Magnetic Resonance–Guided Cardiac Catheterization in a Swine Model of Atrial Septal Defect

Simon Schalla, MD; Maythem Saeed, DVM, PhD; Charles B. Higgins, MD; Alastair Martin, PhD; Oliver Weber, PhD; Phillip Moore, MD

Background—Radiation exposure during cardiac catheterization, limited image planes, and poor soft tissue definition are disadvantages of x-ray fluoroscopy that could be overcome with the use of MRI. This study evaluates the feasibility of real-time MRI (MR fluoroscopy) to guide left and right heart catheterization.

Methods and Results—Anesthetized pigs (n = 7) with defects of the atrial septum were catheterized using venous and arterial access. A prototype active tracking catheter was used to obtain blood pressures and samples from cardiac chambers and great vessels using antegrade, transseptal, and retrograde approaches. MR fluoroscopy was used for catheter steering. Velocity-encoded cine MRI was used to measure pulmonary and aortic blood flow to calculate vascular resistances. Image planes used during catheter manipulation used rapid sequencing to planes directed by the operator to include the tip of the catheter and the chamber to be entered. All areas of interest were effectively entered, and samples were obtained. In the presence of an acute atrial septal defect, a Qp/Qs ratio of 1.3 ± 0.2 was measured, and no significant differences in pressure between inferior vena cava, right atrium, and left atrium were found. Pulmonary and aortic flow were 4.9 ± 0.6 and 3.7 ± 0.4 L/min, and pulmonary and systemic vascular resistance were 312 ± 134 and 206 ± 336 dyns · s · cm⁻⁵.

Conclusions—Left and right heart catheterization using MR guidance is feasible. The combination of hemodynamic catheterization data with anatomic and functional MRI may significantly improve the evaluation of patients with congenital heart disease while avoiding radiation exposure. (Circulation. 2003;108:1865-1870.)

Key Words: magnetic resonance imaging • catheterization • pressure
Real-time image acquisition was performed to image simultaneously catheter tip position and background anatomy by use of a real-time steady-state free precession sequence (SSFP with radial k-space filling: TR, 3 ms; TE, 1.5 ms; flip angle, 60°; slice thickness, 10 mm; field of view, 200 mm; scan matrix, 128×128; 300 ms per image, reconstructed at 10 frames/s using sliding-window reconstruction [view sharing]11,12). A 2-element phased array of surface coils (2 circular 20-cm-diameter coils) was used. The number of trajectories for an image set was 102. However, image reconstruction was performed every 34 radial profiles by use of the sliding-window technique. Latency associated with reconstruction and image display was <50 ms. The interactive scan plane adjustment was performed on the fly, with the time to realize a new plane being just more than the full data acquisition time (300 ms). Planes could be adjusted manually or tracked automatically to include the tip of the active tracking catheter. Catheter tip movements within an imaging plane (in-plane motion) were tracked continuously in real time, whereas through-plane tip tracking was updated on an “on-demand” basis. Neither respiratory navigator techniques nor cardiac triggering was necessary.

Animal Model
Female domestic farm pigs (n=7, 37 to 43 kg; age, 3 months) were studied in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals and with approval of the Committee of Animal Research of the University. After medication with intramuscular injection of 0.04 mg/kg atropine, 2 mg/kg xylazine, and 20 mg/kg ketamine, general anesthesia was initiated with 2% inhalation isoflurane. Animals were intubated and mechanically ventilated. Local anesthesia with 2% lidocaine was injected subcutaneously before placement of 9F femoral arterial and 12F femoral venous introducer sheaths. After vascular access had been established, a needle followed by a balloon catheter (18-mm diameter) was used to puncture the atrial septum and subsequently dilate the defect under x-ray fluoroscopic guidance to allow later transseptal catheter steering. Once the septostomy had been performed, x-ray fluoroscopy was no longer used in the study.

MR Guidance of Cardiac Catheterization
After transfer to the MR system, an active tracking catheter (Philips Medical Systems/Cordis Corp; Figure 1) was introduced via femoral vein. A copper microcoil mounted on the catheter tip was projected continuously as a small cross on MR images (Figures 2 to 6). The microcoil was connected to an external preamplifier box by copper leads. An external plastic sheath was added over the catheter to isolate the components. Because the catheter shaft was seen only occasionally on MR images, steering of the catheter would not be possible without active imaging of the tip. The catheter was guided to the inferior vena cava (IVC), right atrium (RA), right ventricle (RV), and main pulmonary artery (PA). After withdrawal to the RA, the catheter was steered across the septal defect from RA to left atrium (LA) and to the left ventricle (LV). In addition, the catheter introduced into the femoral artery was also advanced retrogradely into the aorta and LV. A pulmonary vein and superior vena cava were also catheterized in 2 animals and the brachiocephalic artery in 1. In all areas of interest, pressure curves and blood samples to determine oxygen saturation and hemoglobin levels were obtained.

MRI Techniques
Real-time image acquisition was performed to image simultaneously catheter tip position and background anatomy by use of a real-time steady-state free precession sequence (SSFP with radial k-space filling: TR, 3 ms; TE, 1.5 ms; flip angle, 60°; slice thickness, 10 mm; field of view, 200 mm; scan matrix, 128×128; 300 ms per image, reconstructed at 10 frames/s using sliding-window reconstruction [view sharing]11,12). A 2-element phased array of surface coils (2 circular 20-cm-diameter coils) was used. The number of trajectories for an image set was 102. However, image reconstruction was performed every 34 radial profiles by use of the sliding-window technique. Latency associated with reconstruction and image display was <50 ms. The interactive scan plane adjustment was performed on the fly, with the time to realize a new plane being just more than the full data acquisition time (300 ms). Planes could be adjusted manually or tracked automatically to include the tip of the active tracking catheter. Catheter tip movements within an imaging plane (in-plane motion) were tracked continuously in real time, whereas through-plane tip tracking was updated on an “on-demand” basis. Neither respiratory navigator techniques nor cardiac triggering was necessary.

Figure 1. Active tracking catheter prototype. 6F tracking catheter was 90 cm long and contained a tracking microcoil near its tip (enlargement). A transmission line exits proximal end of catheter and was used to connect microcoil to MR scanner so that its position could be tracked automatically.

Figure 2. Menu of different image planes obtained with real-time SSFP imaging. Images a–f are image planes used for catheter steering to regions of interest. IVC–RA image plane (a) shows IVC, RA, and LA and was used for advancing catheter along IVC into RA junction and RA. Image plane was then switched to a cardiac 4-chamber (long-axis) view (b) to steer catheter across tricuspid valve into RV. To advance catheter into PA, cardiac short-axis (c) and 4-chamber (b) views were acquired sequentially for positioning of catheter near RV outflow tract. Subsequently, catheter was advanced across pulmonary valve into main PA using RV–PA image planes (d and e). For antegrade left heart catheterization, a, RA–LA image plane (f) was deployed in addition to a cardiac 4-chamber view (b).

Figure 3. Catheterization of main PA with real-time SSFP MRI guidance. Image planes (4-chamber [a], right ventricular outflow tract [b], and 3 outflow-tract–PA planes [c–e]) used for catheter steering and a PA pressure curve in mm Hg are shown.
To calculate pulmonary and systemic vascular resistance, blood flows in the main PA and aorta were measured by use of a retrospectively gated velocity-encoding phase-contrast gradient-echo sequence (TR, 15 ms; TE, 4 ms; flip angle, 20°; scan matrix, 192×1100; slice thickness, 8 mm; field of view, 200 mm). Velocity-encoded range was 150 cm/s for PA and 200 cm/s for aorta. Pulmonary and systemic vascular resistance in dyne · s · cm⁻⁵ were calculated from flow and pressure measurements by use of the formula 

\[
\text{PVR} = \frac{80(\text{PA mean} - \text{LA mean})}{Q_p}
\]

and

\[
\text{SVR} = \frac{80(\text{Aorta mean} - \text{RA mean})}{Q_s}
\]

where \( Q_p \) is pulmonary flow per minute and \( Q_s \) is aortic flow per minute. Left-to-right shunt calculations are given as the \( Q_p/Q_s \) ratio calculated from MR flow measurements. In addition, the \( Q_p/Q_s \) ratio was also calculated from oxygen saturation measurements by use of the following equation:

\[
Q_p/Q_s = \frac{(\text{saturation}_{\text{Aorta}} - \text{saturation}_{\text{IVC}})}{(\text{saturation}_{\text{LA}} - \text{saturation}_{\text{PA}})}
\]

Postmortem Analysis

At the conclusion of the study, animals were euthanized with 150 mg/kg pentobarbital IV. After removal of the heart and adjacent great vessels, visual inspection was performed to assess for pericardial effusion, perforation, and mural hematoma.

Statistical Analysis

All data are expressed as mean±SD. The paired Student’s \( t \) test was used to compare between pressures or oxygen saturations obtained at different regions of interest. Linear regression was calculated to determine the correlation between \( Q_p/Q_s \) ratios obtained from flow and oxygen saturation measurements.

Results

The catheter tip was placed in the areas of interest to obtain pressure curves and blood samples in all animals. During the procedure, there were no significant arrhythmias, perforations, hemorrhages, or other complications. Correct catheter placement was proved by MR images and the corresponding pressure curves. Time for introducing the catheter and steering to IVC, RA, superior vena cava, RV, PA, LA, pulmonary vein, and LV ranged from 10 to 30 minutes, with a decrease with increasing experience. Antegrade transseptal and retrograde catheterization of the LV are shown in Movies I and II.
the PA (Figure 3), both a cardiac short-axis view (Figure 2c) and a 4-chamber view were used for positioning of the catheter near the RV outflow tract. After switching to the RV-PA planes (Figure 2, d and e), the catheter was advanced across the pulmonary valve into the main PA. For antegrade catheterization of the left heart, the catheter was advanced from the IVC-RA junction to the RA and transseptal to the LA by use of an RA-LA view plane (Figure 2f). A 4-chamber imaging plane (Figures 2b and 4) was used to steer the catheter across the mitral valve into the LV. For retrograde left heart catheterization, an image plane showing the aortic arch and LV (Figure 5) was used to advance the catheter along the aortic arch across the aortic valve into the LV. Imaging planes for catheter guidance into the pulmonary veins are shown in Figure 6.

At postmortem, visual inspection of animal hearts and great vessels revealed no evidence of pericardial effusion, perforation, hematoma, or injuries. The presence of atrial septal defect was confirmed in all animals.

### Catheterization Data

Pressures, oxygen saturation, and hemoglobin levels are shown in the Table. Mean heart rate was 87±11 bpm. There were no significant differences in pressure between RA and IVC (P = 0.23) or LA (P = 0.22). No significant differences in oxygen saturation were found between IVC and RA (P = 0.34) or RV (P = 0.21).

PA and aortic flows determined by MR phase-contrast technique were 4.9±0.6 and 3.7±0.4 L/min, indicating a left-to-right shunt of 1.2±0.6 L/min and a Q/R ratio of 1.3±0.2. Calculation of Q/R, from the oxygen saturation measurements was 1.4±0.4, similar to MR flow measurements (r = 0.68, SEM = 0.32, regression line equation y = 1.39x ± 0.45). Pulmonary and systemic vascular resistance values derived from MR flow data and pressure measurements were 312±134 and 2006±336 dyne · s · cm⁻².

### Discussion

The major finding of the present study was that left and right heart catheterization is feasible under MR real-time guidance. This study represents an early step toward MR-guided diagnostic cardiac catheterization. Active catheter tip tracking was highly useful in steering and in selecting regions of interest by use of venous, venous-transseptal, and arterial approaches. To the best of our knowledge, this is the first study to show the feasibility of MR fluoroscopy for left and right heart catheterization with assessment of hemodynamic parameters. MR flow data in combination with blood pressure and oxygen saturation measurements can provide additional insight into systemic and pulmonary flows and intracardiac shunts and can be applied to calculation of pulmonary and systemic vascular resistances. The study results were similar to those of previously reported results based on the standard method of thermodilution and pressure measurements.¹³

The flow volume through the shunt in our atrial septal defect model was small, as was expected for an acutely created defect. Kong et al¹⁴ also observed an increase of the Q/R ratio from 1.03±0.12 to only 1.28±0.23 after creating an acute atrial septal defect in pigs. Calculations of Q/R on the basis of oxygen saturation measurements were consistent with the MR flow data in the present study.

Indications for diagnostic cardiac catheterization in pediatric cardiology are to evaluate congenital heart disease with complex anatomy that cannot be assessed well with echocardiography, such as abnormalities of the pulmonary arteries and the aortic arch. Both regions can be assessed with MRI or MR angiography.¹⁵–¹⁸ Further indications for cardiac catheterization in children are pressure, oxygen saturation, and flow measurements to define the severity of valvular or vascular stenosis and to define ventricular diastolic and systolic function and pulmonary vascular resistance. In the present study, these values were obtained from MR flow measurements and blood pressure and oxygen saturation data. Cine MRI can be used to obtain additional functional indices during MR-guided cardiac catheterizations, including wall motion analysis¹⁹ and LV and RV volumes.²⁰,²¹

The success of cardiac catheterization depends in part on the ability to visualize catheter and central cardiovascular anatomy simultaneously and in real time. A hypothesis explored in this study was whether real-time MRI could provide this ability without radiation exposure. Indeed, MR fluoroscopy in a variety of different imaging planes displayed both cardiovascular anatomy and the catheter tip position in real time. Rapid switching among various imaging planes during the procedure was successful, allowing precise catheter manipulation to the target region of interest.

MR catheter guidance totally eliminates radiation exposure. With x-ray fluoroscopy, cardiac catheterization and long interventional procedures could result in relatively high radiation exposure for patient and staff. It has been estimated that per hour of fluoroscopy, there is a 0.07% to 0.1% lifetime...
risk of developing a fatal malignancy and 1 to 20 genetic defects per 1 million births, \(^2,3\) risks especially important for pediatric patients.\(^1,22\)

High temporal (300 ms) and spatial (1.6 mm) resolution steady-state free precession images were acquired in real time to monitor catheter steering and visualize background anatomy. The imaging speed of 3 frames/s (reconstructed at 10 frames/s) was sufficient for catheter guidance. Blood appeared bright, resulting in a good contrast between vessel lumen and surrounding tissue. Catheter artifacts from the shaft were small and did not superimpose on vascular or chamber walls. However, despite the visualization of the catheter tip during the entire procedure, adjacent parts of the catheter were not reliably visualized. The poor visualization of the catheter shaft can be attributed to out-of-plane movements resulting from cardiac contraction and respiratory motion and the fact that optimal contrast between blood and catheter was not always achieved. Because the slice thickness was 10 mm, distal bending or angulation of the catheter shaft also resulted in a loss of visualization. Imaging large parts of a catheter would be preferable to merely tracking the tip. To keep the catheter in plane, a larger slice thickness may be needed in some locations. In addition, for steering purposes, not only the accurate position of the catheter tip but also visualization of the direction of angulation of the catheter tip are important. As suggested by Zhang et al.,\(^23\) multiple-element coils at different positions near the catheter tip should provide this visualization.

Introduction of MR-guided catheterization into clinical practice depends critically on the development and availability of MR-safe catheters. Radiofrequency-induced heating might occur even in nonferromagnetic metals when used in catheters or guidewires. No guidewires were used in this study, but the catheter prototype contained electrical conductors. No sparking was observed, and no perceptible heating or other adverse effects on the animals were recognized. However, further studies are needed to systematically assess MR safety and optimize catheter prototypes, because heating of guidewires was observed in vitro.\(^24,25\) A preliminary animal study about MR safety of guidewires showed no thermal damage or blood coagulation,\(^26\) but the safety of active tracking catheters with long electrical conductor cables is not known. Using fiberoptic instead of electrical conductors in active tracking catheters might be a strategy to avoid heating.\(^27,28\) The concept of passive tracking with susceptibility markers on a catheter,\(^29,30\) contrast media-filled catheters, or contrast media-filled balloons at the catheter tip\(^31\) is considered a safer approach, but imaging at fast speed with good anatomic information and optimal visualization of the marker’s susceptibility artifacts is at present difficult.\(^12\)

In conclusion, left and right heart catheterization using real-time MR guidance is feasible. It has the potential to change the current x-ray–based diagnostic approach for children with congenital heart disease to avoid radiation exposure. Hemodynamic catheterization data can be combined with anatomic and functional MRI. This may significantly improve the evaluation of patients with complex congenital heart disease. Introduction of MR-guided catheterization into clinical practice depends on the development and availability of MR-compatible catheters.

**References**

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