Quantification of Collateral Blood Flow in Coarctation of the Aorta by Velocity Encoded Cine Magnetic Resonance Imaging

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Background Knowledge about the volume of collateral flow provides insight into the severity of coarctation of the aorta and may be critical in planning the operative approach. There is currently no method for the quantification of collateral flow in coarctation of the aorta. In this study, we applied velocity encoded cine magnetic resonance imaging (VENC-MR) to establish the flow pattern and volume of collateral flow in the descending thoracic aorta in normal subjects and patients with coarctation, introducing a new possibility to quantify the severity of the coarctation by determining the amount of collateral flow.

Methods and Results VENC-MR was used to measure flow in the proximal and distal descending thoracic aorta in 10 normal subjects. In 23 patients with coarctation, flow was measured near the coarctation site and above the diaphragm. Patients were divided into a group with moderate to severe coarctation and a group with mild coarctation on the basis of clinical gradient between upper and lower extremities and the estimation of the gradient across the coarctation by Doppler echocardiography. The gradient across the coarctation and the degree of anatomic narrowing were also assessed by MR imaging. In normal volunteers, VENC-MR showed a 7±6% decrease in total flow, from proximal to distal aorta. The interobserver reproducibility was 3.9% to 4.9% (mean, 4.4%). In patients with moderate to severe coarctation, VENC-MR demonstrated an 83±50% increase in total flow from proximal to distal aorta, yielding a significant change compared with normal subjects (P<.01). Patients with mild coarctation showed a normal flow pattern and no significant change in total flow. There was a significant relation between the amount of flow increase in the distal aorta and the reduction in luminal diameter at the coarctation site (r=.84) as well as the clinical gradient (r=.64).

Conclusions This study shows the normal flow pattern in the descending thoracic aorta and its reversal in coarctation due to collateral flow. Thus, VENC-MR can measure collateral flow in coarctation and serves as a unique method for providing this important measurement of the severity of coarctation of the aorta. (Circulation. 1994;90:937-943.)

Key Words • blood flow velocity • coarctation • heart defects, congenital • magnetic resonance imaging

Coarctation of the aorta is the third most common congenital malformation of the cardiovascular system, occurring in 4.1/10 000 newborns.1 Depending on the degree of severity of the coarctation, a variable collateral supply develops to provide blood flow to the descending thoracic aorta via the subclavian and intercostal arteries.2 Accurate assessment of the site and severity of the structural abnormality is essential for planning surgery.3 The adequacy of collateral flow is usually estimated before surgery by qualitative inspection of the presence and size of collateral arteries displayed by x-ray aortography. No method currently exists for the quantification of collateral blood flow in coarctation.

Magnetic resonance (MR) imaging has been shown to provide both anatomic and functional information about the cardiovascular system. Anatomy is optimally demonstrated on spin-echo images, in which high contrast between moving blood, which is black, and tissue allows excellent depiction of myocardial or vascular structures. MR spin-echo imaging has been shown to be highly effective for the evaluation of thoracic aortic diseases, including thoracic aortic aneurysms, dissections, and coarctations.4-10

Cine MR imaging has been applied to depict moving anatomy and provides information about cardiac and valvular function.11-15 Recent studies have also evaluated the use of cine MR imaging to access the jet (flow void) across the coarctation16 and have inferred estimation of severity based on the length of the flow void.

Further functional information can be provided by velocity encoded cine MR imaging (VENC-MR). VENC-MR provides a measurement of blood flow at any site in the cardiovascular system. This technique has been shown to be effective for measuring gradients across cardiac valves and vascular stenoses17-19 and flow through cardiac shunts in the ascending and descending aorta and in peripheral vessels.20-22

The hypothesis of the present study was that measurement of flow in the proximal and distal thoracic aorta should show an increase from the proximal to the distal aorta in hemodynamically significant coarctations. The rise in flow is due to retrograde flow in the intercostal arteries and other collateral channels. Thus, this approach might provide a measurement of the volume of collateral flow in coarctation. To the best of our knowledge, no other existing technique can provide this information.
Study Population

Normal Volunteers

Ten normal subjects (3 women and 7 men) were studied. Mean age was 32.6 years (range, 28 to 36 years). The subjects had no known cardiac or systemic diseases and did not use any kind of medication. All subjects gave informed consent to participate in this study.

Patients

Twenty-four patients were included in this study. All patients were referred for evaluation of coarctation of the aorta. Mean age was 11.2 years (range, 8 months to 48 years). One patient was excluded because of the presence of a patent ductus arteriosus. The remaining 23 patients were divided into two groups: Group A had moderate to severe coarctation, defined as a pressure gradient of >20 mm Hg across the coarctation by Doppler echocardiography or a pressure gradient of >25 mm Hg between the right arm and the right leg (n=15 patients). Group B had mild coarctation, defined as a pressure gradient of <20 mm Hg across the coarctation by Doppler echocardiography and <25 mm Hg between the right arm and the right leg (n=8 patients).

All but one patient in group A showed a clinical gradient of >25 mm Hg. One patient showed a clinical gradient of 20 mm Hg but was included in group A because the Doppler gradient was 30 mm Hg.

Methods

Magnetic Resonance Imaging Technique

A sagittal spin-echo sequence was used to localize the descending aorta and to prescribe the slices for the VENC-MR sequences. In normal volunteers, three slices were located below the region of the left subclavian artery, at a level just above the diaphragm, and midway between these two. In patients, the three imaging planes were prescribed at the coarctation site, 10 mm below the coarctation, and at a level just above the diaphragm (Fig 1). All imaging planes were positioned perpendicular to the direction of the blood flow, and the velocity encoding was performed in the slice selection direction, which was parallel to the direction of flow. For this purpose, an oblique section was prescribed that was perpendicular to the long axis of the aorta at each site. Because of the curvature of the descending aorta, various obliquities were used at the three sampling sites (Fig 1).

VENC-MR images were acquired by use of ECG referencing, a repetition time (TR) of 24 milliseconds, an echo time of 7 milliseconds, and 10-mm oblique slices at a rate of 16 time frames per RR interval. The matrix size was 128×256, and the number of excitations was two. Reconstruction of VENC-MR data provided both a magnitude and a phase image.

The phase of proton spins was modulated by use of a bipolar gradient pulse for velocity encoding in the slice direction. Each series consisted of two interleaved cine MR acquisitions using different flow-encoding gradients along the same direction. Subtraction of the data from the two acquisitions eliminates phase shifts introduced by chemical shift phenomena and magnetic field inhomogeneities, resulting in cancellation of all phase shifts except those due to flow along the velocity-encoded direction according to the relation

\[ \Delta \text{phase} = \delta \text{Mv} \]
where $\delta$ is the gyromagnetic ratio, $M$ is the difference in gradient moment between two acquisitions, and $v$ is the velocity. If the gradients of the two experiments are chosen to keep the phase shift <180° to avoid aliasing, the velocity component along the velocity-encoded direction can be determined directly from the phase difference and $M$. The peak velocity, which is the predicted highest velocity to be encoded, was selected over the range between 4 and ~4 milliseconds in normal volunteers and between 7 and ~7 milliseconds in patients with coarctation. If the actual maximal velocity exceeds the selected peak velocity, aliasing occurs, with resultant underestimation of the true velocity. Therefore, the peak velocity was set substantially higher than expected to be found in the descending thoracic aorta. It was set higher in the patients so as to avoid any possibility of aliasing by very high jet velocity, which might be predicted at the two sites in the proximal descending aorta.

**Imaging Time**

In normal volunteers, the imaging time was 5 minutes for the locators and 12 minutes for the VENC-MR sequences. In patients, VENC-MR sequences were performed as part of a routine clinical evaluation, and no additional locators were necessary. Additional imaging time was 12 minutes.

**Image Analysis**

Images were analyzed independently by two observers. An observer-defined region of interest (ROI) was drawn around the aorta on the magnitude image (cross-sectional area in square centimeters) and then applied to the corresponding phase image (centimeters per second) for all cardiac phases at each level to give measurements for the calculation of flow (cm$^3$/cm/s cm$^3$/s). Results were reported for each time frame during the cardiac cycle, resulting in a curve of flow versus time. This curve was then integrated to calculate stroke volume in the aorta. Collateral flow was expressed as the percentage of flow increase from the proximal to the distal descending thoracic aorta.

To calculate the gradient, the VENC-MR image slice at the coarctation site was chosen. An ROI (three pixels) was placed at the area of the highest signal intensity in the aortic lumen. The gradient was calculated by use of the modified Bernoulli equation ($p=M^2$, where $p$ is pressure gradient and $v$ is peak velocity).

The percentage reduction in luminal diameter at the site of the coartation was determined by measuring the diameter of the descending aorta 1 cm above the diaphragm, midway in the ascending aorta, and at the coarctation site. The percent stenosis at the coarctation site was expressed according to the equation

$$\% \text{ stenosis} = \frac{\text{diameter of coarctation}}{[(\text{diameter AsAo} + \text{diameter DescAo})/2]} \times 100\%$$

where AsAo is the ascending aorta and DescAo is the descending aorta.

**Statistics**

Linear regression analysis was used to determine the relation among (1) MR-estimated collateral flow, (2) pressure gradient calculated by Doppler echocardiography, (3) pressure gradient calculated by VENC-MR, (4) pressure difference between right arm and right leg obtained at clinical examination, and (5) the degree of narrowing at the coarctation.

Interobserver variability for collateral flow and MR gradient measurements was expressed as the percentage of variability and SD. Percentage of variability was determined as the absolute value of the difference between the two measurements over the mean of the two measurements.

**Results**

**Normal Volunteers**

Fig 2 shows the flow pattern observed at the three levels in the descending aorta. There was a $7\pm6\%$ decrease in total flow from the proximal to the distal part of the descending thoracic aorta. At the level above the diaphragm, $65\pm10\%$ of the total flow was contributed in systole, and $35\pm9\%$ occurred in diastole.

**Patients**

**Flow Pattern**

All patients with moderate to severe coarctation (group A) showed an increase in flow from the proximal to the distal descending thoracic aorta. The mean increase was $83\pm50\%$. The correlation between systolic and diastolic contribution to total flow was $48\pm32\%$ in systole and $52\pm38\%$ in diastole. Fig 3 shows a typical flow curve in a patient with severe coarctation. The relationship of systolic and diastolic flow in these patients was significantly different compared with normal subjects ($P<.01$) and with patients with mild coarctation ($P<.01$).

Seven of 8 patients with mild coarctation showed no increase in flow from the proximal to the distal descending thoracic aorta. One patient showed a 6% increase in flow. Fifty-nine percent of total flow was contributed in systole and 41% of flow in diastole. Fig 4 summarizes the flow changes from the proximal to the distal descending thoracic aorta in all three groups.

**Pressure Gradients**

Clinical gradients (pressure difference between right arm and right leg) were available in all 23 patients. The pressure gradient across the coarctation by Doppler
This patient showed a 47% increase in flow in the distal aorta compared with the proximal aorta.

echocardiography was obtained in 17 patients. Six patients had no Doppler data because of difficulty in visualization of the region of the coarctation. Gradients measured by VENC-MR were available in 18 patients. In 5 patients, no gradient could be measured by VENC-MR because of partial volume effects in patients with very severe coarctation.

There was a close correlation between gradients obtained with VENC-MR and Doppler echocardiography ($r=.95$). Both methods, however, showed poorer correlation with the clinical gradient ($r=.63$ for Doppler echocardiography, $r=.54$ for VENC-MR).

The correlation coefficient for the relation between the increase in flow from the proximal to the distal descending thoracic aorta and the clinical pressure gradient across the coarctation was .76 for gradients obtained with Doppler echocardiography and .80 for gradients measured by VENC-MR.

The amount of flow increase correlated significantly with the clinical gradient ($r=.84, P<.05$) (Fig 5) and the degree of anatomic narrowing at the site of the coarctation ($r=.94, P<.05$) (Fig 6).

**Interobserver Variability**

The interobserver variability and SD for flow change in normal volunteers was 3.9±2.8%. For flow change in patients, the result was 4.2±3.1%, and the interobserver variability for the calculated MR gradients in patients was 4.9±3.5%.

**Discussion**

This study has shown the ability of VENC-MR to measure flow in different parts of the descending thoracic aorta in normal subjects and in patients with coarctation of the aorta. MR imaging was able to calculate the amount of flow change from the proximal to the distal part of the descending aorta and thereby quantify the volume of collateral flow into the distal descending aorta.

The findings in normal volunteers show that there is a slight decrease in the flow volume from the proximal to the distal part of the descending thoracic aorta, probably as a result of blood leaving the aorta into the intercostal arteries. In patients with coarctation, this normal flow pattern is reversed to a variable degree. Patients with moderate to severe coarctation show an increase in flow from the proximal to the distal aorta. This increase is caused by the collateral flow entering the descending aorta via retrograde flow from the intercostal arteries.22 Therefore, determining the amount of flow increase from the proximal to the distal descending thoracic aorta provides a direct measurement of the volume of collateral blood supply to the lower part of the body. Because collateral blood flow develops only if the stenosis in the original vessel is significant enough to cause a lack of blood supply in the dependent part,24 the amount of collateral flow and therefore the amount of flow increase in the descending aorta should be an indicator of the hemodynamic severity of the coarctation. The strong correlation between this functional indicator of the severity and the degree of anatomic narrowing at the site of the coarctation supports this notion.

The present study also disclosed an alteration in the shape of the flow curve between normal volunteers and patients with severe coarctation. Whereas normal subjects and patients with mild coarctation distribute most of the blood flow during systole, patients with moderate...
Fig 6. Plot showing percentage of flow change on the x axis and percentage of anatomic narrowing on the y axis.

to severe coarctation had a temporal shift of the flow curve to the diastolic phase of the cardiac cycle. There are two possible explanations for this phenomenon. This shift in flow curve could be a result of the increased time required for the blood provided by the collaterals to course through the intercostal arteries into the descending aorta. Conversely, this flow pattern in patients with moderate to severe coarctation appears similar to flow patterns obtained in stenotic peripheral vessels and could therefore be caused primarily by delayed transmission of flow through the stenosis in the proximal descending aorta itself. In our study, the flow curve below the coarctation showed the same shape as the one above the diaphragm in terms of diastolic contribution to total blood flow, although no collateral inflow is present at the higher location. This observation supports the latter mechanism as at least contributing to the temporal shift of blood flow to the diastolic part of the cardiac cycle.

It should be recognized that the average age of the volunteers was two decades older than the average age of the patients with coarctation. The flow pattern described as normal in the present study may not be exactly characteristic of the normal aortic flow in young children as a consequence of alteration in aortic compliance and other factors that are known to occur during aging. Previous studies have shown the accuracy of VENC-MR techniques to measure flow in the aorta. This technique has been applied to measure flow changes in the ascending aorta and in the descending aorta in patients with coarctation. Additionally, VENC-MR has been used for the measurement of the volume of left-to-right shunts. Gradients across coarctation of the aorta, across Rastelli conduits, and across valvular stenoses have been measured by VENC-MR to define the peak velocity in the flow jet.

Although the gradients across the coarctation measured by VENC-MR and by Doppler echocardiography correlated clearly in the present study, both showed poor correlation with the clinical blood pressure gradient between the right arm and the right leg. This supports findings of previous studies that the gradient across the coarctation can be misleading in terms of severity of the disease. This may be a problem in severe coarctation because the large amount of collateral blood flow entering the descending aorta raises pressure beyond the coarcta
tion and may minimize the effect of the severe coarctation on distal aortic pressure. To support this theory, studies comparing Doppler gradients with morphological data in patients with coarctation have found poor correlation between the degree of anatomic obstruction and the pressure gradient, especially in patients with a large collateral supply.

In addition, both Doppler echocardiography and VENC-MR were unreliable in measuring the gradient across severe coarctations in the present study. Whereas Doppler echocardiography failed to create adequate signal across the coarctation to visualize the exact location of the narrowing, MR imaging did not give reliable information about the velocity across the coarctation because of partial volume effect and higher orders of turbulent motion in very tight coarctations.

In mild to moderate coarctation, however, Doppler has been found to accurately estimate the gradient. Consequently, the Doppler gradient was considered reliable for dividing patients into groups with gradients above and below 20 mm Hg.

These limitations of gradient-based assessments of the severity of coarctation further suggest that the quantification of the amount of collateral flow might be more useful for the determination of the severity of coarctation of the aorta. However, there are certain patients with severe coarctation who, for unknown reason, have an inappropriately low volume of collateral flow. The present technique may serve as a method to identify these patients with a mismatch between the morphological severity and the volume of collateral flow to the distal descending aorta. Recognizing such a mismatch is important in planning surgical management of these patients.

Clinical Implications

Magnetic resonance spin-echo imaging has been shown to be effective as a noninvasive method for evaluating the morphology of coarctation of the aorta. It accurately depicts the location and the degree of narrowing. However, this morphological information does not necessarily indicate the hemodynamic consequences of the narrowing. Additional VENC-MR information can provide evaluation of both anatomic and hemodynamic severity of the coarctation.

Information about the amount of collateral flow is important for planning surgery. Depending on the quantity of collateral flow, surgery can be performed with cross-clamping alone (high amount of collateral flow), or additional techniques such as left heart bypass, internal shunt, or a jump graft may be applied to ensure proper blood flow to the lower part of the body. In addition, evaluating the flow in the descending aorta could be used to monitor patient outcome after corrective surgery.

Clinical application of this technique might be particularly useful in two clinical situations. First, the presence of collateral circulation might be used to verify the clinical impression that a coarctation is sufficiently severe to require surgery or angioplasty. Moreover, the adequacy of an angioplasty might be documented by reversion of the flow pattern to normal. Second, the absence of adequate collateral circulation defined before surgery would be useful in planning the surgical approach to minimize jeopardy for spinal cord ischemia.

Limitations

This type of evaluation of patients with coarctation could be compromised by partial volume errors caused by a very small size of the ROI in infants with tight coarctations, yielding unreliable measurements of flow at the area below the coarctation. Other limitations include patients with additional cardiovascular malformations, such as a patent ductus arteriosus, which
would make it impossible to distinguish between left to right shunting and collateral flow into the distal descending thoracic aorta. Collateral flow entering below the level of the diaphragm cannot be measured by this method because the physiological outflow of blood through the cavalia artery would prevent accurate measurements at a lower level. This leads to underestimation of the total volume of collateral flow. However, measuring the blood flow at the same location in all patients still provides sufficient data for defining characteristics indicative of hemodynamically significant coarctations.

Conclusions
This study demonstrates the effectiveness of VENC-MR for quantifying flow in the descending thoracic aorta in normal subjects and in patients with coarctation of the aorta. In patients with hemodynamically significant coarctation of the aorta, the normal flow pattern is reversed. The increasing volume of flow in the distal thoracic aorta in patients with moderate to severe coarctation represents the contribution to total flow made by the collateral circulation via the intercostal arteries, and this measurement may serve as an additional parameter for predicting the severity of the anatomic and physiological obstruction. It may also be used to detect a mismatch between the severity of the anatomic obstruction and collateral flow, which can be a central factor in planning the surgical procedure.

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