Magnetic resonance imaging: evaluation of palliative systemic–pulmonary artery shunts

MARK D. JACOBSTEIN, M.D., BARRY D. FLETCHER, M.D., A. DENNIS NELSON, PH.D., MARK CLAMPITT, R.T., RALPH J. ALFIDI, M.D., AND THOMAS A. RIEMENSCHNEIDER, M.D.

ABSTRACT Eleven patients with a total of 17 palliative systemic–pulmonary artery shunts underwent evaluation by electrocardiogram-gated magnetic resonance imaging (GMRI). GMRI successfully imaged 11 of 17 shunts (65%), including five of nine Blalock-Taussig shunts, four of six Glenn shunts, and both aortopulmonary shunts. All shunts except for the Waterston were imaged on coronal sections during end-systole. The single Waterston shunt was seen on sagittal and transverse scans. Shunt localization and identification were facilitated by obtaining multiple, contiguous sections through the body. Glenn shunts could be imaged entirely in one section, although multiple sections were required to locate the correct plane. Blalock-Taussig shunts generally required multiple sections to image different segments of the shunt. Both aortopulmonary shunts were seen as direct side-to-side connections of the aorta and pulmonary artery. GMRI permitted assessment of the size, course, patency, and distribution of systemic–pulmonary artery shunts as well as the size and morphology of the proximal pulmonary arteries. We conclude that GMRI is a useful, noninvasive method for imaging the anatomy of systemic–pulmonary artery shunts.

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CONGENITAL heart defects characterized by cyanosis and decreased pulmonary blood flow are often palliated by creation of systemic–pulmonary artery shunts. All of the operations that have been devised increase pulmonary blood flow and differ primarily in terms of which specific vessels are anastomosed. The evaluation of patients who have previously undergone palliative shunt procedures frequently includes imaging of the shunt and pulmonary arterial anatomy. This generally requires invasive angiographic studies, either during cardiac catheterization or, more recently, with digital subtraction techniques.

Noninvasive imaging of systemic–pulmonary artery shunts has been unsatisfactory. Ultrasonography is limited by the poor echographic accessibility of these structures, which are extracardiac and enveloped by lung tissue. We have previously reported our experience with electrocardiogram-gated magnetic resonance imaging (GMRI) in patients with congenital heart defects.1 2 Included in our early work were two patients in whom palliative systemic–pulmonary artery shunts were successfully visualized.1 We have since had the opportunity to study a much larger number of patients with these shunts. This article presents our experience with GMRI in depicting a variety of systemic–pulmonary artery shunts in young patients with cyanotic congenital heart disease.

Patients and methods

Eleven patients with cyanotic congenital heart disease in whom 17 palliative systemic–pulmonary artery shunts were present underwent evaluation by GMRI. Five patients had pulmonic atresia: two with intact ventricular septum, two with large ventricular septal defects, and one in association with a univentricular heart. Three patients had tricuspid atresia and the remaining three had atrophicventricular septal defects, with severe pulmonic stenosis in two and a tight pulmonary arterial band in the other. Six patients had two shunts. There were nine Blalock-Taussig shunts, six Glenn shunts, one Waterston shunt, and one Potts shunt. Patients ranged in age from 1 to 21 years (mean 13). Only one patient was under 2 years of age. This patient was sedated with 2 mg/kg meperidine, 1 mg/kg promethazine, and 1 mg/kg chlorpromazine. Informed consent was obtained in all cases from the patient or the patient’s guardian.

Images were obtained with a superconducting magnet operating at 0.3 T (Technicare; Solon, OH). At this field strength the resonant frequency for protons is 12.85 MHz. Infants were placed within a smaller 29 cm head-coil radio antenna inserted into the 100 cm magnet bore to improve signal-to-noise ratio. A 90 degree saturation-recovery pulse was followed in 15 msec by a 180 degree pulse, resulting in a peak “read” echo 30 msec after the 90 degree pulse. Image acquisition was gated to systole by initiating the 90 degree saturation-recovery pulse at a prede-
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determined time after the R wave of the patient’s electrocardiogram to coincide with end-systole. The electrocardiogram was transmitted to the controlling computer telemetrically as previously described.2

Multiple, nonsimultaneous, parallel sections could be obtained in three orthogonal planes: transverse, coronal, and sagittal. All patients were evaluated in transverse and coronal planes, with five to eight scans obtained in each plane. Because of time constraints, only four patients were imaged in the sagittal plane. Each scan had a thickness of 1.4 cm and, since multiple contiguous sections were obtained, an entire volume was imaged and displayed tomographically. Depending on the patient’s heart rate, individual scans required from 3 to 5 min, with data collected over 256 consecutive heart beats. Since simultaneous multislice capabilities were not available at the time of this study, a complete examination required about 60 min.

GMRI studies were evaluated by two of the authors (M. D. J. and B. D. F.). Since the authors were aware of the patients’ clinical diagnoses, strict criteria were established for identifying successful studies. For Blalock-Taussig and Glenn shunts, a positive study required longitudinal imaging of the shunt and had to include imaging of the pulmonic anastomosis. For aortopulmonary shunts, a positive study had to identify the confluence of aorta and pulmonary artery on at least two separate, preferably orthogonal planes. GMRI findings were compared with cineangiograms or digital subtraction angiograms to verify morphology and patency of the shunt. Two-dimensional and Doppler echocardiographic studies were also available for review.

Results

Table 1 lists the clinical diagnoses of the 11 patients and compares the results of GMRI with those of the “standard” clinical methods for evaluating systemic–pulmonary artery shunts. GMRI successfully imaged 11 of the 17 systemic–pulmonary artery shunts (65%), including five of nine Blalock-Taussig shunts (figures 1 to 3), four of six Glenn shunts (figure 3), and both aortopulmonary shunts (figure 4). These shunts were determined to be patent based on the absence of signal inside the lumen of the shunt. Patency was confirmed in these patients upon review of the angiographic studies. The six shunts that were not adequately visualized were also determined to be patent angiographically. Two-dimensional echocardiograms failed to clearly image any of the shunts, although Doppler echocardiographic examination of the pulmonary arteries detected abnormal flow profiles consistent with systemic-pulmonary artery shunts in 10 of 13 (77%) cases. Auscultation was not very sensitive, since only six of 11 (54%) systemic–pulmonary artery shunts demonstrated continuous murmurs even though all 11 were patent and functioning.

All shunts successfully imaged with GMRI were visualized on coronal scans except for the Waterston shunt, which was observed on sagittal and transverse sections. Six shunts were not considered adequately visualized, but four of these were partially seen. One Blalock-Taussig and both “missed” Glenn shunts were imaged in cross section on transverse scans but did not fulfill our criteria for successful studies, since they were not imaged longitudinally. One other Blalock-Taussig shunt was partly imaged on a coronal

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AVC = atrioventricular; PA = pulmonic atresia; IVS = intact ventricular septum; VSD = ventricular septal defect; LBT = left Blalock-Taussig; NA = not available; PAB = pulmonary arterial band; PS = pulmonic stenosis; RBT = right Blalock-Taussig; SV = single ventricle; TA = tricuspid atresia; Wat = Waterston; + = shunt identified; – = shunt not identified.

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scan but the pulmonary insertion was not identified. Of the nine Blalock-Taussig shunts, six were left-sided and three were right-sided. Three of six left-sided (figures 2 and 3) and two of three right-sided Blalock-Taussig shunts (figure 1) were visualized. Sequential coronal sectioning from ascending aorta anteriorly to descending aorta posteriorly facilitated imaging, since the usual course of the Blalock-Taussig shunt from its systemic, subclavian origin is inferior and slightly posterior (figure 1). As a result, different segments of the shunt were observed on different coronal sections. At its origin, seen on relatively anterior scans, the Blalock-Taussig shunt forms an acute inferior angle with the ascending aorta or aortic arch (figure 1, A) rather than the obtuse angle formed by the normal subclavian artery. More posterior coronal sections imaged the distal (pulmonary) portion of the shunt (figures 1, C, 2, and 3). In only one patient could the entire Blalock-Taussig shunt be visualized in a single plane. The four Glenn shunts were all imaged on single coronal sections through the superior vena cava (figure 3), although multiple sections were required to locate the specific plane that included the shunt. The superior vena cava coursed inferiorly and slightly to the right to communicate with the right pulmonary artery rather than entering the right atrium. The single Potts shunt was identified on a coronal scan as a direct side-to-side anastomosis of descending aorta and left pulmonary artery. The Waterston shunt was imaged as a direct side-to-side connection of the posterior ascending aorta and the right pulmonary artery (figure 4).

In addition to its ability to determine the course and patency of visualized shunts, GMRI could also qualitatively estimate the anatomic size and pulmonary arterial distribution of systemic–pulmonary artery shunts. Furthermore, GMRI studies permitted evaluation of proximal pulmonary arterial size and morphology. Two of the Blalock-Taussig shunts appeared to be large (figure 1) with normal branch pulmonary arteries; three shunts were believed to be small (figures 2 and 3), although the branch pulmonary arteries appeared only mildly hypoplastic. These findings were confirmed by the angiographic results. All four Glenn shunts appeared large without discrete areas of narrowing. In one, the Glenn shunt appeared to communicate only with the right lower and middle lobe pulmonary arteries. This was also confirmed by angiographic findings.

Discussion

Magnetic resonance imagers produce tomographic sections through the body with superb contrast and spatial resolution in multiple planes. Diagnostic-quality cardiovascular imaging has been made possible with the introduction of electrocardiographic gating.
techniques to circumvent the blurring of detail produced by cardiac motion. Several factors contribute to excellent imaging of blood vessels. First, intrinsic to GMRI, there is excellent contrast between relatively bright, stationary blood vessel walls and the dark appearance of rapidly flowing blood. Contrast agents are not required and ionizing radiation is avoided. Second, unlike high-frequency ultrasound waves, nuclear magnetic resonance (NMR) signals are not significantly attenuated by increasing distance from the energy source, and therefore, at currently used field strengths, resolution of remote structures deep within the body is unimpaired. As a result, compared with ultrasonography, GMRI is able to visualize anatomic details at a far greater range or depth. Finally, in contrast to ultrasound, GMRI is not adversely affected by overlying lung or bone.

Our results demonstrate the utility of GMRI in the evaluation of patients with palliative systemic–pulmonary artery shunts. No other noninvasive imaging modality, including ultrasound, is capable of reliably visualizing shunt anatomy. Although Doppler echocardiography can detect the abnormal flow profiles associated with systemic artery–pulmonary artery shunts, it is not an imaging technique and cannot provide spatial information about the shunt anatomy. GMRI, on the other hand, successfully identified 11 of 17 systemic–pulmonary artery shunts and confirmed shunt patency. In addition, it was possible to qualitatively judge the size and distribution of systemic–pulmonary artery shunts as well as size and morphology of the proximal pulmonary arteries. Furthermore, based on our experience with GMRI, it should also be possible to determine from transverse scans whether or not there is continuity of the main and branch pulmonary arteries (unpublished data).

Since current GMRI studies are displayed tomographically, shunt imaging and identification are greatly enhanced by obtaining multiple, contiguous, parallel sections. Although it was not available at the time of this study, the technology now exists to obtain multiple sections simultaneously. This will vastly improve the diagnostic yield of GMRI, since more scans will be available in less total time, an important consideration in pediatric patients who do not tolerate long procedures. In general, coronal sections proved to be most valuable for imaging systemic–pulmonary artery shunts, although the Waterston shunt was seen on transverse and sagittal sections. Although it is possible to obtain cross-sectional images of Blalock-Taussig and Glenn shunts, we do not consider that sufficient for imaging purposes. On transverse scans, Blalock-Taussig shunts are difficult to distinguish from other structures and Glenn shunts cannot be differentiated from...
the normal superior vena cava. In addition, cross-sectional images of these shunts will not usually demonstrate the pulmonary arterial anastomosis.

Blalock-Taussig shunts can be demonstrated as they arise from the aortic arch or innominate artery (formerly subclavian artery) and descend to the right or left pulmonary artery. Since these shunts also course somewhat posteriorly as they descend, it is not usually possible to image the entire shunt from systemic origin to pulmonic insertion in any one coronal section. The proximal portion is best seen on relatively anterior sections that cut the ascending aorta longitudinally (figure 1, A). More posterior scans, which image the aortic arch in cross section, will demonstrate the anastomosis to the right or left pulmonary artery (figures 1, C, 2, B, and 3, A). Unlike the normal subclavian artery, which forms an obtuse inferior angle with the aorta as it courses to the arm, the Blalock-Taussig shunt is seen to angle acutely inferiorly as it traverses to the pulmonary artery (figure 1).

**FIGURE 3.** Glenn shunt and left-sided Blalock-Taussig shunt in a patient with pulmonic atresia and ventricular septal defect. A, Superior vena cava courses to right to enter right pulmonary artery (Glenn shunt, curved arrow). Note distribution largely to lower and middle lobes of lung. Small Blalock-Taussig shunt (small arrow) is seen circling the aorta cut in cross section. The left pulmonary artery is mildly hypoplastic. B, Angiographic frame demonstrating Blalock-Taussig shunt (arrow). C, Angiographic frame showing Glenn shunt.
Glenn shunts, unlike Blalock-Taussig shunts, can generally be imaged in their entirety in a single plane. On coronal sections the normal superior vena cava can be easily identified entering the right atrium (figure 1, A). In patients with Glenn shunts (figure 3), the superior vena cava bypasses the right atrium and courses slightly posteriorly and to the right to enter the right pulmonary artery. The two aortopulmonary shunts (figure 4) were identified as direct side-to-side anastomoses of ascending or descending aorta and right or left pulmonary artery. There is no true "vessel" comprising the shunt.

The effect of flow on the intensity of NMR signals emitted from intraluminal protons is complex. With laminar blood flow in a nonpulsatile system there is a parabolic distribution of flow velocities across the vessel lumen, with the fastest flows at the center. Therefore there is a greater potential, theoretically, for signals to occur at the periphery of the vessel. In a pulsatile system, however, flow is sometimes slower centrally, resulting in a cyclical shifting of the high-intensity signals from the peripheral to the central part of the vessel. Turbulent blood flow, which might be expected with systemic-pulmonary artery shunts, may produce a subpopulation of excited protons that fail to escape the imaged volume, thus emitting signal. However, since the velocity vectors of protons in turbulent flowing blood are randomly oriented with respect to the localizing magnetic field gradients, the signal is dispersed across the lumen. Finally, the gating interval is an important determinant of intraluminal signal intensity simply because pulsatile flow travels at varying velocities throughout the vessel relative to the imaging plane—all influence the ultimate intensity of signals emitted from intraluminal protons.

cardiac cycle.\textsuperscript{12} We purposely gated to end-systole to minimize signals from flowing blood and thus maximize the contrast between blood vessels and their lumina.

According to Kaufman et al.,\textsuperscript{7} based on their imaging parameters and techniques, flow velocities greater than 10 cm/sec usually result in no signal. At peak systole, flow velocities in arteries almost invariably exceed this critical velocity by a factor of 7 or more,\textsuperscript{13, 14} therefore it is not surprising that in our study, the lumina of those patent systemic–pulmonary artery shunts that used systemic arteries appeared dark. Although it might be expected that Glenn shunts, with intrinsically slower flow rates, might exhibit some intraluminal signals, this was not the case. Presumably this is related either to the specific parameters of imaging that were used or to the fact that these vessels were imaged longitudinally. Although further work will be needed before the effect of flow on GMRI is completely understood, it is conceivable that in the near future, GMRI studies may also include accurate quantification of flow velocities in blood vessels, including shunts.

In conclusion, GMRI is the only noninvasive imaging technique currently capable of visualizing palliative systemic–pulmonary artery shunts with a high degree of success. With GMRI it was possible to qualitatively determine size, patency, course, and distribution of systemic–pulmonary artery shunts as well as the size and morphology of the proximal pulmonary arteries. GMRI is uniquely suited to imaging of shunts because it is safe, does not require intravascular contrast agents or ionizing radiation, has excellent range of visualization within the body, and is not affected by overlapping structures such as lung or bone. Currently, it is limited by the tomographic display format, which may not correspond to the planes of the shunt. Future applications of this imaging method may include accurate quantitative estimates of blood flow velocity. We believe GMRI is an excellent method for noninvasive determination of the size, course, and patency of palliative systemic–pulmonary artery shunts.

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