest correlation was observed between pulse pressure and peak systolic gradient ($r = 0.51$; $p = 0.004$) but the DV/SV velocity ratio appeared to be independent of blood pressure measurements with no significant correlations found (Table 1).

JACC Vol. 46, No. 6, 2005
September 20, 2005:1045–53

Table 1. Blood Pressure Measurements and Correlations With Echocardiographic Parameters

	Group 1 Pre-Stenting	Group 1 Post-Stenting	Group 2 Post-Surgery	Correlations (p Value)						
				Peak Systolic Gradient, mm Hg	SVHTi, ms	SPHTi, ms	DVHTi, ms	DPHTi, ms	DV, cm/s	DV/SV ratio
Systolic BP, mm Hg	145 ± 20	129 ± 23	133 ± 21	r = 0.47 (p = 0.009)	r = 0.44 (p = 0.02)	r = 0.48 (p = 0.008)	r = 0.42 (p = 0.02)	NS	r = 0.45 (p = 0.01)	NS
Diastolic BP, mm Hg	80 ± 13	70 ± 11	80 ± 8	NS	r = 0.41 (p = 0.02)	r = 0.37 (p = 0.04)	r = 0.39 (p = 0.04)	r = 0.39 (p = 0.04)	NS	NS
Pulse pressure, mm Hg	65 ± 18	59 ± 21	53 ± 19	r = 0.51 (p = 0.004)	NS	NS	NS	NS	r = 0.39 (p = 0.04)	NS
Mean BP, mm Hg	107 ± 18	101 ± 22	106 ± 13	NS	NS	NS	NS	NS	NS	NS

BP = blood pressure. DPHTi = diastolic pressure half-time index; DV = diastolic velocity; DVHTi = diastolic velocity half-time index; DV/SV ratio = diastolic velocity/systolic; SPHTi = systolic pressure half-time index; SVHTi = systolic velocity half-time index.

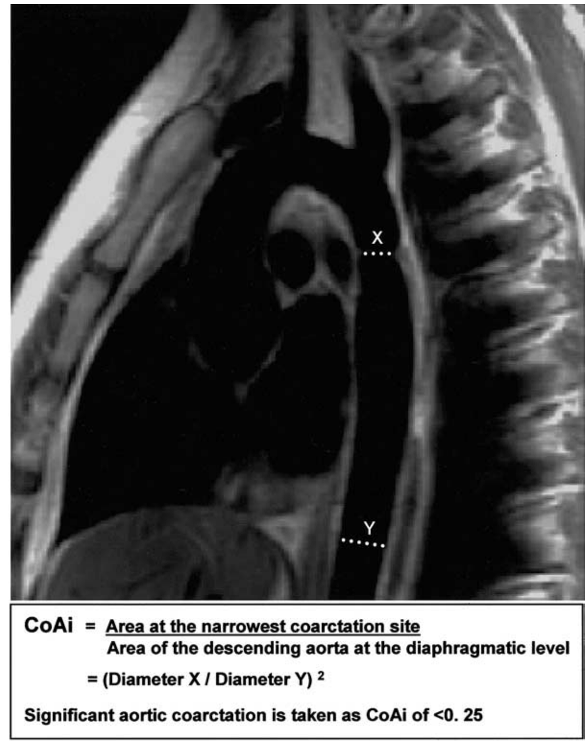

Figure 2. Turbo spin echo cardiovascular magnetic resonance image of a patient with CoA, before coarctation and after stenting, and the calculated coarctation index (CoAi). X = diameter across the narrowest coarctation site; Y = diameter of the descending thoracic aorta at the diaphragmatic level.

Echocardiographic data. All echocardiographic indexes were obtainable in all patients.

PRE-COARCTATION VERSUS POST-COARCTATION STENTING (GROUP 1). Stenting increased the CoAi from 0.13 ± 0.09 to 0.69 ± 0.32 ($p < 0.001$). Significant reductions were noted in the peak SPG ($p = 0.001$), DV ($p = 0.001$), diastolic/peak systolic velocity ratio ($p = 0.001$), EDTV ($p = 0.005$), DVHTi ($p = 0.001$), DPHTi ($p = 0.001$), and changes in the diastolic tail (DT) and abdominal aortic flow pattern, as summarized in Table 2. The change in SVHTi and SPHTi did not reach statistical significance. After stenting, there was a clear change in the DT and abdominal aortic flow pattern (Figs. 3A and 3B). All patients but one had regression of the DT, and the abdominal aortic flow changed from continuous to pulsatile.

A CoAi of <0.25 indicated severe aortic coarctation. The relationship between CoAi and peak systolic pressure gradient ($R^2 = 0.511$; $p < 0.001$), EDTV ($R^2 = 0.482$; $p = 0.001$), DV ($R^2 = 0.591$; $p < 0.0001$), peak SV/DV ratio ($R^2 = 0.614$; $p < 0.0001$), DVHTi ($R^2 = 0.510$; $p < 0.0001$), and DPHTi ($R^2 = 0.491$; $p < 0.0001$) are as shown in Figures 4A to 4F.

GROUP 1 (POST-STENTING) VERSUS GROUP 2 PATIENTS. To ascertain the influence of stenting on flow dynamics across the coarctation, we compared group 1 patients after stenting with patients in group 2 who had previous surgical repair.

Table 2. Coarctation Index and Echocardiographic Measurements of Group 1 and Group 2 Patients

	Group 1 Pre-Stenting Mean ± SD (n = 13)	Group 1 Post-Stenting Mean ± SD (n = 13)	Group 2 (Post-Surgical Repair) Mean ± SD (n = 11)	p Value (Group 1 Pre- Versus Post-Stenting)	p Value (Group 1 Post-Stenting Versus Group 2)
Peak systolic gradient, mm Hg	59 ± 13	27 ± 10	13 ± 4	0.001	<0.001
DV, cm/s	256 ± 38	120 ± 38	63 ± 15	0.001	<0.001
DV/SV index	0.71 ± 0.06	0.43 ± 0.09	0.34 ± 0.06	0.001	0.01
EDTV, cm/s	73 ± 30	28 ± 10	23 ± 12	0.005	NS
SVHTi, ms	189 ± 59	151 ± 18	147 ± 24	0.75	NS
SPHTi, ms	127 ± 34	99 ± 38	103 ± 21	0.10	NS
DVHTi, ms	123 ± 65	45 ± 17	56 ± 38	0.001	NS
DPHTi, ms	69 ± 31	27 ± 13	32 ± 23	0.001	NS
DT pattern, n	10 prominent DT, 3 small DT	1 prominent DT, 12 small DT	None had prominent DT, 9 small DT, 2 no DT	0.003	NS
Abdominal aortic flow pattern, n	10 continuous flow; 3 pulsatile flow	3 continuous flow; 10 pulsatile flow	All pulsatile flow	0.005	NS

DT = diastolic tail; EDTV = end-diastolic tail velocity; NS = not significant; other abbreviations as in Table 1.

No significant statistical differences were found (Table 2) except in their peak SPG ($p < 0.001$), DV ($p < 0.001$), and DV/SV ratio ($p = 0.01$), which were significantly lower in the surgical group.

DV AND DV/SV RATIO—SENSITIVE NEW INDEXES FOR ASSESSMENT OF COARCTATION SEVERITY. Diastolic velocity and pressure decay were significantly prolonged in severe aortic coarctation, often with a continuous flow pattern throughout diastole. On stepwise multivariate regression analysis, DV ($p < 0.0001$) had the highest sensitivity in showing independent association with CoAi, which was our gold standard for assessing coarctation severity. Diastolic velocity >193 cm/s had 100 % sensitivity and 100% specificity in predicting patients with severe aortic coarctation (Fig. 5A). Diastolic velocity may be affected by the preceding SV. To correct this, DV was indexed to the preceding peak SV. This DV/SV ratio correlated with CoAi ($r = 0.76$; $p < 0.001$), and a ratio of >0.53 had a 100% sensitivity and 96% specificity for predicting severe coarctation (Fig. 5B). A comparison of multiple receiver-operating characteristic curves (Fig. 6) showed DV to have the greatest sensitivity and specificity when compared with peak SPG and DV/SV ratio.

Reproducibility. Rates of intraobserver variability on peak SPG and DV were 6.4% and 3.3%, respectively. Rates of interobserver variability on the same measurements were 6.8% and 3.7%, respectively.

DISCUSSION

In the presence of significant CoA, SPG between the proximal and distal aorta results in high velocities during ventricular systole, which in severe coarctation, may persist during ventricular diastole. This diastolic pressure gradient gives rise to the DT; the greater the diastolic pressure gradient, the more prominent and longer the DT, thus accounting for longer DVHTi and DPHTi, increased early DV, as well as EDTV.

Our study showed that after successful coarctation stenting, there are significant changes not only in the systolic forward flow velocity and gradient but more importantly in the diastolic flow profile and the abdominal flow pattern.

Peak SPG. In our study, the peak SPG by Doppler was positively correlated with CoAi, which reduces significantly after stenting. Peak SPG has been used widely as a surrogate marker for the severity of aortic coarctation (7,8,18) in a manner similar to aortic valve stenosis. It has been correlated with other non-invasive modalities, including arm-leg systolic pressure difference (8), CMR CoAi (17), and invasively with pressure gradient measured at catheterization (7). However, it is influenced by stroke volume (9,14), geometry of obstruction (10), collateral networks (9,14), and aortic compliance (11), which may be altered after stenting. Peak SPG and SV and DV in patients after stenting were significantly higher than the post-surgical group, even after the coarctation had been relieved successfully, reflecting the alteration in flow dynamics along the stent.

SVHTi and DVHTi. Carvalho et al. (14) were the first in 1990 to highlight the use of SVHT and DVHT in patients with CoA. However, these values were not indexed to heart rate. Lim and Ralston (13) used indexed systolic and diastolic pressure half-times (SPHTi, DPHTi) as well as the systolic and DV half-times (SVHTi, DVHTi) in the detection of significant coarctation in 68 consecutive patients with suspected CoA. Like Carvalho et al. (14) and Lim and Ralston (13), our data also showed that the DV rather than the SV and pressure half-time indexes were more useful in the assessment of CoA severity. The DVHTi was closely correlated with the CoA index but not the SVHTi and SPHTi.

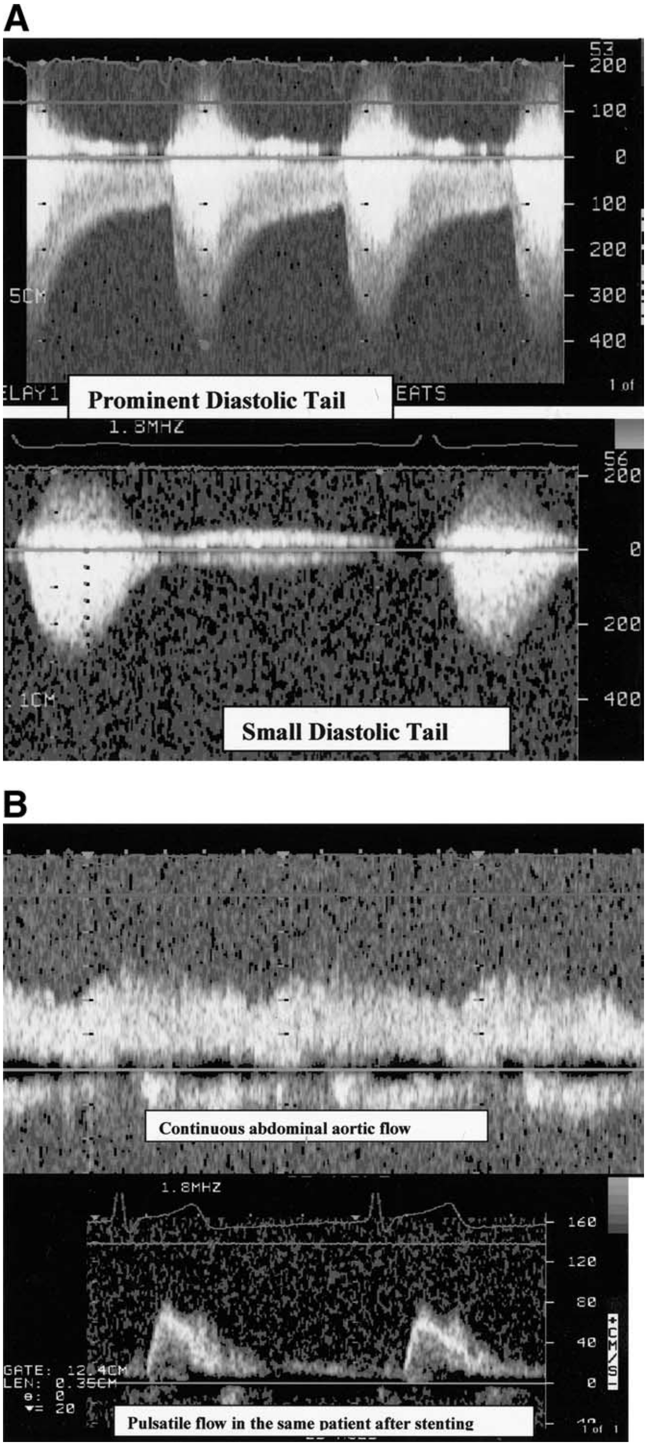

Figure 3. **(A)** Continuous-wave Doppler of the descending thoracic aorta showing prominent "diastolic tail" pattern before coarctation stenting and regression to a smaller "diastolic tail" in the same patient after stenting. **(B)** Pulsed-wave Doppler of the abdominal aorta showing continuous-flow pattern before coarctation stenting and return to pulsatile flow in the same patient after coarctation stenting.

DV and DV/SV ratio—sensitive new markers of aortic coarctation. Our results suggest that DV on its own is equal if not better than peak SPG in the assessment of CoA severity. Diastolic velocity of >193 cm/s had a 100% sensitivity and specificity in the detection of severe aortic coarctation assessed by a CoAi of <0.25. This absolute measurement of DV taken at the end of the T wave on the electrocardiogram would be faster, easier, and less cumbersome to measure than the diastolic indexes of DVHTi and DPHTi, which require further indexing to the cardiac cycle. In addition, we also propose using the ratio of the DV to SV as a further index for the assessment of CoA severity. The DV/SV ratio of >0.53 had a sensitivity of 100% and specificity of 96% for detecting severe CoA. By indexing to the systolic velocity, this ratio would be less affected by variation in heart rate, stroke volume, and aortic compliance. In addition, this ratio had no significant correlations with blood pressure measurements and, hence, could be used to assess aortic coarctation independent of the effects of systemic blood pressure. In some patients with very tight and tortuous aortic coarctation (aortic lumen 1 to 2 mm) in which the flow is minimal and both SVs and DVs are low, this DV/SV ratio may be more useful than the absolute DV itself.

Abdominal aortic flow pattern. In our study, all the patients with prominent DT (n = 10) had continuous abdominal aortic flow before stenting. After stenting, all but one patient had regression of the DT, but only in seven patients did the abdominal flow return to a more pulsatile form. In the post-surgical repair group with no preceding prominent DT, all patients had pulsatile abdominal aortic flow. The pressure gradient across the aortic coarctation result in altered flow pattern in the abdominal aorta (19,20) with loss of pulsatility as the flow becomes continuous through diastole (19). Our group had recently shown (21) that the presence and extent of the collateral circulation network in CoA was an important determinant of abdominal aortic flow pattern. After stenting, as the collateral flow volume decreased, abdominal aortic pulsatility returned. In reality, the final profile of the abdominal aortic flow probably reflects the complex interaction between diastolic pressure gradient, the relative compliance of the abdominal aorta and the change in flow through the meshwork of collateral circulation.

Study limitations. Limitations of this study include using the simplified rather than the modified Bernoulli equation, which includes the pre-obstruction velocity (V_1) in pressure gradient calculation. This is generally accurate, provided that V_1 is <1 m/s (7). In patients with very severe CoA (diameter <2 mm), it is possible for the peak pressure gradient to be low without DT because there is minimal antegrade flow through a very small orifice in both systole and diastole. Echocardiographic measurements of flow velocities and pressure gradients for aortic coarctation assessment were compared with CoAi, which is an index of severity based on the area of narrowing and not on the hemodynamics. This study analyzes the Doppler profile in adult patients with established collaterization of their potentially less-compliant CoA; thus, there may be a difference

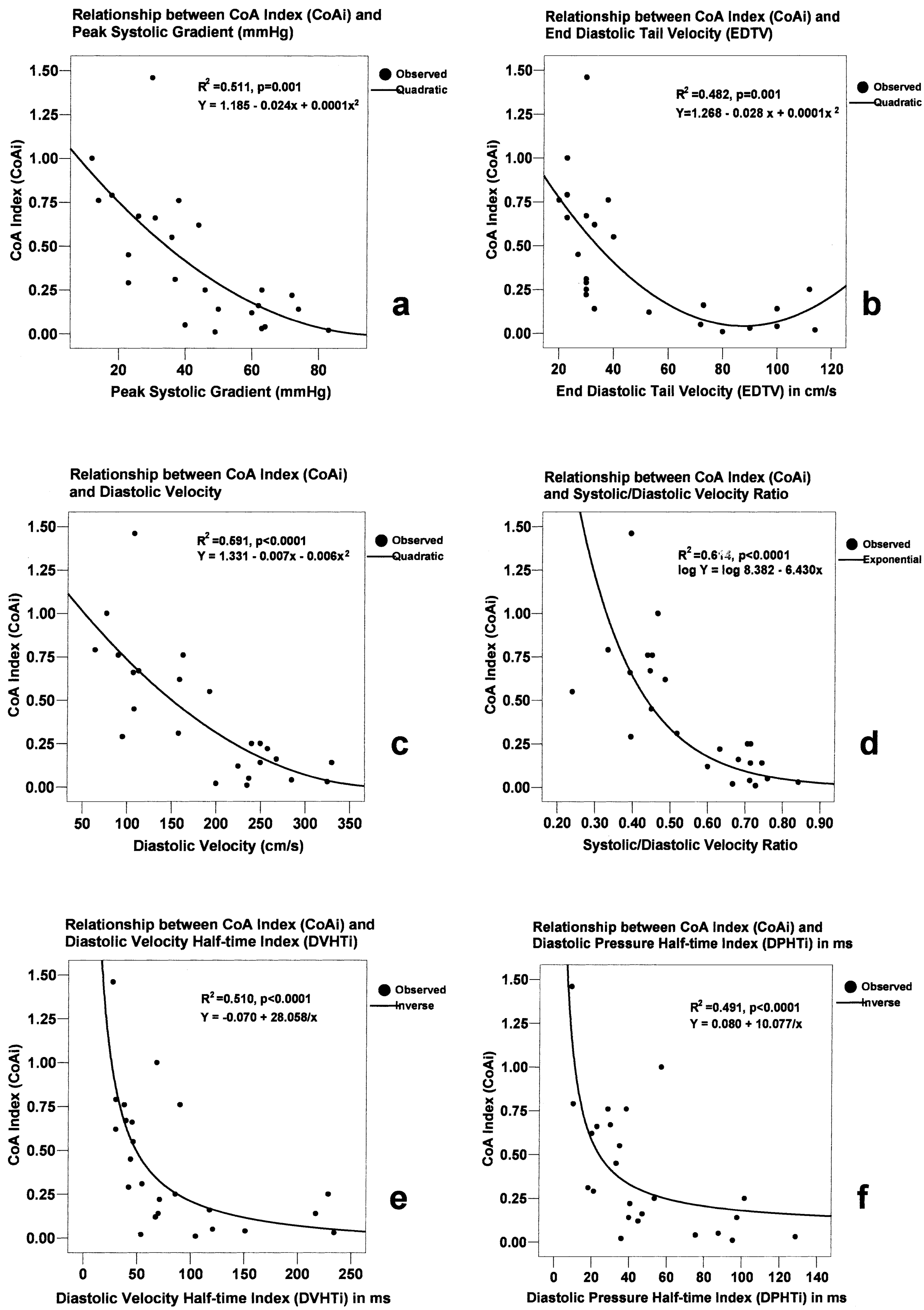

Figure 4. Relationship between coarctation (CoA) index and peak systolic gradient **(a)**, end-diastolic tail velocity **(b)**, diastolic velocity **(c)**, systolic/diastolic velocity ratio **(d)**, diastolic velocity half-time index **(e)**, and diastolic pressure half-time index **(f)** in patients from group 1 before and after stenting. **Filled circles** = observed; **line** = inverse.

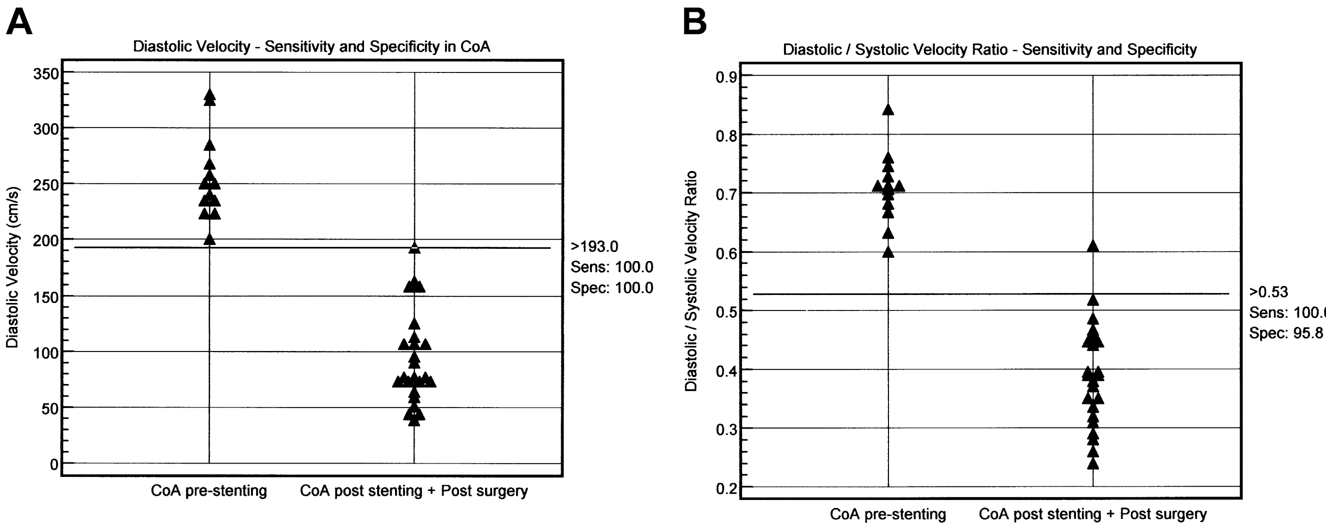

Figure 5. **(A)** Interactive dot diagram of diastolic velocity (DV) in patients with coarctation (group 1 prestenting) and in patients without significant coarctation (post-stenting/post-surgical group). Diastolic velocity >193 cm/s has a sensitivity (Sens) of 100% and a specificity (Spec) of 100%. **(B)** Interactive dot diagram of DV/systolic velocity ratio in coarctation (CoA) patients (group1 pre-stenting) and in patients without significant coarctation (post-stenting/post-surgical group). Diastolic velocity/systolic velocity ratio of >0.53 has a sensitivity of 100% and a specificity of 96%.

in the Doppler profile when compared with infants, children, or even adolescents with significant coarctation.

Clinical implications and conclusions. Patients with significant coarctation have distinguishing features in the descending thoracic and abdominal aortic flow velocities and profiles, such as increased peak SPG, increased DV, prolonged pressure half-times, the presence of DT, and continuous abdominal aortic flow. After stenting or surgical repair, these abnormal flow features often regress and may normalize. Diastolic velocity >193 cm/s and DV/SV ratio >0.53 identified 100% of the patients with severe coarctation defined by CMR imaging CoAi <0.25. We propose using these two simple measurements in addition to the other parameters for the assessment of coarctation severity before stenting and during serial follow-up.

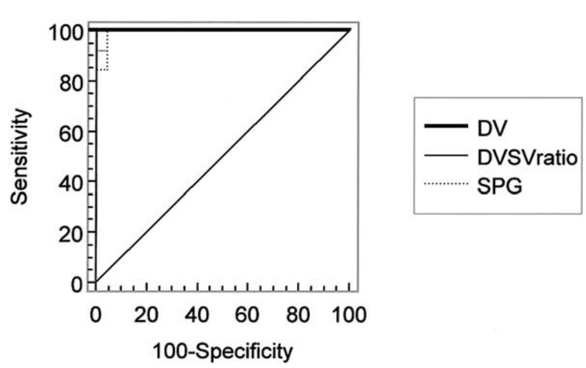

Figure 6. Receiver-operating characteristic (ROC) curves for comparison of diastolic velocity (DV), diastolic/systolic velocity (DVSV) ratio, and peak systolic pressure gradient (SPG) as indexes of coarctation severity. CI = confidence interval. Area under ROC curve for diastolic velocity (DV) = 1.000 (SE = 0.000, 95% CI = 0.904 to 1.00); area under ROC curve for diastolic/systolic velocity ratio (DV/SV ratio) = 0.997 (SE = 0.011, 95% CI = 0.898 to 1.000); area under ROC curve for peak systolic pressure gradient (SPG) = 0.994 (SE 0.016, 95% CI 0.892 to 1.000).

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