Interventional Cardiovascular Magnetic Resonance: Initial Clinical Experience for Right Heart Catheterization

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Introduction

Right heart catheterization (RHC) is the gold standard technique to assess pulmonary blood pressures in the diagnosis of pulmonary hypertension. Blood pressures are measured invasively using a catheter navigated through the right chambers of the heart under X-ray fluoroscopic guidance in the cath lab.

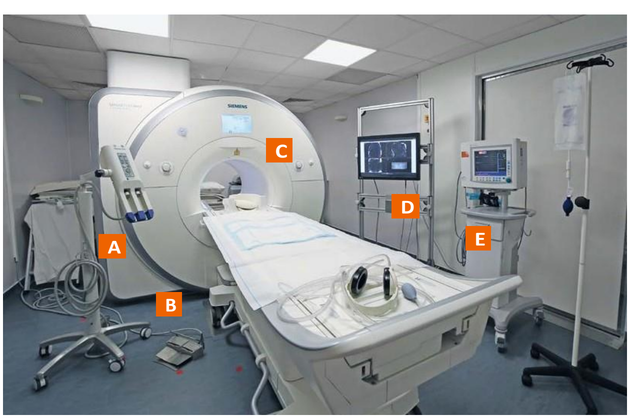
Over the past two decades, cardiovascular magnetic resonance (CMR) has emerged as a valuable technique for real-time guidance of cardiovascular procedures. Unlike traditional X-ray guidance, MR-guided catheterization is free of ionizing radiation and offers accurate measurements of cardiac function, volumes and blood flow, along with an excellent myocardial tissue characterization. The first MR-guided RHC procedures in humans were reported by Razavi et al. about 15 years ago [1]. In recent years, several centers have confirmed the feasibility, the safety, and the benefits of combining RHC with MRI [2–4]. Nowadays, the adoption of MR-guided RHC is progressively expanding from clinical research sites, using hybrid X-ray/CMR suites, to routine clinical practice with conventional CMR facilities.

Our institution is equipped with a 1.5T CMR scanner with a high throughput of about 5,500 CMR exams per year. We started an interventional CMR program in December 2018.

The aim of our study is to evaluate the feasibility and the safety of MR-guided RHC. 35 patients will be included by December 2019.

Methods

The research protocol was approved by the national Institutional Ethics Committee (2017-A03145-48). All patients provided informed written consent.



1 CMR suite and equipment: automated contrast injector (A), foot switch (B), 1.5T MAGNETOM Aera MR scanner (C), in-room monitor for Monte Carlo prototype display[1] (D), hemodynamic recording system (E).

2 The two interventional cardiologists filling the balloon of the catheter with a diluted solution of Gadolinium, so that the tip will be visible on CMR images. Their comfort is improved as they don't have to wear a heavy lead apron, that is mandatory in the cath lab for X-ray protection.

CMR suite and equipment

As shown in Figure 1, the procedures were performed in a conventional 1.5T CMR scanner (MAGNETOM Aera, Siemens Healthcare, Erlangen, Germany) with an 18-channel body cardiac coil. The MR room was equipped with an MR-compatible monitor[2] (prototype by EIZO GmbH, Rülzheim, Germany) to support real-time catheter guidance. Each procedure was performed with a 7 French three-lumen Swan-Ganz catheter (Edwards Lifesciences, Irvine, CA, USA) with femoral venous puncture. The balloon at the tip of the catheter was filled with a diluted gadolinium contrast solution (1/20, Dotarem, Guerbet, Aulnay, France), to allow its visualization on MR images as a bright spot (Fig. 2). Invasive blood pressures were recorded using an MR-compatible hemodynamic monitoring system[2] (non-commercially available). MR-conditional guidewires embedded with passive markers were available if needed (Nano4Imaging, Aachen, Germany).

Catheter guidance

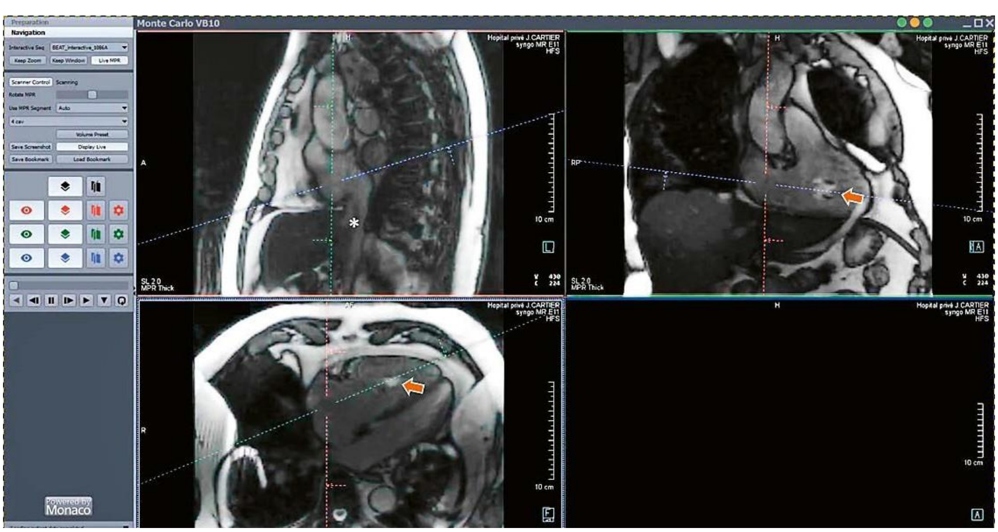
The MR-guided catheter navigation was done with an interactive real-time balanced steady-state free precession (b-SSFP) sequence (main parameters: TR/TE = 277/1.7 ms, FOV = 320 mm, matrix = 160, voxel size = 2 x 2 x 5 mm) allowing passive catheter tracking. Three planes were sequentially acquired with a frame rate of 1 per second. In addition, the workflow was supported by the Monte Carlo prototype[1] (Siemens Healthcare, Erlangen, Germany), consisting of an MR-compatible footswitch and a software application, installed on a remote computer connected to the MR host console. With Monte Carlo, the MR scans could be controlled and the MR images including the catheter tip were visualized (Fig. 3) on the mirrored in-room monitor and the screen in the control room. Reference views were planned by the technologist prior to catheter insertion: inferior vena cava long axis, 4-chamber view, right ventricular outflow track (RVOT) view, and bifurcation of the pulmonary artery (Fig. 4). Then, during catheter navigation, these views could be interactively selected and moved by the technologist to easily follow the catheter motion in real time.

MR-guided right heart catheterization procedure

The clinical staff consisted of two interventional cardiologists, two technologists, and a cardiologist specialized in CMR. Femoral venous access was obtained using ultrasound guidance. The catheter was inserted and navigated through the right heart. The interactive real-time sequence was used to visualize and follow the tip of the catheter, which appeared as a white spot in the images. Three different slices were updated every second and displayed on the in-room monitor for the cardiologists. All views could also be interactively modified, if needed. The sequence could be paused either by the interventional cardiologist using the foot switch or by the technologist via the Monte Carlo prototype. Communication between the cardiologist (in the MR room) and the technologist (in the control room) was ensured by the conventional MR communication system (Intercom). No additional MR-compatible communication system was available.

CMR diagnostic imaging

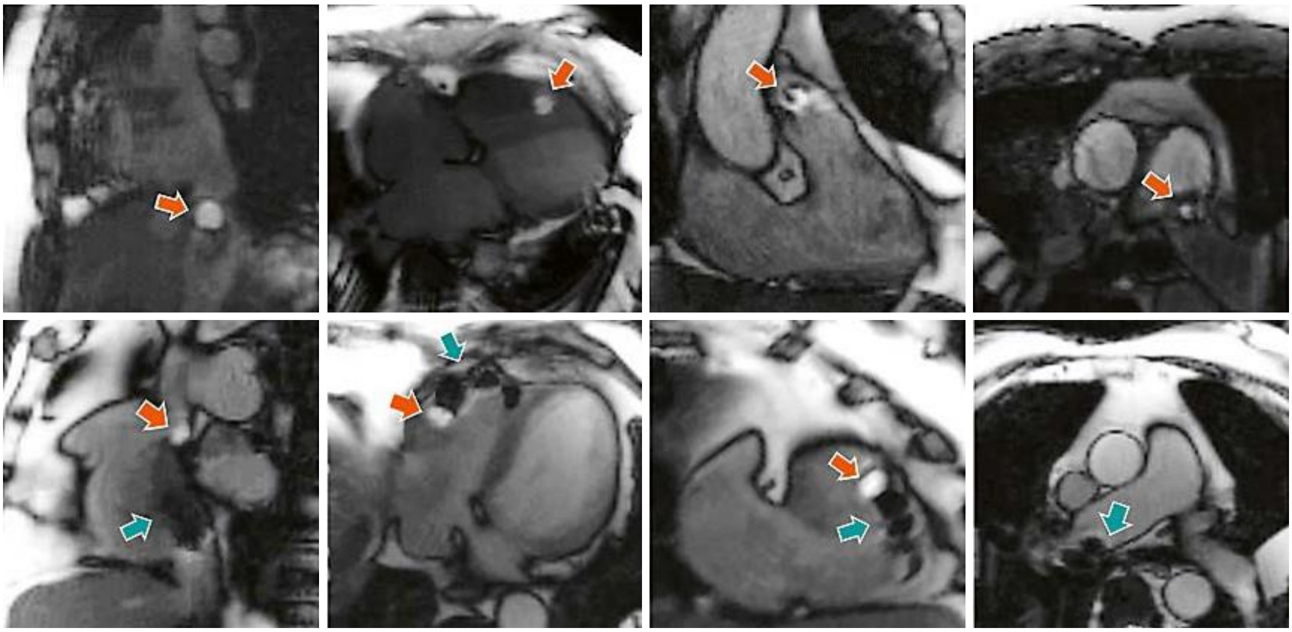
All patients underwent a diagnostic CMR exam directly after the catheterization procedure. Function evaluation was performed using a Compressed Sensing cine sequence with retrospective gating across two heartbeats. Two-chamber, four-chamber, two left-ventricle-outflow-track (LVOT), two right-ventricle-outflow-track (RVOT)



3 Monte Carlo interface showing three interactive views: vena cava long axis (top left, inferior vena cava depicted by an asterisk), 4-chambers (bottom left) and right ventricle outflow track view (top right). The tip of the catheter appears as a white spot in the images (orange arrow) and could be followed by the interventional cardiologist while it is navigated through the heart.

[1]*Work in progress: the application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.*

[2]*The information shown herein refers to products of 3rd party manufacturers and thus are in their regulatory responsibility. Please contact the 3rd party manufacturer for further information.*



4 Interactive real-time views used for catheter visualization without (top) and with a guidewire (bottom) in two patients. From left to right, as the catheter is navigated through the right side of the heart: vena cava long axis, 4-chambers, right ventricle outflow track and pulmonary artery bifurcation. The tip of the catheter can be seen as a white spot (orange arrow), corresponding to a diluted solution of gadolinium inside the catheter balloon. The guidewire is made visible by its markers creating signal void in the images (blue arrows, bottow row).

views were acquired, as well as a stack of 8-mm thick short-axis slices encompassing the whole ventricles. Aortic and pulmonary artery blood flow were measured by through-plane velocity-encoding phase-contrast sequences. Whereas cardiac output is usually measured by thermodilution in the cath lab, it was assessed non-invasively in our protocol, using the aortic blood flow sequence. The pulmonary to systemic blood flow ratio (Qp/Qs ratio) was calculated to exclude a potential left-right shunt. Then, a bolus of gadolinium was injected for first-pass perfusion imaging at rest. Late gadolinium enhancement imaging was acquired 10 minutes after injection. A real-time cine sequence could be added to assess the septal shift toward LV during inspiration in case of suspicion of constrictive pericarditis. All image viewing and interpretation were performed with *syngo*.via (Siemens Healthcare, Erlangen, Germany), using the 'MR Cardiac Analysis' workflow.

Results

Population

18 patients (67 ± 11 years, 11 men) were referred for MR-guided RHC from December 2018 to September 2019. Indications for RHC were pulmonary artery hypertension (15 patients), dilated cardiomyopathy (two patients), restrictive cardiomyopathy (one patient) and restrictive pericarditis (one patient).

Procedure

Hemodynamic measurement and diagnostic CMR were successfully completed in all patients without complications. The overall procedure was performed within approximately one hour, including less than 30 minutes dedicated to diagnostic CMR. A guidewire was used when manipulation of the catheter was more difficult, especially in very dilated right heart chambers. The other benefit of the guidewire was the passive markers that appear hypointense in images and help to visualize the catheter shaft.

Safety

MR-guided RHC showed excellent safety without any major adverse events. The interventional cardiologists reported a good noise tolerance using headset hearing protection. Dispensing with lead aprons, mandatory in the cath lab, improved the comfort of the operators.

Future perspectives

CMR has proven to be of great interest for the guidance of cardiovascular interventions such as hemodynamic characterization in pulmonary hypertension. The commercial availability of MR-conditional instrumentation will be the key to facilitating its adoption for more complex procedures, such as electrophysiology (EP) and radiofrequency (RF) ablation for cardiac arrhythmia (atrial flutter, atrial fibrillation and ventricular tachycardia). Pre-procedural

CMR is currently used for the assessment of scar distribution using high-resolution LGE imaging. Identification of arrhythmogenic substrate might enable an improved, targeted ablation strategy and have an impact on the procedural success [5]. However, it is even more attractive to replace X-ray fluoroscopic guidance with CMR, as direct visualization of lesion transmurality and gaps would potentially help to decide whether the ablation procedure is complete or not. It has been shown that RF lesions and surrounding edema could be well depicted with 3D non-contrast CMR sequences [6–8]. The feasibility of MR-guided EP and RF ablation in patients has been reported in a few early clinical studies [9–11]. Novel MR-conditional catheters are equipped with small coils that allow active tracking with automatic alignment of MR planes during catheter navigation. Further developments are under way to introduce these interventions into a routine CMR workflow (commercially available EP and ablation catheters, external defibrillators and other MR-conditional devices).

Conclusion

MR-guided RHC is safe and feasible in a fully clinical CMR facility. Patients benefit from a combined radiation-free RHC and a diagnostic CMR exam within one hour. Comfort of the interventional cardiologists is improved as they do not have to wear a heavy lead apron. This is a significant first step toward more sophisticated cardiovascular interventions under MR guidance, such as RF ablation for the treatment of arrhythmia. The direct visualization of RF lesions on MR images might be of particular value to assess the completeness of the procedure. This real-time feedback might help to avoid recurrence of the arrhythmia and thus the need to repeat procedures for improved and cost-effective patient care.

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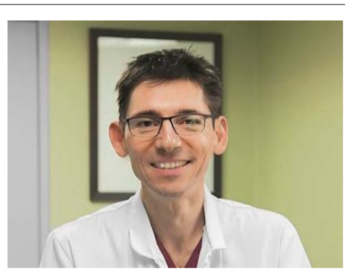

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