# Cardiac interventions guided by magnetic resonance imaging

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## Abstract

Mortality rates in patients with congenital heart disease have decreased significantly over the past decades. However, many of these patients require long-term care and repeated cardiac interventional or surgical procedures. This requires the development of optimized diagnostic tools that are better able to guide therapy, the establishment of non ionizing and less invasive interventional methods, and the progressive replacement of surgical by transcatheter techniques. Interventional magnetic resonance imaging (iMRI) has the potential to make important steps towards these goals. This review presents the current situation and expected future developments in the field of iMRI, with a focus on congenital heart diseases.
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## Introduction

At present there is a clear trend of replacing X-ray fluoroscopy by alternative imaging modalities, fueled mainly by the association of X-ray technology with significant exposure of patients and medical staff to ionizing radiation, its lack of visualization of soft tissue and its limited ability to acquire quantitative cardiovascular functional data. Interventional magnetic resonance imaging (iMRI) is a young, emerging technology that has already been demonstrated to have the potential to complement, or even to replace in part, X-ray-guided procedures. MRI-guided intervention can add considerable benefit in procedures that rely on good visualization of soft-tissue or 3-dimensional anatomy, in addition to immediate pre- and postinterventional assessment of physiologic parameters of cardiovascular function. As experience in the technically challenging field of iMRI is accumulating rapidly, much interesting new work can be expected in the near future.

## Hardware and software considerations

Considerable efforts have recently been undertaken by the manufacturers to design magnetic resonance scanners that provide improved patient access. Siemens offers a short-bore 1.5 Tesla scanner with bores of length 125 cm and width 70 cm. Philips has recently released a fully open 1.0 Tesla system that may be suited for cardiac iMRI, although experience in using it for cardiac imaging is still at its very beginnings.

Most up-to-date scanners are commercially equipped with interactive user interfaces and fully refocused steady-state free precession sequences that are suited for real-time imaging. During imaging, the interventionalist has to compromise between temporal resolution, spatial resolution, and signal-to-noise ratio. Most groups operate at an acquisition frame rate of 1–10 frames per second and a maximum pixel matrix of $192 \times 256$. The implementation of ultra-fast sequences for ventricular function analysis, magnetic resonance angiograms or real-time flow measurements are an important add-on to iMRI [1,2]. Finally, investigational iMRI laboratories should be operated in conjunction with X-ray fluoroscopy, either as an adjunct to MRI or as a safety back-up.

## Catheter tracking – is it finally getting there?

Extensive research in recent years has resulted in some promising solutions that allow fast and patient-safe catheter tracking. Catheter tracking is typically classified as passive, hybrid, and active approaches.

Passive tracking devices produce negative contrast (dysprosium, carbon dioxide, iron oxide) or positive contrast (gadolinium, fluorine-19), are considered safe, and are simple to manufacture. Although passive devices often generate only modest signal contrast to their background, they are, if carefully chosen in respect to the requirements of an interventional procedure, well suited for a variety of applications (*Figure 1*).

Resonance circuits, as used in hybrid designs, produce an intense local signal readily perceptible to the observer (*Figure 1*) [3,4]. In addition, this approach allows automated slice tracking using fiberoptics for safe signal transmission. Nevertheless, resonance circuits are technically difficult to manufacture and are currently not readily available.

Active tracking methods allow automated slice/catheter detection, but suffered for a long time from the drawback of safety issues as a result of heating during radiofrequency transmission. A new concept for safe bioelectrical signal transmission was recently proposed that is based on the integration of miniature transformers into the transmission line (*Figure 1*) [5]. This concept is expected to be applied to the construction of clinically available devices soon.

## Endovascular implants

Endovascular implants currently in use are too numerous to be individually discussed in this report. Generally, devices made from nitinol alloys produce only slight local susceptibility artifacts on MRI (*Figure 2*). Devices made from platinum generate moderate artifacts that can be limited by using appropriate pulse sequences. However, the implantation of devices with high stainless steel content, which causes severe image distortion, should be avoided in patients in whom repeat MRI examinations are planned.

## Experimental application and first steps towards clinical investigation

### *MRI-guided cardiac catheterization*

Catheterization guided by magnetic resonance imaging was one of the first MRI-guided investigations to be performed in a clinical setting. This approach is appealing because it allows simultaneous derivation of pressures, blood flow, and ventricular volume data for the assessment of pulmonary arterial resistance or ventricular pressure–volume loops (*Figure 1*) [6–8].

### *Atrial and ventricular septal defects*

Many large centers have partially or completely abandoned X-ray fluoroscopy for the closure of atrial septal defects. MRI-guided transcatheter closure of atrial septal defects is of potential clinical interest, because there would be no need to sedate the patient as for closure under transesophageal echocardiography guidance. Several animal studies and a clinical landmark report have demonstrated that atrial septal defects can be effectively closed under iMRI using the self-centring Amplatzer Septal Occluder [9–11]. However, to make the step into clinical application, convincing proof of the following will be necessary: appropriate positioning of the device in defects with a small rim or within large atrial aneurysms, and exclusion of minor residual shunts after implantation. To our knowledge, there are no reports of successful MRI-guided transcatheter closure of ventricular septal defects.

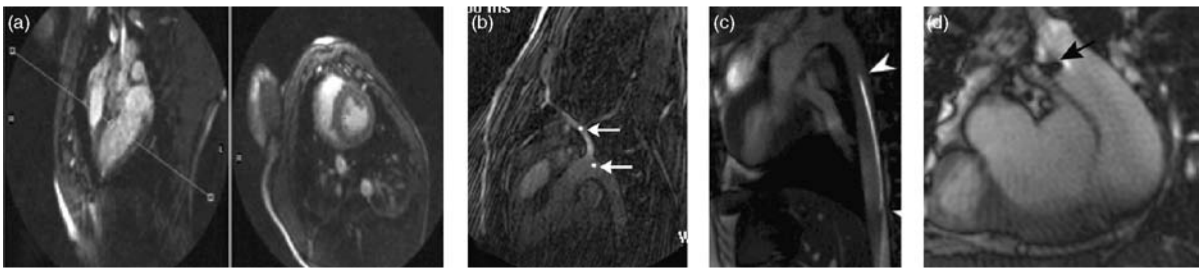


*Figure 1. Examples of catheter tracking. (a) Active catheter tracking using bioelectrically safe transmission lines for cardiac catheterization (courtesy of S. Weiss, Philips Medical Systems, Hamburg). (b) Hybrid catheter tracking in a delivery system for carotid stents. (c) An electrophysiology catheter in pigs (courtesy of H. Quick, University Hospital, Essen). (d) Passive tracking of a flow-directed catheter for assessment of pulmonary vascular resistance in a patient with failing Fontan circulation.*

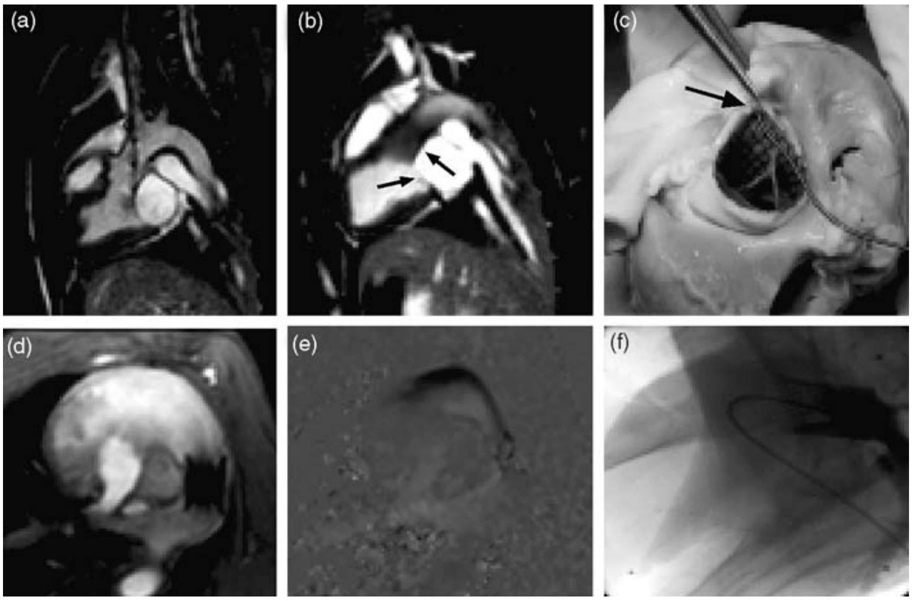


*Figure 2. (a–c) Magnetic resonance images showing accurate implantation of aortic valved stents in pigs in relationship to the coronary arteries and the mitral valve. (d–f) In the pulmonary position, magnetic resonance imaging provides invaluable information about the site of the stent and its surrounding soft-tissue anatomy and quantitative blood flow, unlike conventional angiography.*

## Aortic coarctation and aortic aneurysm

Magnetic resonance imaging is the method of choice to assess the 3-dimensional course and wall morphology of the aorta in conjunction with functional data – an essential prerequisite for successful intervention. For this reason, the aorta has been subjected to extensive iMRI research. Several animal studies have been able to demonstrate the feasibility of iMRI-guided stent placement in aortic coarctation [12,13]. Moreover, these studies showed that potential inadvertent effects, such as aneurysm formation or even wall rupture, can be detected and adequately treated under iMRI (*Figure 3*) [14]. Treatment of aortic aneurysms was reported to provide appropriate device apposition, restore normal lumen contour, and enable laminar luminal flow without any internal endo leaks [14].

Work in my own department has demonstrated that MRI-guided balloon angioplasty of aortic coarctation

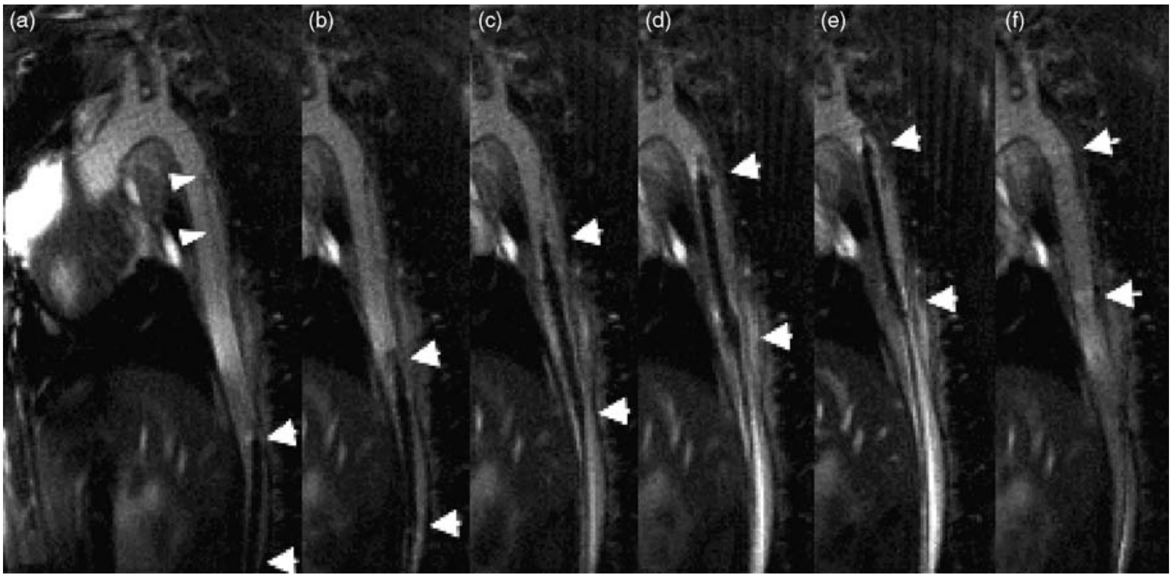


*Figure 3. (a) Real-time magnetic resonance imaging (MRI) of aortic dissection (small arrowheads). (b–e) Advancement of a stent-graft delivery system. (f) After implantation, the lumen of the stent-graft and its adhesion to the aortic wall are well visualized on MRI. (Courtesy of H. Quick, University Hospital, Essen).*

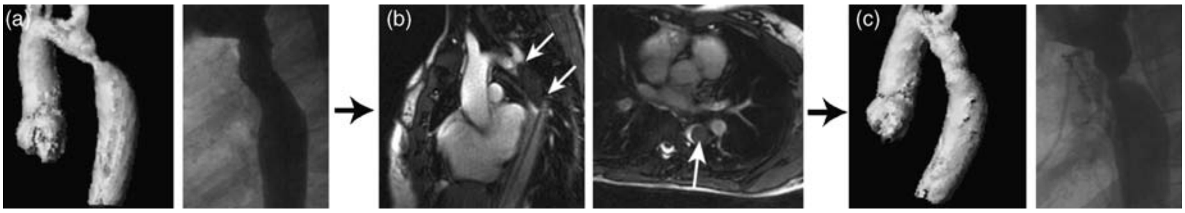


*Figure 4. Magnetic resonance imaging (MRI)-guided balloon angioplasty in patients with aortic coarctation. (a, c) Assessment of anatomy before and after intervention, using 3-dimensional MRI (left) compared with X-ray angiography (right). (b) Angioplasty was monitored with real-time MRI in arbitrary planes.*

can be effectively and safely performed in the clinical setting (*Figure 4*) [15]. Importantly, MRI enabled the non invasive assessment of anatomy and function before and after intervention, and thus substantially shortened the interventional procedure time. Current research projects aim to extend this work by delivering endovascular stents in aortic coarctation under combined X-ray/MRI guidance.

## Pulmonary artery stenosis

Similar to aortic coarctation, pulmonary stenosis can be accurately and non invasively assessed before and after intervention using MRI. However, the tortuous course of catheters through the right ventricle and pulmonary arteries requires high-end MRI catheter tracking solutions that are not yet readily available, and therefore the amount of practical experience is limited. Nevertheless, iMRI-guided stent placement and angioplasty of the pulmonary arteries have been successfully performed in animal studies [16,17].

## Pulmonary and aortic valved stents

Percutaneous transcatheter placement of valved stents has evolved, in the past 5 years, into an exciting and dynamic field of research. MRI has been shown to be particularly useful, not only in postinterventional assessment of function, but also in guiding the implantation of valved stents under conditions of complex anatomy, such as that of the coronary arteries or the mitral valve (*Figure 2*) [18,19].

## Transvascular drug delivery

Local growth factor, gene, and cell therapy have raised great expectations as effective means of treating myocardial disease. Intramyocardial injection was demonstrated to be efficient and is routinely performed under X-ray guidance. However, X-ray has distinctive disadvantages in comparison with MRI: it does not visualize soft tissue or the distribution of the substances delivered, and suffers inaccuracy in targeting the region of interest. In contrast, MRI targets dyscontractile myocardium or fibrous scar tissue, or both (*Figure 1*). Moreover, animal studies have demonstrated that MRI-guided myocardial drug delivery enables monitoring of the substances delivered, in multiplanar views of the dynamic distribution over time [20,21].

## Electrophysiological studies

Magnetic resonance imaging-guided electrophysiological studies can be expected to have major future clinical impact that is based on the elimination of often very high doses of ionizing radiation to the patient and the medical staff, and a more comprehensive 3-dimensional view of mapping conducting pathways. Successful iMRI acquisition of intracardiac electrocardiograms and the feasibility of radiofrequency ablation, in addition to the visualization of scar tissue after ablation, have been demonstrated in animal models [22,23].

## Summary

During recent years, MRI techniques have emerged for real-time visualization of anatomy, and for ultrafast assessment of cardiovascular function. These features have made MRI into a dynamic modality that is suited to guiding endovascular interventions and to providing immediate information on the physiologic response to pharmacological or catheter-based treatment. Nevertheless, continuing efforts are needed to resolve the technically challenging problems of iMRI, which are as plentiful as the promises held out by this emerging imaging modality. ■

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## REFERENCES

1. Korperich H, Gieseke J, Barth P, et al. Flow volume and shunt quantification in pediatric congenital heart disease by real-time magnetic resonance velocity mapping: a validation study. *Circulation*. 2004;109:1987–1993.

2. Mohrs K, Petersen S, Voigtlaender T, et al. Time-resolved contrast-enhanced MR angiography of the thorax in adults with congenital heart disease. *AJR Am J Roentgenol*. 2006;187:1107–1114.
3. Kuehne T, Weiss S, Brinkert F, et al. Catheter visualization with resonant markers at MR imaging-guided deployment of endovascular stents in swine. *Radiology*. 2004;233:774–780.
4. Hegde S, Miquel M, Boubertakh R, et al. Interactive MR imaging and tracking of catheters with multiple tuned fiducial markers. *J Vasc Interv Radiol*. 2006;17:1175–1179.
5. Weiss S, Vernickel P, Schaeffter T, Schulz V, Gleich B. Transmission line for improved RF safety of interventional devices. *Magn Reson Med*. 2005;54:182–189.
6. Kuehne T, Yilmaz S, Steendijk P, et al. Magnetic resonance imaging analysis of right ventricular pressure–volume loops: in vivo validation and clinical application in patients with pulmonary hypertension. *Circulation*. 2004;110:2010–2016.
7. Muthurangu V, Atkinson D, Sermesant M, et al. Measurement of total pulmonary arterial compliance using invasive pressure monitoring and MR flow quantification during MR-guided cardiac catheterization. *Am J Physiol Heart Circ Physiol*. 2005;289:H1301–H1306.
8. Kuehne T, Yilmaz S, Schulze-Neick I, Wellnhofer W, Ewert P, Lange P. MRI guided catheterization for assessment of pulmonary vascular resistance: in-vivo validation and clinical application in patients with pulmonary hypertension. *Heart*. 2005;91:1064–1069.
9. Schalla S, Saeed M, Higgins C, Martin A, Weber O, Moore P. Magnetic resonance-guided cardiac catheterization in a swine model of atrial septal defects. *Circulation*. 2003;108:1865–1870.
10. Schalla S, Saeed M, Higgins C, Weber O, Martin A, Moore P. Balloon sizing and transcatheter closure of acute atrial septal defects guided by magnetic resonance fluoroscopy: assessment and validation in a large animal model. *J Magn Reson Imaging*. 2005;21:204–211.
11. Rickers C, Jerosch-Herold M, Hu X, et al. Magnetic resonance image-guided transcatheter closure of atrial septal defects. *Circulation*. 2003;107:132–138.
12. Raval A, Telep J, Guttman M, et al. Real-time magnetic resonance imaging-guided stenting of aortic coarctation with commercially available catheter devices in Swine. *Circulation*. 2005;112:699–706.
13. Saeed M, Henk C, Weber O, et al. Delivery and assessment of endovascular stents to repair aortic coarctation using MR and X-ray imaging. *J Magn Reson Imaging*. 2006;24:371–378.
14. Eggebrecht H, Kuhl H, Kaiser G, et al. Feasibility of real-time magnetic resonance-guided stent-graft placement in a swine model of descending aortic dissection. *Eur Heart J*. 2006;27: 613–620.
15. Krueger J, Ewert P, Yilmaz S, et al. MRI guided balloon angioplasty of coarctation of the aorta: a pilot study. *Circulation*. 2006;113:1093–1110.
16. Kuehne T, Saeed M, Higgins C, et al. Endovascular stents in pulmonary valve and artery in swine: feasibility study of MR imaging-guided deployment and postinterventional assessment. *Radiology*. 2003;226:475–481.
17. Rickers C, Seethamraju R, Jerosch-Herold M, Wilke N. Magnetic resonance imaging guided cardiovascular interventions in congenital heart diseases. *J Interv Cardiol*. 2003;161:143–147.
18. Khambadkone S, Coats L, Taylor A, et al. Percutaneous pulmonary valve implantation in humans: results in 59 consecutive patients. *Circulation*. 2005;112:1189–1197.
19. Kuehne T, Yilmaz S, Meinus C, et al. Magnetic resonance imaging-guided transcatheter implantation of a prosthetic valve in aortic valve position: feasibility study in swine. *J Am Coll Cardiol*. 2004;44:2247–2249.
20. Krombach GA, Pfeffer JG, Kinzel S, Katoh M, Gunther RW, Buecker A. MR-guided percutaneous intramyocardial injection with an MR-compatible catheter: feasibility and changes in T1 values after injection of extracellular contrast medium in pigs. *Radiology*. 2005;235:487–494.
21. Saeed M, Martin AJ, Lee RJ, et al. MR guidance of targeted injections into border and core of scarred myocardium in pigs. *Radiology*. 2006;240:419–426.
22. Susil RC, Yeung CJ, Halperin HR, Lardo AC, Atalar E. Multifunctional interventional devices for MRI: a combined electrophysiology/MRI catheter. *Magn Reson Med*. 2002;47:594–600.
23. Dickfeld T, Kato R, Zviman M, et al. Characterization of radiofrequency ablation lesions with gadolinium-enhanced cardiovascular magnetic resonance imaging. *J Am Coll Cardiol*. 2006;47:370–378.