Magnetic Resonance Phase-Shift Velocity Mapping in Pediatric Patients With Pulmonary Venous Obstruction

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OBJECTIVES
This study evaluated the accuracy, advantages and clinical efficacy of magnetic resonance (MR) phase-shift velocity mapping, in delineating the site and the hemodynamic severity of pulmonary venous (PV) obstruction in patients with congenital heart disease (CHD).

BACKGROUND
Magnetic resonance phase-shift velocity mapping of normal pulmonary veins and of obstructed PV pathways have been previously reported in a mainly adult population.

METHODS
The study population (33 pts) underwent MR phase-shift velocity mapping of their PV pathways. These results were compared with cardiac catheterization and Doppler echocardiography data.

RESULTS
The study population (0.4 to 19.5 years) consisted of a study group (PV pathway obstruction, n = 7) and a control group (no PV obstruction, n = 26). No patients had any left-to-right shunt lesions. The MR imaging displayed precise anatomical detail of the pulmonary veins. Phase velocities in the control group ranged from 20 to 71 cm/s, whereas velocities in the study group ranged from 100 to 250 cm/s (p = 0.002). The MR phase velocities (154 ± 0.53 cm/s) compared favorably with Doppler echocardiography (147 ± 0.54 cm/s), (r = 0.76; p = 0.05). The MR velocity mapping was 100% specific and 100% sensitive in detecting PV obstruction, although the absolute gradient measurements among MR phase mapping, echocardiographic Doppler and catheterization did not show statistically significant correlation.

CONCLUSIONS
In the absence of any associated left-to-right shunt lesions, PV velocities of 100 cm/s and greater indicated significant obstruction. The MR phase-shift velocity mapping, together with MR spin echocardiography and MR angiography, provides comprehensive anatomic and physiologic data that may obviate the need for further invasive studies.

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Manuscript received June 26, 1997; revised manuscript received March 6, 2001, accepted March 23, 2001.

Quantification of blood flow through pulmonary venous (PV) pathways is of major clinical interest in the assessment of the severity of PV obstruction. Cardiac catheterization has long been the standard method for evaluation of patients with total anomalous pulmonary venous return (TAPVR) obstruction. Catheterization is an invasive procedure, resulting, in radiation exposure and possible hemodynamic compromise. The risks of cardiac catheterization in this group of patients are increased because of the frequently associated pulmonary hypertension. Furthermore, direct pulmonary vein pressure measurements may be technically difficult or impossible to obtain. Patients with intact atrial septa may require transseptal puncture in order for the physician to perform direct pulmonary vein pressure measurements. Pulmonary artery wedge pressures are therefore frequently used as an indirect measurement of pulmonary vein pressures.

Echocardiography is useful in some patients but may be suboptimal due to poor postsurgical echocardiographic windows, poor anatomical detail of peripheral pulmonary veins and difficulty in obtaining adequate alignment of the turbulent jets to measure accurate gradients by Doppler (1). The advent of transesophageal echocardiography (TEE) with Doppler may facilitate pulmonary vein velocity measurements (2,3). Nevertheless, TEE also has significant limitations in that it is an invasive procedure usually requiring general anesthesia in children.

Several magnetic resonance (MR) techniques have been reported for direct flow quantification (4−8). At the present time MR phase mapping based on linearity between phase angle and velocity of moving blood in a gradient field seems to be the method of choice (9,10). The MR phase velocity mapping can be used to display the anatomy of the heart and vessels in high resolution and to measure blood flow velocity and characterize its pattern noninvasively in any plane or direction (11−14). Magnetic resonance phase-velocity mapping studies of anatomically normal pulmonary veins have been performed in adults (15); MR phase velocity mapping for assessment of venoatrial pathways after the Mustard operation for transposition of the great arteries has been previously reported in a mainly adult population (16).

STUDY PURPOSE
The purpose of this study was to evaluate the accuracy, the advantages and the clinical efficacy of MR phase-shift
velocity mapping in delineating the site and the hemodynamic severity of PV obstruction in a group of pediatric patients with documented PV pathway stenosis.

**METHODS**

**Study design.** This prospective study compared the PV gradient measurements obtained by MR phase-shift velocity mapping with those determined by cardiac catheterization and/or Doppler echocardiography. Patients studied had a known variety of congenital heart lesions and obstructed PV pathways. The observer analyzing the MR-determined gradients was blinded to the echocardiographic and catheterization data.

**Patient population.** The study population was selected from a group of patients referred to The Children’s Heart Center at Emory University for MR studies over a two-year period. The study population consisted of a control group of patients with no PV obstruction and a study group of patients with documented PV obstruction (Table 1). Patients were excluded if they had prothetic valves, pacemakers, and surgical clips near the region of study or any arrhythmia. Each patient underwent echocardiographic examination and/or cardiac catheterization and angiography.

**Imaging examinations. MRI.** Magnetic Resonance imaging examinations were performed on a 1.5-tesla ACS Gyrosan (Philips Medical System, Holland) at Emory University Hospital and on a 1.5-tesla Signa scanner (GE Medical Systems, Milwaukee, Wisconsin) at Egleston Children’s Hospital. Black-blood spin “echo” acquisitions were electrocardiographically synchronized (S) with a repetition time (TR) equal to the RR cycle length and an echocardiographic time (TE) of 30 ms. The spin echocardiographic images (5-to-8 mm thick, 0 gap) were used to define the anatomy. Bright-blood, cine gradient echocardiographic images (image matrix 128x128 or 256x256 pixels) were electrocardiographically synchronized, and images were acquired in the transverse, coronal, and sagittal planes. These cine images were used to display the flow jets and to locate a suitable slice for the acquisition of the velocity flow maps at the sites of stenosis (17). Using the spin echocardiographic and gradient echocardiographic images as guides, the flow-mapping scan was planned in an oblique transverse orientation so that the jet was contained in the plane of the imaging slice (Fig. 1). This orientation was chosen so that the maximum jet velocity could be easily detected. Phase-shift velocity mapping measurements were performed using TE of 7 ms and a TR of 14 ms (Fig. 2). Velocity encoding was done in the left-right direction only. A single direction of velocity encoding could be performed because of the careful planning of the slice location. Retrospective cardiac gating was done, and 14 time points per cardiac cycle were obtained. The slice thickness was 8 mm and the matrix was 128x256. Velocities in the range of ±2 m/s were encoded, and the data acquisition time was approximately 4 min, depending on the heart rate. When aliasing in the phase images was seen, the velocity encoding value was increased to 300 cm/s.

In the study group, the pressure gradient at the site of obstruction was estimated using the modified Bernoulli equation: P = 4 (Vt2 – Vu2), where p is the pressure gradient in mm Hg, Vt is the velocity in the stenosis in ms, and Vu is the upstream velocity in m/s.

Patients were referred for MR studies by clinical cardiologists. The data gained was used for this study. Informed consent was obtained prior to all MR studies. Each study took ~60 to 90 min. Postprocessing time required an additional 20 to 30 min. Children <3 years of age were sedated with chloral hydrate (100 mg/kg/po), while uncooperative patients between 3 and 7 years were sedated with Nembutal (5 to 6 mg/kg IV). Parents were instructed to keep children awake and to avoid feeding them for 5 to 6 h prior to the study. Sedated patients were monitored by pulse oximetry, electrocardiogram (ECG) and closed-circuit television.

**ECHOCARDIOGRAPHY.** A complete two-dimensional and Doppler examination was performed from the subxiphoid, apical, parasternal, and suprasternal approaches. Evaluations were performed with 7.5–, 5.0–, or 3.5–MHz phased array transducers (Hewlett-Packard Sonos 2500 Andover,

<table>
<thead>
<tr>
<th>Table 1. Comparison of Demographics Between the Control and Study Groups</th>
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<tr>
<td><strong>Control Group</strong> (No pulmonary venous obstruction)</td>
</tr>
<tr>
<td>Patient number</td>
</tr>
<tr>
<td>Gender</td>
</tr>
<tr>
<td>Age (median)</td>
</tr>
<tr>
<td>Diagnosis</td>
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Massachusetts). All echocardiographic examinations were supervised and interpreted by a staff echocardiographer. Echocardiographic evidence of PV pathway obstruction was based on two-dimensional evidence of pulmonary vein narrowing, and/or Doppler color evidence of a turbulent flow pattern and demonstration of Doppler continuous flow pattern without phasic variation (18). Sedation with oral chloral hydrate (75 to 100 mg/kg; maximal dose 1 g) was used when necessary.

CARDIAC CATHETERIZATION AND CINEANGIOGRAPHY. Comprehensive cardiac catheterization including angiography was performed. Aortography, ventriculography, pulmonary arterial and selective pulmonary arterial angiography were performed in biplane anteroposterior, lateral, and axial views. Cardiac catheterization and angiography confirmed the presence of PV obstruction by demonstrating delayed clearance of contrast media in the pulmonary arteriogram, a narrow site along the PV pathway, or a pressure gradient across the site of obstruction (19). The pulmonary to systemic flow and vascular resistance ratios and pulmonary arteriolar resistance were all determined.

Statistics. The Fisher exact two-tailed test was used in comparing sex distribution between the study and the control groups. Continuous variables were assessed to determine whether they were normally distributed using the Shapiro-Wilks statistic. In the comparison of two continuous variables, not normally distributed, the Wilcoxon rank-sum test was used and, for normally distributed variables, the independent t test was used. Comparisons of two normally distributed measurements in the same patient were performed using the paired t test and correlation coefficients were calculated.

RESULTS

Study population. The study population consisted of 33 patients, who underwent MR studies between March 1994 and March 1996. The demographics of the control group and study group are shown in Table 1. No significant differences existed between the two groups in gender or in

Figure 1. Sequential left parasagittal fast field echocardiographic real (FFER) magnitude images in a pt post-TAPVR repair. (A) Left upper and lower pulmonary veins (solid arrow) entering the left atrium. (B–D) The progression of images from (B) to (D) show increasing turbulence in the left atrium (arrow), indicating acceleration of blood flow due to the stenosis.

Figure 2. Phase-shift mapping image of stenosed left pulmonary veins with overlay of velocity curve. Velocity phase mapping again shows flow acceleration (increasing darkness of flow signal) arising from the left upper and lower pulmonary veins (solid arrows). The velocity cursor (labeled 1) is located at the maximal velocity point. Graphic display of velocity is shown in cm/s.
age distributions. No patients had any associated left-to-right shunt lesions.

Peak pulmonary vein phase-shift velocities. The comparison of peak MR phase-shift pulmonary vein velocities is shown in Figure 3. Patients in the study group had significantly higher peak pulmonary vein velocities when compared with the control group ($p = 0.002$). The range for peak pulmonary vein velocities was 20 cm/s to 71 cm/s for the control group and 100 cm/s to 250 cm/s for the study group. The median pulmonary vein velocity for the control group was 39 cm/s compared with 140 cm/s for the study group. The mean ± SD for the control group was 40 ± 14 cm/s and for the control group was 154 ± 57 cm/s.

Magnetic resonance phase-shift velocities compared with Doppler echocardiography. The results of the peak pulmonary vein blood flow velocities in the seven patients in the study group who underwent both MR phase-shift velocity mapping and Doppler echocardiography of their obstructed PV pathways are displayed in Table 2. Statistical analysis confirms a significant correlation between the two modalities.

Comparison of MR phase-shift velocity mapping gradients with Doppler echocardiography and cardiac catheterization. Six of seven patients in the study group underwent echocardiographic and cardiac catheterization evaluation. The peak PV gradients obtained by each of the above modalities are compared with the MR phase-shift velocity mapping gradients as shown in Table 3.

Magnetic resonance phase-velocity mapping detected gradients from 5 mm Hg to 18 mm Hg in this patient group, whereas the Doppler echocardiography gradients ranged from 3 to 12 mm Hg and the catheterization gradients ranged from 1 to 14 mm Hg. Patient no. 2 had mild gradients detected by all three modalities at the anastomosis site; however, only MR imaging and cardiac catheterization demonstrated residual anomalous drainage of the right upper pulmonary vein (RUPV) to the superior vena cava (SVC). Only phase-shift velocity mapping revealed a 10-mm Hg gradient at the right upper pulmonary vein to SVC anastomosis. Echocardiography failed to detect this anomalous drainage, and at catheterization no gradient could be measured at the RUPV to SVC junction owing technical difficulties in catheter manipulation.

DISCUSSION

Study data. To our knowledge there is one other study in which MR phase velocity mapping has been used to estimate pressure gradients within obstructed venoatrial pathways (16). The study by Sampson et al. (16) examined 21 patients aged 3 to 28 years (mean age, 19.3 years), with transposition of the great arteries, after undergoing the Mustard operation. In four cases in which peak velocity measurements were made with both MR phase-shift velocity mapping and Doppler “echo,” there was agreement between the techniques.

Our study was performed in an entirely pediatric population group. We demonstrated that young patients with small vessels and rapid heart rates did not preclude satisfactory studies. We were able to obtain pulmonary vein velocities in all patients, with the youngest patient being 0.4 years. Results with MR velocity mapping of PV flow

**Table 2**. Peak Pulmonary Vein Blood Flow Velocity (cm/s) of Patients With Pulmonary Venous Pathway Obstruction from MR Velocity Mapping and Doppler Echocardiography

<table>
<thead>
<tr>
<th>Phase Velocity Mapping MR (cm/s)</th>
<th>Doppler Echocardiography (cm/s)</th>
<th>Diagnosis</th>
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</thead>
<tbody>
<tr>
<td>100</td>
<td>140</td>
<td>Cor Triatriatum</td>
</tr>
<tr>
<td>110</td>
<td>110</td>
<td>TAPVR</td>
</tr>
<tr>
<td>110</td>
<td>90</td>
<td>TAPVR</td>
</tr>
<tr>
<td>140</td>
<td>170</td>
<td>dTGA s/p Mustard</td>
</tr>
<tr>
<td>160</td>
<td>120</td>
<td>TAPVR</td>
</tr>
<tr>
<td>210</td>
<td>140</td>
<td>TAPVR</td>
</tr>
<tr>
<td>250</td>
<td>260</td>
<td>TAPVR</td>
</tr>
<tr>
<td>Mean 154 ± 0.53</td>
<td>147 ± 0.54</td>
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Paired $t$-test, $p = 0.64$; Correlation coefficient, $r = 0.76$; $p = 0.047$.

DTGA = d-transposition of the great arteries; MR = magnetic resonance; Mustard Operation = intra-atrial leaflet correction of dTGA; TAPVR = total anomalous venous return.
velocity in the control group concur with a previously published MR velocity mapping study performed in adults with normal PV flow (15) as well as published transesophageal Doppler echocardiography studies (2,3,12). The fact that there were no patients in the study with left-to-right shunt lesions warrants special mention. The increased PV return associated with left-to-right shunt lesions results in increased pulmonary vein flow velocities even in the absence of pulmonary vein obstruction. Pulmonary vein velocities greater than 100 cm/s being indicative of PV obstruction must be taken in context, recognizing that in this study population there were no patients with associated left-to-right shunt lesions.

In our study, in the absence of any associated left-to-right shunt lesions, MR phase-shift velocity mapping was both 100% sensitive and specific in identifying PV obstruction (p = 0.002), with phase mapping velocities equal to or greater than 100 cm/s indicating PV obstruction. A statistically significant correlation (r = 0.76; p = 0.047) was found between peak pulmonary vein velocities measured with MR phase-shift velocity mapping and Doppler ultrasound. In the six patients who had catheterization performed (Table 3) the correlation with MR phase-shift velocities was not statistically significant. This may be due to incorrect assessment of the true gradients by either modality, observer error (incorrect velocity jet interrogation) or to the difference in patient basal hemodynamic state (sedation, heart rate, etc.) (20). Inaccurate MR velocity maps may be due to local signal loss, background noise, and edge spikes or phase wrapping (17). Faulty gradient measurement by cardiac catheterization might be due to incorrect catheter placement (partial wedging), indirect pulmonary wedge pressures rather than direct pulmonary vein measurements, incorrect transducer balancing, and other factors. Nevertheless, MR phase-shift velocity mapping did detect all patients with documented cardiac catheterization PV obstruction, and further clinical management planning was not affected by quantitative differences in the measured gradients.

Study limitations. The small number of patients in the study population is a shortcoming that is difficult to overcome because obstruction of PV pathways is extremely rare. A multicenter study would be required to address this issue. A further limitation of this study is that no interobserver or intraobserver variability measurements were performed. In patients undergoing cardiac catheterization following TAPVR correction, rather than subjecting patients to the risks of transseptal puncture in order to perform direct pulmonary vein measurements, pulmonary arterial wedge pressure measurements were performed. Therefore, direct catheter-determined gradients were not available in some patients. Assessment of hemodynamic parameters such as heart rate and blood pressure during the various diagnostic parameters was not included in the study design. Despite the possible hemodynamic variability between studies done at different times, MR velocity mapping retained its diagnostic efficacy.

Value of MR studies. The combination of “static” or spin echocardiographic imaging and cine angiographic imaging (Fig. 1) in multiple planes, which is not available with any other imaging modality, allows for visualization of structures along any oblique, linear or short axis trajectory. Phase-shift velocity mapping interrogation of the stenotic sites enables gradient assessment and quantification.

Adequate transthoracic echocardiographic delineation of anatomy and Doppler gradient assessment of anomalous PV drainage may be difficult to obtain (21) in the more complex forms of TAPVR and therefore cardiac catheterization (22) or TEE imaging may be warranted (21). Although thoracic imaging is noninvasive and easily accomplished with little risk to the patient, TEE in the very young and often hemodynamically unstable pt is not an innocuous procedure; it may require anesthesia with all its attendant risks. The MR examinations provided excellent anatomic definition in all patients, especially postsurgery, when suboptimal imaging windows was not an issue.

Cardiac catheterization with cardiac angiography provides important information with regard to the surgical planning and medical management of this group of patients. Direct catheter pull-back measurements, by way of a transseptal approach, allows accurate gradient assessment pre- and postpulmonary venous pathway obstruction. Usually the interatrial communication is closed at the time of surgical correction, and patients with residual PV obstruction postsurgical repair are therefore a high-risk group because not only do they have associated pulmonary hypertension but

| Table 3. Comparison of MR, Doppler Echocardiography and Catheterization-Derived Peak Pulmonary Vein Blood Flow Gradients (mm Hg) in Patients With Pulmonary Venous Pathway Obstruction |
|-----------------|-----------------|-----------------|-----------------|
| Patient No.     | Diagnosis       | MR (mm Hg)      | Echocardiography (mm Hg) | Catheterization (mm Hg) |
| 1               | dTGA S/P Mustard | 8               | 12              | 14              |
| 2               | TAPVR           | 5 (10)          | 3               | 1               |
| 3               | TAPVR           | 5               | 3               | 8               |
| 4               | TAPVR           | 8               | 8               | 10              |
| 5               | TAPVR           | 10              | 6               | 8               |
| 6               | TAPVR           | 5               | 5               | 8               |
| Mean            |                 | 8.5 ± 5.1       | 6.2 ± 3.4       | 8.2 ± 4.2       |

*Right upper pulmonary vein to superior vena cava (SVC) gradient (see text). Abbreviations as in Table 2.
they may also require atrial septostomies for direct pulmonary vein pressure measurements. Because of the added risks of atrial septostomies, frequently indirect pressure measurements are obtained by way of simultaneous left ventricle end diastolic pressures and pulmonary arterial wedge pressures.

Magnetic resonance studies are noninvasive and do not result in any radiation exposure to the pt or the medical staff. Complete MR studies of complex congenital heart disease (CHD; heterotaxy syndrome) have been shown to be comparable with echocardiography in terms of duration of study and sedation requirements (23). A complete MR study (spin echocardiography, cine MRI and phase-shift velocity mapping) may be less costly and more time-efficient than cardiac catheterization with angiography (267). 

Although we utilized MR phase-shift velocity mapping to determine peak pulmonary vein velocities, MR phase-shift velocity mapping has tremendous potential in the study and timing of velocity profiles throughout the cardiac cycle. It may provide a wealth of information not only in the assessment of obstructed vessels but also in the understanding of normal and abnormal flow patterns within the various blood vessels and heart chambers. Use of MR phase-shift velocity mapping might prove to be an invaluable aid in our understanding of both normal and abnormal diastolic function.

In conclusion, the utilization of these various MR techniques can provide anatomic as well as hemodynamic information that may not be easily attainable or accessible by any other single imaging modality. Magnetic resonance evaluation of pediatric patients with PV pathway obstruction associated with complex CHD may obviate the need for further invasive studies.

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REFERENCES


