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Cavotricuspid Isthmus Ablation Guided by Real-Time Magnetic Resonance Imaging

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Magnetic resonance imaging (MRI) has evolved as a standard cardiac imaging technique. Interventional procedures guided by real-time MRI may derive potential benefit from a fluoroscopy-free working environment, more detailed insights into the target anatomy, and additional information on organ tissue properties relevant for pathomorphology as well as therapy delivery.

Electrophysiological (EP) procedures in a magnetic resonance (MR) scanner require new workflows with different, MR safe, interventional materials and hardware setup, different approaches to intracardiac orientation and catheter tracking, and an adapted patient management. Recently, invasive diagnostic EP procedures have been described in animal studies and in a clinical setting. Actual catheter ablation has so far only been reported in a limited number of animal series.

Methods

Hereby, we report on a MRI-guided cavotricuspid isthmus ablation. A 74-year-old man without structural heart disease was admitted with documented episodes of paroxysmal symptomatic typical right atrial flutter. At the ablation procedure the patient presented in sinus rhythm.

The patient was enrolled into a clinical study approved by the local ethics committee and by the German Federal Institute for Drugs and Medical Devices (BfArM). He provided written and verbal informed consent. In this study, we used MR conditional catheters (Vision, Imricor Medical Systems, Burnsville, MN) and an MR conditional EP recording system (Bridge MR EP Recording System, Imricor Medical Systems, Burnsville, MN). The material is designed for use in 1.5 T closed bore scanners and imposes no limitations on the catheter trajectory, scanner landmark, or patient position. The catheter allows for all clinical scan protocols and is safe for use in normal and first level controlled operating modes.

MR Conditional Catheters

Although the appearance and functionality are similar to conventional ablation catheters, the design of the MR conditional catheter differs substantially. All ferromagnetic materials are removed to eliminate the potential for force and torque to be imposed by the static field. Electrical isolation is provided between catheters, at the EP recording system, to prevent the formation of large inductive loops and coupling with the gradient fields. Metallic temperature sensors and structural components are replaced with nonconductive materials to eliminate coupling with the radiofrequency (RF) field. A novel electrode wire configuration attenuates currents induced by the RF field while passing relevant electrophysiology signals. Passive markers are placed near the tip to aid in MR guidance. Electrodes are formed from materials with a low magnetic susceptibility to reduce unintended image artifacts. The catheter shaft is 8.5 F and has a patient-insertable length of 115 cm. The deflectable length is 104 mm, the 90° reach is 83 mm, and the 180° reach is 53 mm. The catheter incorporates 2 gold electrodes at the distal tip for electrogram recording and pacing. Unipolar RF ablation energy is delivered through the distal 3.5 mm gold tip electrode that includes 6 open irrigation holes. A commercially available Covidien E7507 Adult REM PolyHesive II Patch serves as indifferent electrode.

MR Conditional Safety Testing

Vision Catheter and Bridge MR EP recording system safety verification included testing for (1) magnetic displacement force and torque, (2) gradient-induced current, and (3) RF heating.

1. The weight of catheter was 79.4 N, whereas its magnetically induced force was <7.7 N. The torque experienced by the catheter was found to be <2.2 mN*m, which is well below the torque owing to gravity of ≈351 mN*m.

2. Individual catheters and multiple electrically isolated catheters pose negligible risk of gradient-induced cardiac stimulation. However, when connected to a conventional EP recording system, multiple catheters can form a large inductive loop (catheter–tissue–catheter EP recording system), which may result in gradient-induced currents capable of unintended stimulation. The MR conditional Bridge MR EP recording system provides >5 MΩ of catheter-to-catheter isolation resulting in negligible gradient-induced low frequency current even with multiple catheters connected, thereby eliminating the potential for gradient-induced cardiac stimulation.

3. Testing for RF heating was performed using an Achieva 1.5T MRI system (Philips Healthcare, Best, The Netherlands). The tests were performed for varying catheter insertion depths in a saline-filled phantom (ASTM 2182-02a) with a conductivity of 5.0 mS/cm±5%. Pretesting concluded that multiple catheters used simultaneously do not heat more than a single catheter; therefore, all tests were performed on a single catheter. No catheter irrigation was used for cooling during the testing. The reported testing was performed using a balanced turbo field echo sequence with a reported specific absorption rate of 4.0

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W/kg. Ten catheters were tested. The average temperature rise for all catheters at all insertion depths measured 0.34±0.08°C. The single highest observed temperature rise was 0.5°C and was recorded at a ring electrode.

Further RF-induced heating was evaluated for the indifferent electrode and the complete ablation circuit. Evaluation included particular focus on testing configurations where cord and pad of the indifferent electrode were exposed to the maximum energy transfer from the MRI system, including Eddy current-generating orthogonal electric fields. No configuration tested resulted in measurable temperature rise at the return electrode.

**MR Conditional EP Setup**

The Bridge MR EP recording system is split into 2 primary components: a patient interface module and a host computer workstation. The patient interface module resides near the patient in the magnet room; receives, filters, and digitizes ECG and electrogram signals; and sends them to the outside workstation via fiber optic cable. The signal processing in the patient interface module removes noise caused by the MRI. The patient interface module also receives commands from the workstation, acts as a user programmable stimulator, passes tip temperature data to the computer workstation via a separate fiber optic channel, and delivers ablation energy to the ablation catheter from a conventional ablation generator through an integrated RF line filter.

**Catheter Tracking in the MR environment**

In the scanner (1.5 T Intera, Philips, Best, The Netherlands; with 5-channel phased-array surface cardiac coil) intracardiac catheter visualization and navigation were achieved by passive tracking using commercially available interactive real-time steady-state free precession MRI sequences (movie I–IV in online-only Data Supplement) with typical parameters: repetition time, 2.9 ms; echo time, 1.4 ms; flip angle, 25°; slice thickness, 10 mm; field of view, 350x350 mm; matrix size, 176x132, and frame rate, 8 images per second. Throughout the procedure, the catheter was tracked in 2 orthogonal planes: comparable with fluoroscopic right anterior oblique and left anterior oblique projections (Figure 1). Catheter tracking represents one of the main difficulties for MR-guided EP procedures because the fundamental difference from a fluoroscopic working environment is the use of planar versus projection (summation) imaging. In preclinical work, we have developed a process of passive MR catheter tracking based on a combination of scanning protocol, catheter technology and handling technique. After successful use during invasive diagnostic EP studies, we applied that approach for the actual catheter ablation. The process of passive catheter tracking can be summarized as follows: (1) MR imaging with thick planes (slice thickness, 10 mm) aimed to visualize not only the catheter tip but also as much of the shaft and the curve as possible. The flip angle (between 20° and 30°) was further crucial to create enough contrast between the body of the catheter and the surrounding blood pool. (2) The vision catheter included 2 MRI markers to aid passive tracking. The first is an inductively coupled visualization marker located 3 mm proximal to the tip. Such a coil is capable of creating a white spot of signal enhancement, although its effectiveness is pulse sequence and trajectory dependent. The inductively coupled marker proved to be less useful during our procedures. The second is a small ferrous marker located 1.5 cm proximal to the tip. That marker creates an image signal void (a dark spot) and was well visible during the real-time pulse sequences. (3) For catheter handling we followed the concept one manipulation–one scan (ie, at one time the catheter was only bent/stretch, rotated, or advanced/retracted). Complex motion was not performed. After each step of manipulation the radiologist scrolled through the right anterior oblique/left anterior oblique planes to find the exact catheter position. The plane for real-time scanning during manipulation (right anterior oblique/left anterior oblique) was chosen at the discretion of the electrophysiologist. (4) Intracardiac electrograms were always additionally considered when assessing the catheter position.

**Figure 1.** Ablation in the magnetic resonance (MR) imaging scanner. A, Surface ECG and bipolar intracardiac electrograms from the coronary sinus catheter (positioned at 4 o'clock at the mitral annulus) and the ablation catheter (positioned in the cavitricuspid isthmus) are shown immediately before and after the second radiofrequency (RF) pulse delivered in the MR scanner (at 9:04 am). Note the reduction of the atrial electrogram component (red arrow) induced by RF energy delivery. B and C, Passive catheter tracking in 2 orthogonal planes equivalent to fluoroscopic right anterior oblique (RAO) (B) and left anterior oblique (LAO) (C). White arrows point to the course of the ablation catheter. The catheter tip is positioned over the inferior tricuspid annulus reaching into the right ventricle (RAO). The catheter is directed toward the lateral side (A2) of the cavitricuspid isthmus (LAO). In both planes the course of the catheter can be followed from the inferior caval vein into the right atrium, and down to the cavitricuspid isthmus. AAO indicates ascending aorta; abl, ablation; CS, coronary sinus; IVC, inferior vena cava; LV, left ventricle; RV, right ventricle; and RA, right atrium.
Patient Management

According to our study protocol, 2 vision catheters were introduced into the right atrium and the coronary sinus, while the patient was in a biplane fluoroscopic EP laboratory (Artis Zee, Siemens, Forchheim, Germany). Access sites and catheters were covered with sterile sheets while the patient was transferred on a MR table to the scanner (≈20 m away).

The patient was in light sedation using midazolam. Patient monitoring included noninvasive and invasive blood pressure monitoring, monitoring of oxygen saturation, and ECG monitoring. In the EP laboratory and during transport to the MR scanner, clinical standard equipment was used for that purpose.

After arrival in the MR department the MR table and the patient were checked for absence of any ferromagnetic materials by 2 co-workers according to the 4 eyes rule. Afterward, standard ECG cabling, oxygen monitoring, and blood pressure monitoring were disconnected for about 30 seconds and the table entered the magnet room. Immediately thereafter monitoring was reestablished with invasive arterial blood pressure monitoring (through the waveguide), MR compatible monitoring of oxygen saturation, and ECG cabling provided by the Bridge MR EP system. A sterile working environment was reestablished before the table entered the scanner.

During the procedure the operator and one nurse were continuously in the magnet room. Communication was enabled through a wireless communication system, comprising a DX100 Wireless Basestation, 2 HS15D Dual Muff headsets for inside the magnet room, and 2 WH200 all-in-one wireless headsets for the control room (Clear-Com, CA). The system allowed for simultaneous real-time communication between the magnet room and the control room. As safety back-up an external defibrillator was in place in front of the magnet room, and one EP laboratory and one surgical operating room were blocked.

Mapping and Ablation

Total procedure time measured 120 minutes. Time in the MRI scanner was 52 minutes. Ablation was performed point-by-point with RF pulses of 40 W, flow rate of 8 cc/min, an upper temperature limit of 41°C, and 60-second burning time. Figure 1 illustrates local electrogram reduction before and after RF energy delivery. After 3 RF pulses, the isthmus was successfully ablated. While in the MRI,
bidirectional isthmus block was shown by (1) wide double potentials and (2) differential pacing from within the coronary sinus and from the lateral side of the isthmus (Figure 2). After successful ablation, the patient was brought back into the EP laboratory to validate the end point on a conventional EP recording system (Prucka, Cardiolab, GE Healthcare, USA) within a fluoroscopic mapping environment (Figure 3).

Summary
We demonstrated feasibility of MRI-guided cavotricuspid isthmus ablation. Once it has been shown that existing EP endpoints can be reliably reached, approaches to treat other and potentially more complex arrhythmias may follow. The potentially additive clinical benefit of tissue and substrate imaging during or after complex ablations has to be evaluated.

Limitations
Passive catheter tracking, as performed in this study, is difficult, time consuming, and inferior to conventional fluoroscopy. Active tracking is likely to be needed in the future. It can be achieved by 2 ways (1) using scanner algorithms together with MR tracking coils on the vision catheter or (2) bringing MR compatible versions of existing EP tracking technologies (Carto, NavX) into the magnet room.

Tissue visualization before, during, and after RF ablation is the topic that is most fascinating for electrophysiologists. Our study, however, was primarily designed to show feasibility of RF ablation in the MR scanner with the ability to achieve an existing procedural EP end point.

Parts of the procedure (puncture, catheter advancement) were still performed outside the scanner in a conventional EP laboratory. Lack of MR compatible material for access site puncture and difficulties of catheter tracking were the reasons for such a study design with focus on safety and maximum scanner time available for mapping/ablation.

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