Mapping and Ablation of the Pulmonary Veins and Cavo-Tricuspid Isthmus with an MRI Compatible Externally-Irrigated Ablation Catheter and Integrated Electrophysiology System

Running title: Ganesan et al.; MRI-guided biatrial ablation

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Abstract:

Background - MRI-guided interventional electrophysiology (EP) has rapidly emerged as a promising alternative to X-ray guided ablation. We aimed to evaluate an externally-irrigated MRI-compatible ablation catheter, and integrated EP pacing and recording system, testing the feasibility of pulmonary vein (PV) and cavo-tricuspid isthmus (CTI) ablation.

Methods and Results - Externally irrigated MRI-compatible ablation and diagnostic electrophysiology catheters and an integrated EP recording system (Imricor Medical Systems, Burnsville, MN) were tested in n=11 sheep, in a 1.5T MRI scanner. Power controlled (40W, 120 second duration) lesions were formed at the PV and CTI. Real-time intracardiac electrograms were recorded during MR imaging. Steady state free precession (SSFP) non-breath hold images were repeatedly acquired to guide catheter navigation. Lesion visualization was performed using non-contrast (T2-weighted turbo spin echo pulse sequence) and gadolinium-DTPA enhanced T1-weighted imaging (inversion-recovery gradient echo pulse sequence). Catheters were able to be visualised and navigated under CMR guidance. 8±2.5 lesions (RF time 16±4.2 mins) were formed at the PV ostia, and 6.5±1.3 lesions (RF time 13±2.2 mins) at the CTI, with the endpoint of bidirectional block. Mean procedure time was 150±55 minutes. Lesion visualisation with both T2W imaging and contrast-enhanced imaging correlated with sites of injury at autopsy.

Conclusions - These data demonstrate the feasibility of using multiple catheters, an integrated EP pacing and recording system, and externally-irrigated ablation with CMR guidance to undertake clinically relevant biatrial mapping and ablation.

Key words: ablation; catheter ablation; electrophysiology; magnetic resonance imaging
Introduction

In the past decade, a variety of technology advancements including electroanatomic mapping, intracardiac echocardiography and external catheter irrigation have contributed to the rapid expansion of complex arrhythmia ablation. Despite these innovations, conventional X-ray guided fluoroscopy remains the foundation of catheter navigation in the majority of contemporary ablation procedures. Fluoroscopy-guided ablation suffers from a number of important technical drawbacks including limited anatomical resolution, lack of feedback regarding catheter contact or lesion characteristics, as well as requiring exposure of patient and operator to ionising radiation.

It is in this context that magnetic resonance imaging guided ablation has steadily emerged as a promising alternative in interventional electrophysiology. MRI-based ablation offers a number of potential advantages over traditional fluoroscopically-guided procedures, including: 1) improved anatomic visualization of the heart and surrounding structures; 2) avoidance of ionising radiation; and 3) intra-procedural visualization of lesion formation.

Previous studies of MRI-guided ablation have predominantly used single non-irrigated catheters to evaluate the efficacy of test lesion formation, without real-time electrophysiological assessment of lesion integrity in the MRI scanner. Modern clinical electrophysiology procedures typically use multiple catheters, along with integrated pacing and recording systems, to diagnose and ablate cardiac arrhythmias. Furthermore, complex procedures, such as atrial fibrillation ablation, typically use externally-irrigated catheters to achieve adequate lesion depth and improve safety profile. In the current study, we used a novel MRI-compatible electrophysiology pacing and recording system, in combination with an MRI-compatible externally-irrigated ablation catheter and MRI-compatible mapping catheters to demonstrate the
feasibility of pulmonary vein (PV) and cavo-tricuspid isthmus (CTI) ablation, the targets of ablation in atrial fibrillation and atrial flutter, respectively.

Methods

A total of 11 Merino Cross wethers (weight 54±1 kg) were studied. All procedures were conducted in accordance with the guidelines outlined in the “Position of the American Heart Association on Research Animal Use” adopted on November 11, 1984 by the American Heart Association. Approval for the performance of the study was provided by the Animal Ethics Committees of SA Pathology and the University of Adelaide, Adelaide, Australia.

MRI-compatible ablation and diagnostic catheters

Studies were conducted with novel MRI-compatible diagnostic and open irrigated ablation catheters (Figure 1) (Imricor, Burnsville, MN). All catheters contained a passive coil, tuning circuitry, and a passive ferrous marker to facilitate passive tracking in the MRI environment. All catheters were 8.5-French diameter with a usable length of 115 cm. All electrodes were constructed of gold, the tip electrode was irrigated and measured 3.65 mm and each ring electrode measured 1.5 mm. Details of catheter construction are provided in Supplemental Material. Tip temperature measurement was accomplished via a custom fiber optic temperature sensor located in the distal electrode. This optical fiber sensor was connected to an external fiber optic unit via a connector in the catheter handle. The ablation catheter was connected to a standard clinical radio frequency ablation generator (T11, St. Jude Medical) located outside in the control room. A map of the layout of the MRI suite is provided in the Supplemental Material. External irrigation was performed with a standard irrigation pump (CoolPoint, St. Jude Medical) located outside in the control room, and connected to the irrigation lumen of the catheter with high-pressure tubing.
Intracardiac electrocardiogram recording and signal processing

Real-time intracardiac electrograms were recorded and displayed with a custom MRI-compatible electrophysiology pacing and recording system (Bridge, Imricor, Burnsville, MN). The Bridge system has passed the IEC 60601-1 standard for electrical safety as well as extensive MRI compatibility testing, specifically low frequency induced currents due to gradient interactions with loops formed by multiple catheters. Signals were collected by conditioning signals through hardware, digitizing the signals, applying a set of selectable digital infinite impulse response (IIR) filters, and sending data to the host computer that resides in the MR control room. Monitors were placed in the magnet room which mirrored displays of the MR computer and the Horizon host computer, allowing simultaneous visualization of the real-time electrograms and MR images by the catheter operator and support staff.

MRI imaging

MRI was performed on a 1.5T Siemens Sonata scanner, located adjacent to the fluoroscopy lab. An eight channel radiofrequency body coil was used and signal was received through a cardiac surface coil. ECG electrodes were connected for ECG gating and images were displayed on an in room MR compatible monitor console. Survey and reference scans were performed in three orthogonal planes. A passive tracking strategy was used for catheter navigation. Details of MRI image acquisition are provided in the Online Data Supplement.

Animal Experimental Model

All animals underwent induction of general anesthesia outside the MRI-suite with diazepam 0.3mg/kg and thiopentone, followed by intubation and ventilation using 2-3% isoflurane in 100% oxygen. During experimental procedures, the anesthesia machine was placed outside the MRI-suite with extension tubing passed to the animal located in the MRI-suite.
Electrophysiology Studies

The following MRI-compatible catheters (Imricor, Burnsville, MN) were used for each experiment: a 4-pole diagnostic catheter was introduced via the left internal jugular vein and positioned within the coronary sinus; a 4-pole diagnostic catheter was introduced via the right femoral vein and positioned at the right ventricular apex; and the 2-pole externally irrigated ablation catheters were introduced via the right femoral vein. The diagnostic catheters and ablation initially positioned using fluoroscopy, and subsequently navigated within the atria using MRI imaging.

Trans-septal puncture was performed using conventional techniques with an SL0 sheath (St Jude Medical) and a BRK-1 needle using fluoroscopy in an adjacent laboratory. The SL0 sheath was used to introduce the MRI-compatible ablation catheter placed in the left atrium. The animal was then transported to the MRI suite, and the left atrial ablation was commenced.

Pulmonary Vein Ablation

The catheter was identified under MRI guidance, and navigated to the ostia of the pulmonary veins or left atrial appendage. Ablation was performed at the ostia of the pulmonary vein using a power control mode at 40W, with irrigation using normal saline set at a fixed rate of 15mL/min. Ablation energy was applied for 120 seconds before the catheter was repositioned. MRI imaging was not performed during the application of ablation energy. Catheter tip temperature was monitored continuously via a custom fiber optic temperature sensor built into the catheter tip.

Cavo-tricuspid isthmus ablation

The catheter was then navigated to the cavo-tricuspid isthmus, under MRI guidance. It was placed at the inferior isthmus, in a position analogous to the 6 o’clock position in a simulated conventional LAO view. Radiofrequency ablation of the cavo-tricuspid isthmus was performed
by gradual withdrawal of the ablation catheter from the tricuspid annulus while continuous pacing was performed from the coronary sinus to monitor conduction delay and block. For the current study, discrete power-controlled ablation lesions were applied to the CTI at 40W for a fixed time of 120 seconds. At each point the effect of ablation was monitored using voltage abatement before and after the application. The end point of CTI linear ablation was the demonstration of bidirectional conduction block with the presence of on-line double potentials, and activation detour during coronary sinus pacing and using differential pacing techniques. MRI imaging was not performed during pacing maneuvers.

Pathologic Examination

At the experimental conclusion, animals were euthanized with a lethal dose of phenobarbitone after injection with 20mL of 2% 2,3,5 triphenyl tetrazolium chloride (Sigma-Aldrich, St Louis, MO). The heart was removed via a midline sternotomy, and examined macroscopically. The left atrium was opened with an incision at the inferior wall of the left atrial appendage. The right atrium was opened with a linear incision connecting the superior and inferior vena cavae. Macroscopically identifiable lesions were photographed and underwent histologic examination. Sections from ablated lesions were fixed in 10% buffered formalin, paraffin-embedded, and 6μm sections cut and stained with haematoxylin and eosin (H&E).

Statistical analysis

Statistical analysis was performed using Microcal Origin (Northamptom, MA). Data are expressed as mean±SD.

Results

Catheter navigation

The diagnostic and ablation catheters were able to be visualised and tracked in all cases. The
catheter design incorporated MRI tracking markers that enabled identification of the MRI catheter tip. The most useful cardiovascular magnetic resonance (CMR) sequence for catheter localisation in this case series was a non-breath-hold ‘bright blood’ (steady state free precession) imaging. The catheter tip was identified in each chamber of interest by the relative location of the bright and dark tracking markers (Figure 1D). The diagnostic catheters in the coronary sinus and right heart were able to be identified in all cases (Figure 2A & B). In all cases, the catheter was able to be navigated near to the pulmonary vein ostia for left atrial ablation, and to the CTI for ablation (Figure 3A & B).

**Intracardiac electrograms recordings and pacing**

Intracardiac electrograms were able to be recorded from diagnostic and ablation catheters in all cases within the MRI field (Figure 1D). There was no evidence of induced current stimulation in any catheter position or orientation. Pacing was able to be performed in all cases. Electrograms were continuously recorded during MR image acquisition (Figure 1E). During the application of RF energy, electrograms were transiently lost in the ablation catheter. MR images were not acquired during the application of RF energy.

**Ablation at the PV Ostia**

Radiofrequency ablation lesions were then created in the left atrium, at the ostia of the pulmonary veins. Example images demonstrating visualisation near the pulmonary veins are shown (Figures 3A-C), and in movies 1 and 2, Supplemental Data. In a subset of animals, lesion visualisation was attempted with T2W turbo spin echo imaging with Gadolinium contrast-enhanced imaging. Myocardial injury was able to be demonstrated in the left atrium (Figure 3C). A mean of 8±2.5 lesions were applied (RF time 16±4.2 mins). Ablation was associated with abolition of the local electrogram amplitude (Figure 3D). Mean electrogram decrease was
92±2%. Ablation lesions were associated with macroscopic pallor (Figure 3E), and microscopic transmural necrosis, including coagulation necrosis and myocytolysis (Figure 3F).

**Ablation of the Cavo-tricuspid Isthmus**

After ablation at the pulmonary vein ostia, the catheter was withdrawn to the cavo-tricuspid isthmus. The ablation catheter was typically visualised in a simulated LAO view (Figure 4A). The catheter was positioned at the CTI such that the bipole recorded an approximately equal atrial and ventricular electrogram. The catheter was gradually withdrawn proximally within the CTI, applying point by point lesions for 120 seconds. Linear lesion was completed until the right atrial-inferior vena cava junction was reached. Bidirectional block was assessed by determining the presence of contiguous on-line double potentials, demonstrating an activation detour by pacing either side of the line and using differential pacing⁹ (Figure 5). In 11/11 cases bidirectional block was achieved with a conduction delay of 175±13ms lateral to the line during septal pacing within the MRI scanner. In a subset of animals, lesion visualisation was attempted with T2W turbo spin echo imaging with Gadolinium contrast-enhanced imaging. Myocardial injury was able to be demonstrated at the CTI and RV septum (Figure 4D). The mean total procedure duration was 150±55 minutes.

**Procedure complications**

Animals tolerated the procedure well. None of the animals developed cardiac tamponade, extra-cardiac injury, or conduction system injury.

**Discussion**

This study provides important new information on the use of CMR to facilitate cardiac mapping and ablation. It demonstrates:
- The feasibility of ablation procedures involving multiple catheters, with an integrated electrophysiology pacing and recording system within the MRI suite, without limitations on scan sequence or power limitations to ensure safe operation.

- The use of an externally irrigated ablation catheter, navigated using CMR to undertake reliable ablation at the ostia of the pulmonary veins and linear ablation at the cavo-tricuspid isthmus.

- Recording of real-time electrograms from multiple catheters within the MRI field, to permit reproducible “in MRI” electrophysiological evaluation of bi-directional block at the cavo-tricuspid isthmus for the first time.

Together, these findings provide further evidence for the likely role of CMR as an imaging modality for complex interventional electrophysiology procedures.

**Electrophysiology Procedures**

The MRI environment poses significant safety and technical challenges for EP procedures involving multiple catheters. There are safety concerns regarding unintended catheter heating caused by radiofrequency coupling\(^{11}\), and electrophysiological device malfunction, for example, through electric interference during imaging\(^{12,13}\). The low-frequency magnetic gradients used for spatial encoding are associated with induced currents, which may be of sufficient amplitude to induce unwanted myocardial stimulation, an effect particularly associated with the use of multiple-looped catheters\(^{14}\). The current study demonstrated the feasibility of the use of multiple catheters with an integrated MRI-compatible pacing and electrophysiology recording system, in which these risks were not directly observed.

**Catheter Navigation and Ablation**

The procedures undertaken in this study included ablation adjacent to the pulmonary veins, and
linear ablation at the cavo-tricuspid isthmus using catheter navigation guided by passive tracking of catheters. The catheters were navigated by iterative steps, using repeat imaging at each location to visualise the catheter tip, before moving to the next location. Using this process of passive tracking, navigation of the ablation catheter was able to performed at the pulmonary veins and cavo-tricuspid isthmus. Although catheters were introduced by fluoroscopy, no specific issue was identified in terms of movement of the catheters in transfer of the animal from X-ray to CMR suite.

**Electrophysiology Pacing and Recording System**

The integrated pacing and recording system permitted the recording of intracardiac electrograms. The feasibility of left atrial and linear ablation in the CMR-suite was demonstrated, and bidirectional block was confirmed at the CTI during the procedure. No limitations on imaging power or catheter positioning were required.

**External Irrigation**

The study also represents the first use of an externally-irrigated MRI ablation catheter, with demonstration of lesion transmurality at pathologic examination. Saline irrigation cools the tissue-electrode interface, and decreases the risk of surface coagulum formation, increasing effective power delivery into the tissues. This consideration is of particular importance in modern EP applications such as atrial fibrillation, atrial flutter and ventricular tachycardia ablation.

**Lesion Visualization**

Lesion visualisation is one of the potential advantages of MRI-based ablation over conventional X-ray procedures. Lesion visualisation has previously been demonstrated for RF ablations, with recent MR thermography studies demonstrating the possibility of accurate non-invasive
prediction tissue destruction during RF ablation procedures.\textsuperscript{23-25} In our study, we attempted to perform lesion visualisation in a subset of animals. Lesion visualisation was possible, using both non-contrast (T2-weighted turbo spin echo pulse sequence) and gadolinium-DTPA enhanced T1-weighted imaging (inversion-recovery gradient echo pulse sequences). Future more definitive lesion visualisation studies are planned with this ablation system.

\textit{System Limitations}

The current study used passive tracking to allow imaging of the ablation catheter in the heart. Although mild image degradation was present at times during these procedures, image quality was adequate to enable accurate catheter identification and positioning at the pulmonary veins and cavo-tricuspid isthmus. Passive tracking of the ablation catheter required acquisition of survey scans to enable identification of the catheter tip, accounting for the relatively long procedure times during each procedure. The particular passive tracking approach used in our study requires the catheter to be stationary to allow the tip to be localised by the imaging operator, leading to a time delay before the catheter may be able to be moved, contributing to the extended procedure times seen in our study. Active automated catheter trip tracking is an area of current innovation, which would allow the real-time identification and visualization of the catheter within the MRI images and has been incorporated into the next generation of the current catheter. Active tracking is expected to enable shorter procedure times. The current study was also limited in that pulmonary vein ablation was performed without attempting pulmonary vein isolation. PV isolation in this model will require additional catheter and sheath development, due to the specific anatomical considerations of the pulmonary vein the sheep.

\textit{Safety}

Catheter navigation and the application of radiofrequency ablation were able to be carried out
successfully in all cases. No cardiac tamponade or extra-cardiac injury was identified during the experiments.

**CMR-guided electrophysiology**

The past decade has seen the steady evolution of technology required for CMR-guided electrophysiology procedures. Lardo and co-workers first demonstrated RF ablation in the CMR suite in 2000. Since that time, feasibility of diagnostic electrophysiology studies, electroanatomic mapping and trans-septal catheterization have all been demonstrated in the CMR suite. Recently, a number of groups have developed MRI-compatible catheters capable of performing RF ablation in single catheter experimental studies, in anatomically guided procedures. Nordbeck et al demonstrated the possibility of lesion formation using a carbon fiber based catheter. Schmidt et al demonstrated the feasibility of left atrial lesion formation and AV node ablation. Hoffmann et al demonstrated anatomically guided cavotricuspid isthmus ablation in a pig model. Vergara et al demonstrated the feasibility of real-time lesion visualisation ablation in a pig model, where left atrial ablation was performed in 2 animals, a group which has previously pioneered the use of CMR for visualisation of fibrosis.

**Clinical Implications**

The current study demonstrates the feasibility of performing clinical procedures with multiple catheters in the CMR suite, under MRI guidance with the assistance of an integrated MRI-compatible pacing and recording system. The study also demonstrates the use of an externally irrigated MRI-compatible ablation catheter, opening the door to complex ablation for atrial fibrillation, atrial flutter and ventricular tachycardia. These studies represent a significant step towards the clinical application of MRI-guided interventional electrophysiology. The study has particular relevance for pediatric patients, who may experience multiple procedures over a
lifetime, in a population with potentially enhanced oncologic risk due to medical radiation. The data presented may also have relevance for clinical electrophysiology operators, who, in contemporary X-ray laboratories are exposed to risks related to ionising radiation, as well as the occupational hazard of prolonged use of lead aprons.

**Conclusion**

CMR-guided electrophysiology procedures offer a number of potential advantages, including direct visualisation of anatomy, avoidance of ionising radiation, and intra-procedural lesion visualisation. The data presented here represent a further step towards realising the promise of magnetic resonance guided imaging in the clinical setting.

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**Conflicts of Interest:** Mr Sunnarborg and Mr. Lloyd are employees of Imricor Medical Systems, Burnsville, MN, USA. Dr Selvanayagam reports having received lecture fees from Medtronic, Phillips and Siemens and having received research funding from Siemens and Bayer. Dr Sanders reports having served on the advisory board of St. Jude Medical, Bard Electrophysiology, Biosense-Webster, Medtronic, Sanofi-Aventis, and Merck. Dr Sanders reports having received lecture fees from St. Jude Medical, Bard Electrophysiology, Biosense-Webster, Medtronic and Merck. Dr. Sanders reports having received research funding from St. Jude Medical, Bard Electrophysiology, Biosense-Webster and Medtronic.
References:


**Figure Legends:**

**Figure 1.** CMR –guided ablation setup. A. Diagram of MRI-compatible ablation catheter with deflectable tip. B. Photograph of MRI-ablation catheter, showing gold electrodes. C. Example of the tracking markers used to detect catheters demonstrated in a saline bath phantom. (Inset) Catheter tip shown in detail. A number of markers were present on the catheter, including: 1. the capacitor marker (dark artefact, see diagram in 1A) 2. Passive coil (bright artefact, see 1A) and 3. Tip (dark artefact, see 1A). D. Example of real-time electrogram recordings inside the MRI.
scanner. ABL=ablation catheter, CS=coronary sinus catheter (proximal and distal poles), and RV=right ventricular catheter. E. Example of real-time electrogram recordings inside the scanner during MR image acquisition, and with image acquisition off.

**Figure 2.** Demonstration of catheter setup, with multiple catheters in-situ. A. Steady state free precession (SSFP) non-breath-hold images - coronal view. Diagnostic catheters in right ventricle (x), and coronary sinus (y). * denotes junction of left atrium (LA) and left ventricle (LV) cavity at the level of the atrioventricular groove. RV=right ventricle. RVOT = right ventricular outflow tract. B. SSFP – oblique sagittal view, demonstrating the catheter ascending from the inferior vena cava (IVC) into the right ventricular apex (arrow). C. SSFP –axial view showing 2 catheters in inferior vena cava (arrow).

**Figure 3.** Images of MRI-guided left atrial ablation. A. SSFP- axial view. Ablation catheter visualised crossing inter-atrial septum into left atrium (x). Catheter in coronary sinus (y). B. SSFP - oblique sagittal. Two ablation catheters are visualized ascending from the IVC, one directed anteriorly towards the RV (x) and the other (y) directed posteriorly towards the LA (*), adjacent to the right pulmonary vein (RPV). C. Late gadolinium enhancement image in left atrium at the junction of LA and LV at level of atrioventricular groove (*), showing myocardial injury (white arrow) with gadolinium-DTPA enhanced T1-weighted imaging (inversion-recovery gradient echo pulse sequence). Inversion time was kept deliberately long to make the injury more apparent. D. Example macroscopic coagulation necrosis of near right superior pulmonary vein. Ablation lesions are seen as areas of pallor (white arrows) at the lower edge of the pulmonary vein ostium. The middle arrow is directed towards a lesion causing haemorrhagic necrosis. E.
Microscopic pathology of ablation lesion near the ostium of the right superior pulmonary vein (2x), showing severe transmural myocardial damage and haemorrhage (arrow), with linear bands of coagulation necrosis (arrow heads) at respective cardiac surfaces. F. Example of the impact of ablation on electrogram amplitude in the left atrium. Ablation leads to loss of local signal amplitude.

**Figure 4.** A. SSFP-coronal- Ablation catheter visualised at the cavotricuspid isthmus. B. Macroscopic pathology showing cavotricuspid isthmus ablation (CTI, white arrow) at the tricuspid valve annulus between right atrium and right ventricle. C. Late gadolinium enhancement image in left ventricle (*) adjacent to the CTI and RV septum, showing myocardial injury (white arrow) with gadolinium-DTPA enhanced T1-weighted imaging (inversion-recovery gradient echo pulse sequence). Ablation catheter is seen (#).
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1. MRI ablation catheter construction details

The catheters used a composite shaft comprised of various extrusions, polymer braiding and a polymer pull-wire to provide unidirectional deflection and steerability. Electrode wires utilized reactive filtering to eliminate RF induced heating by providing a high impedance at 64MHz and eliminating resonance association with insertion depth. Additionally, the ablation catheter had open loop irrigation and tip temperature sensing capability. The catheters used in the study included specialized filtering designed to reduce RF heating at the tip and ring electrodes to less than 2 degrees C when testing in a phantom under worst case conditions. The catheters have previously been tested in a phantom compliant to ASTM 2182-02a modified to include ports allowing for testing of multiple catheters over the full range of possible catheter insertion depths. The irrigation lumen of the catheter runs the entire length of the catheter and connects to an external irrigation pump through a hub in the catheter handle.

2. MRI image acquisition parameters

Black blood (HASTE) images were performed in the axial and coronal planes (6mm slices, no gap) to provide full coverage of the heart. Steady state free precession (SSFP) non-breath-hold images (echo time, 1.35 ms; repetition time, 2.69 ms; flip angle, 70°; slice thickness, 5 to 8 mm; matrix, 168 X 256) were repeatedly acquired to guide the catheter to the target region using passive catheter tracking. Markers in the catheter (Figure 1D) were used to ensure adequate visualization of the catheter at the cavitricuspid isthmus (CTI), pulmonary veins and left atrium with follow up imaging performed after manipulation of the catheter. Steady state free precession cine imaging in three LV long axis planes, (horizontal long axis (HLA), vertical long axis (VLA)
and left ventricular outflow tract (LVOT)) and short axis planes (from base to apex) were acquired. This was followed by atrial cines (6mm slice, 0 mm gap). The sequence parameters were: echo time, 1.35 ms; repetition time, 2.69 ms; flip angle, 70°; slice thickness, 6 mm; no slice gap, matrix, 150 X 256. All cine images were performed during breath-hold by apnea ventilation setting and with retrospective ECG gating. Lesion visualization was performed using both non-contrast (T2W imaging) and contrast enhanced imaging. To detect myocardial edema following ablation, T2W turbo spin echo imaging was performed during breath-hold with prospective ECG gating with the following parameters: TR 800 ms, TE 60ms, matrix 160 X 256, and slice thickness 5.0 mm. 0.1mmol/Kg Gadolinium-DTPA was injected between 15 minutes and 60 minutes after ablation, and imaging thereafter was performed at different time points after administration of the contrast agent (5 to 60 minutes). We used an inversion-recovery gradient echo sequence as previously described1. Inversion times were adjusted to null normal myocardium (typically 320 to 400 ms; pixel size, 1.7 X 1.4 mm). In all cases, imaging was repeated for each short-axis image in 2 separate phase-encoding directions to exclude artefact. Late gadolinium enhancement was deemed to be present only when the area of signal enhancement could be seen in both phase-swapped images and a cross-cut long-axis image.
Map of MRI room layout

Map of MRI room

The layout of the MRI room is shown in the map above.

a. Ventilator, with tubing connected to the head of the animal passed through waveguide 1

b. Screens showing CMR images, and EP recordings. These were conventional monitors located outside the 5 gauss line.

c. MRI machine

d. Bridge electrophysiologic recording system, which was connected externally to the PC/monitor in the control room via cabling passing through the waveguide

e. RF generator and Irrigation pump

f. Monitor for Bridge electrophysiologic recording system
g. MRI imaging controls and operator

4. MRI induced heating

The catheters used in the study included specialized filtering designed to reduce RF heating at the tip and ring electrodes to less than 2 degrees C when testing in a phantom under worst case conditions. The catheters were tested in a phantom compliant to ASTM 2182-02a modified to include ports allowing for testing of multiple catheters over the full range of possible catheter insertion depths. The phantom was centered in the bore with the landmark located at the center of the phantom. The test media had a conductivity of 5.0 mS/cm ±5%. To ensure that the catheter was exposed to the maximum incident fields for all tests, the catheter was placed no more than 4cm from the wall of the phantom. The reported testing was performed using a balanced turbo field echo sequence with a reported SAR of 4.0W/kg on an Achieva 1.5T MRI system (Philips Healthcare, Best, The Netherlands). The figure below shows the maximum temperature rise measured for a sample of 10 catheters.
5. Bidirectional Block Across CTI

Schematic showing the procedure used to assess bidirectional block at the CTI in the MRI scanner. A 4-pole catheter was positioned in the lateral right atrium. After complete isthmus block was achieved, an activation detour is demonstrated along the lateral right atrium with proximal to distal activation timing during CS pacing (A). The catheter was then placed on the CTI line. During septal pacing, contiguous double potentials are observed on-line due to 2 opposing wavefronts (B). Differential pacing was performed. During pacing from the low right atrium adjacent to the line (C, upper panel), delay to the CS catheter was longer, than pacing more lateral to the line (C, lower panel).
5A Activation detour

5B On line double potentials

5C Differential pacing

SVC
IVC
CS
Movie Legends:

Movie 1 – Oblique sagittal view. The right superior pulmonary vein catheter is scene ascending upwards and into the RSPV.

Movie 2 – Coronal view. The coronary sinus catheter is scene descending on the left inferiorly and into the coronary sinus os. The ablation catheter can be scene ascending upwards, and crossing the the interatrial septum. The image demonstrates the motion of the catheter in and out of the imaging plane during image acquisition.

References:
