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Acute Cardiac MRI Assessment of Radiofrequency Ablation Lesions for Pediatric Ventricular Arrhythmia: Feasibility and Clinical Correlation

Elena K. Grant, MBChB[1,2], **Charles I. Berul, MD**[1], **Russell R. Cross, MD**[1], **Jeffrey P. Moak, MD**[1], **Karin S. Hamann, RNC**[1], **Kohei Sumihara, RCIS**[1], **Ileen Cronin, FNP**[1], **Kendall J. O'Brien, BA**[1], **Kanishka Ratnayaka, MD**[2,3], **Michael S. Hansen, PhD**[1,2], **Peter Kellman, PhD**[1,2], and **Laura J. Olivieri, MD**[1]

[1]Department of Cardiology, Children's National Health System, 111 Michigan Avenue NW, Washington, DC, USA

[2]Division of Intramural Research, Cardiovascular and Pulmonary Branch, National Heart Lung and Blood Institute, National Institutes of Health, Building 10, Room 2c713, MSC 1538, Bethesda, MD 20892-1538, USA

[3]Department of Cardiology, Rady Children's Hospital, 3020 Children's Way, San Diego, CA 92123, USA

Abstract

Background—Arrhythmia ablation with current techniques is not universally successful. Inadequate ablation lesion formation may be responsible for some arrhythmia recurrences. Peri-procedural visualization of ablation lesions may identify inadequate lesions and gaps to guide further ablation and reduce risk of arrhythmia recurrence.

Methods—This feasibility study assessed acute post-procedure ablation lesions by MRI, and correlated these findings with clinical outcomes. Ten pediatric patients who underwent ventricular tachycardia ablation were transferred immediately post-ablation to a 1.5T MRI scanner and late gadolinium enhancement (LGE) imaging was performed to characterize ablation lesions. Immediate and mid-term arrhythmia recurrences were assessed.

Results—Patient characteristics include median age 14 years (1 – 18 years), median weight 52 kg (11 – 81kg), normal cardiac anatomy (n = 6), d-transposition of great arteries post arterial switch repair (n = 2), anomalous coronary artery origin post repair (n = 1), and cardiac rhabdomyoma (n = 1). All patients underwent radiofrequency catheter ablation of ventricular arrhythmia with acute procedural success. LGE was identified at the reported ablation site in 9/10 patients, all arrhythmia-free at median 7 months follow-up. LGE was not visible in 1 patient who

Corresponding author: Elena Grant, MBChB, Children's National Health System – Cardiology, 111 Michigan Avenue NW Washington District of Columbia 20010, United States, T: 202-476-2020 F: 202-476-5000,; elena.grant@nih.gov, egrant@childrensnational.org.

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had recurrence of frequent premature ventricular contractions within 2 hours, confirmed on Holter at 1 and 21 months post-procedure.

Conclusions—Ventricular ablation lesion visibility by MRI in the acute post-procedure setting is feasible. Lesions identifiable with MRI may correlate with clinical outcomes. Acute MRI identification of gaps or inadequate lesions may provide the unique temporal opportunity for additional ablation therapy to decrease arrhythmia recurrence.

Keywords

congenital heart disease; magnetic resonance imaging; arrhythmia; electrophysiology; ablation

Background

While transcatheter therapies have revolutionized management of ventricular arrhythmias, radiofrequency (RF) catheter ablation is not 100% successful and there is still a significant risk of arrhythmia recurrence. Intra-procedural assessment of adequate ablation lesion creation is currently performed via indirect measures, including termination of arrhythmia, changes in the intracardiac electrogram, measurements of impedance, power delivered and catheter tip thermal changes. Despite these outcome measures, the recurrence risk following acutely-successful ablation of ventricular arrhythmia in the pediatric population is still reported as 8–20%.[1–3] Peri-procedural visualization of the affected tissue may help to identify inadequate lesions or gaps in a planned lesion set, which could potentially be used to guide further ablation and reduce risk of arrhythmia recurrence. Preclinical studies have demonstrated that acute arrhythmia ablation lesions can be visualized by cardiac magnetic resonance imaging (CMR).[4–8] There have been limited clinical reports of acute ablation lesion imaging using CMR in adults, though these reports mainly focused on assessment of atrial lesions[9–13] or late CMR assessment of ventricular lesions.[14] There is no published data on CMR assessment of ablation lesions in children or patients with congenital heart disease.

Diagnostic CMR imaging in children generally requires higher temporal and spatial resolution compared with adults given their smaller hearts and faster heart rates.[15] Presence and conspicuity of acute ventricular tachycardia ablation lesions has thus far not been demonstrated. This pilot study therefore aimed to determine whether acute ventricular ablation lesions can be visualized by CMR in the pediatric population, and whether CMR lesion presence correlates with clinical outcomes.

Methods

With IRB approval, and informed consent and assent, where appropriate, consecutive patients referred to the Children’s National Health System electrophysiology laboratory for an electrophysiology study with potential for ablation of ventricular tachycardia were prospectively enrolled. Pre-ablation CMR, when available for clinical purposes, was reviewed for presence of any pre-existing scar.

Standard electrophysiology study and radiofrequency ablation procedures were performed with a 3D electroanatomic mapping system (CARTO-3, Biosense Webster, Diamond Bar, CA, USA) in a unique interventional cardiac magnetic resonance suite, allowing patients to slide from the fluoroscopy room to the CMR room without interruption of anesthesia or need for transfer off the bed. Patients were transferred from the fluoroscopy portion of the interventional CMR suite to a 1.5 Tesla MRI scanner (Siemens Healthcare, Erlangen, Germany) for immediate post-procedural CMR imaging. Per the IRB limit on additional sedation based on available evidence[16], a maximum of 30 minutes additional sedation time was available for post-ablation CMR. Following 0.15 mmol/kg intravenous gadolinium injection, each patient underwent rapid late gadolinium enhancement (LGE) imaging during free breathing under sedation using a previously described motion-corrected, single shot sequence.[17, 18] Continuous stacks of LGE images were obtained in two planes to localize and measure the LGE in the affected ventricle. Each CMR image set was analyzed by two pediatric cardiologists expert in interpretation of CMR, blinded to location of the ablation lesion site(s). Evidence of ablation lesion by CMR was defined as per preclinical description of new late gadolinium enhancement at the predicted ablation lesion location.[4] Some patients in this study underwent additional imaging sequences for technical development of optimal acute post-ablation CMR imaging to increase likelihood of lesion identification using a novel dark blood imaging protocol using T2 prep between the IR preparation and readout allowing nulling of both myocardium and blood to increase contrast of the ablation lesion.[19]

Patients were followed at standard clinical intervals for arrhythmia recurrence including obtaining a symptom history, physical, a 12-lead electrocardiogram and 24-hour Holter monitor one month post-procedure.

Results

Between 11/2014 and 12/2015, 10 patients underwent ablation of ventricular tachycardia or frequent premature ventricular contractions with post-ablation LGE imaging, summarized in table 1 and imaging findings available in the Supplemental Figure. The 10 patients were aged 1.8 to 18 years; 6 patients had normal cardiac anatomy, 2 had D-transposition of the great arteries status post arterial switch procedure, 1 had an anomalous origin of the coronary artery status post coronary unroofing procedure, and 1 had tuberous sclerosis associated cardiac rhabdomyomas. There were no MRI or anesthesia related adverse safety events. Nine patients had clinically indicated pre-ablation CMR, and none had evidence of pre-ablation LGE. Arrhythmia was reported to have limited the technical quality of 5/9 of these studies precluding accurate assessment of cardiac function and chamber volume which rely on precise ECG-gating. No patients required additional pharmacologic therapy to obtain rate or rhythm control for adequate imaging to identify LGE using a single shot, motion-corrected SSFP technique[18] which has a high success rate for LGE imaging in the setting of ectopic beats as long as the coupling interval is adequate to allow for image acquisition, on the order of 400 ms.

During the electrophysiology procedure, the arrhythmogenic substrate was identified by a combination of activation and automated pace mapping using the PaSo system (Biosense

Webster, Diamond Bar, CA, USA) in 9 patients with intra-procedural ventricular tachycardia (VT) and by localization of an abnormal left ventricular potential in 1 patient without intra-procedural spontaneous or inducible arrhythmia. Table 1 summarizes clinical characteristics, electrophysiology study findings and ablation parameters for the cohort. All patients underwent radiofrequency ablation; 4 patients underwent ablation with a standard radiofrequency ablation catheter, and 6 patients underwent ablation with a continuously-irrigated radiofrequency ablation catheter. The number of lesions per patient was 17.2 +/− 9.6, range 8 to 42. Acute procedural success, as defined by termination of the arrhythmia without recurrence in 30 minutes, was attained in all 10 patients.

CMR LGE was performed between 30 and 60 minutes following the application of the final ablation lesion, depending on time of overall electrophysiology procedure termination. All patients were in sinus rhythm without pharmacologic rate or rhythm control at the time of post-ablation CMR LGE. As exemplified in Figure 1, a new region of subendocardial LGE was identified on CMR LGE imaging at the reported ablation site in 9/10 patients. In patients who underwent additional research imaging, the novel dark blood imaging protocol[19] increased contrast of the ablation lesion site making the lesion easier to identify as illustrated in Figures 1 and 2. In one of the 10 patients (Supplemental Figure: case 5) there was no ventricular late enhancement seen despite successful termination of intra-procedural arrhythmia with radiofrequency ablation. CMR sternal wire artifact did not interfere with lesion identification in the three patients who had previously undergone cardiac surgery for congenital heart disease. As shown in Figure 2, one patient with a visible ablation lesion returned for repeat research CMR during the follow up period with persistence of LGE at the reported ablation site one month post-ablation.

The 9 patients with CMR identifiable lesions were arrhythmia- and symptom-free at median 7 months post ablation (range 1–20 months). The patient in whom a lesion could not be identified by CMR had early recurrence of frequent premature ventricular contractions within 2 hours post-procedure, confirmed on Holter monitoring one month later and at last follow up 21 months post-procedure.

Discussion

We chose to study ventricular arrhythmia ablation lesions in the pediatric population given the relatively high risk of life-threatening ventricular arrhythmia recurrence following ablation[1–3], the hypothesis that acute confirmation of a visible CMR LGE lesion at the ablation site may correlate with arrhythmia recurrence risk and the lack of other studies of this type in the pediatric age range. This pilot feasibility study is the first to demonstrate that acute ventricular radiofrequency ablation lesions can be visualized by CMR with LGE imaging in children immediately following ablation with various types of ablation methods (standard and irrigated tip RF ablation catheters). Our imaging findings are keeping with the expected time course of CMR ablation lesion development and appearance described in preclinical studies[4–6]. Given that there was no LGE identified on pre-procedure CMR in the 9 patients who had studies performed, we believe the LGE identified post-procedure in the region of the reported ablation site was appropriately attributed to the ablation lesion. Despite the challenges of higher temporal and spatial resolution required for pediatric CMR,

LGE was identifiable at the reported ablation site in the 9 patients who had successful ablation without arrhythmia recurrence. Transfer to MRI immediately post ablation and the additional sedation time required for imaging (on the range of 20–25 minutes) were not associated with any adverse safety outcomes.

There was no identifiable ablation lesion on CMR LGE imaging in the only patient who had early recurrence of arrhythmia, leading us to speculate that there is a possible correlation between lesion visibility with CMR, and arrhythmia recurrence risk. As detailed in table 1, there were no specific alterations to the standard electrophysiology procedure that would explain absence of CMR LGE for the patient with arrhythmia recurrence (case 5). Our study is obviously limited by the number of patients and further studies are necessary to verify clinical correlation of acute ablation lesion CMR appearance before considering applying post-ablation CMR to routine clinical practice. If the findings are confirmed through larger studies, acute post-ablation CMR could be used to ensure adequate ablation lesion creation by guiding targeted ablation of lesion gaps or extension of lesion depth. Similar studies have been performed in adults post atrial fibrillation ablation with CMR scar quantification results suggesting that poor scar formation correlates with risk of atrial fibrillation arrhythmia recurrence.[20,21]

During the imaging protocol, CMR lesion identification was partially guided by knowledge of the ablation site, allowing for specific site imaging in orthogonal planes. In cases with discrepancy between reported ablation site and actual ablation site, lesions may be difficult to identify by CMR. Even with knowledge of the likely ablation lesion location, the selected CMR orthogonal planes may not capture the lesion in all planes due to size discrepancy between CMR slice thickness (usually about 10 mm) and ablation lesion (usually about 4–6 mm). In-plane image resolution for the single shot motion-corrected LGE technique is adequate to characterize lesions within the imaging plane, but lesions may be missed between imaging planes. As lesions may only be partially captured within the constraints of selected imaging planes and slice thickness, they cannot be reliably quantified in terms of a percentage or even depth of the substrate tissue. Lesion conspicuity may also be dependent on tissue type and thickness. CMR is used in clinical practice to identify ventricular lesions including myocarditis and myocardial infarction, though is less commonly employed for study of the atria or other thin walled cardiac structures, which have a different tissue profile with increased challenges in differentiating tissue and lesion boundaries from the surrounding blood pool[19]. Therefore, our findings in ventricular ablation lesions may not necessarily be applicable to atrial ablation lesions. With further optimization of imaging protocols we hope to continue this study in pediatric patients undergoing atrial arrhythmia ablation. The novel dark blood imaging protocol increased conspicuity of the ablation lesions in this study as illustrated in Figure 2. One could hypothesize that this type of dark blood imaging protocol could potentially add to the sensitivity of CMR ablation lesion detection compared to more traditional LGE bright blood techniques. Of course, a major limitation of using CMR or any other imaging modality determining lesion visibility to confirm adequate lesion creation is that ablation in any location that is not at the origin of arrhythmia may result in a visible lesion but will not correlate with successful arrhythmia treatment.

The 30-minute limit for additional sedation time including patient transfer to MRI and research imaging necessitated prioritization of LGE in the imaging protocol and limited time for additional sequences to identify and quantify edema and fibrosis, such as T2-weighted imaging and T1 native contrast. [9, 12, 22] The results of follow-up imaging for 1 patient (Figure 3) with a visible acute ablation lesion persisting at 1 month follow-up imaging in our study suggest that the acute LGE CMR may correlate with permanent tissue injury rather than simply acute edema. While CMR imaging at a time point beyond the acute post-ablation period may more accurately identify ablation scar as opposed to temporary edematous changes, the need for an additional sedation in young children is avoided by acute post-procedure imaging. In addition, the temporal nature of immediate post-ablation imaging may provide the opportunity for identification of inadequate lesions allowing for lesion modification to reinforce ablation lines of block or inadequate ablated tissue during the same sedation procedure. This may reduce the chance of needing repeat ablation attempts for arrhythmia recurrence. Ultimately with the advent of technology for real-time MRI-guided atrial arrhythmia ablation currently being trialed in adults[23–25], the finding that acute ventricular ablation lesions are visible by CMR in the pediatric population may be of tremendous importance if real-time MRI guided technology proves to be feasible and efficacious.

Other imaging modalities have been studied for identification of acute arrhythmia ablation lesions including intracardiac echocardiography[26] and optical coherence tomography,[27] which has higher axial resolution than MRI and are not adversely affected by arrhythmia, though these techniques usually rely on fluoroscopic guidance for catheter manipulation especially in the pediatric population. Despite the aforementioned resolution challenges associated with CMR in the pediatric and arrhythmia populations we believe that it is still may be the imaging modality of choice for identification of acute ablation lesions. Children are particularly susceptible to effects of ionizing radiation and patients with congenital heart disease who have increased lifetime cumulative radiation exposure risk;[28] therefore, any adjunctive imaging technology for electrophysiology procedures should ideally be radiation sparing.

Conclusion

Acute ventricular radiofrequency ablation lesions can be visualized by CMR in the pediatric population with LGE imaging techniques. CMR lesion appearance may correlate with clinical outcomes and therefore may be useful to predict arrhythmia recurrence risk. Ablation lesion LGE could guide further fluoroscopic and 3D electroanatomic mapping ablation procedures, and in the future real-time MRI guided ablation. Further study will determine reproducibility of these results and optimize imaging protocols to increase resolution, decrease scan time and definitively distinguish edema from long-term scar.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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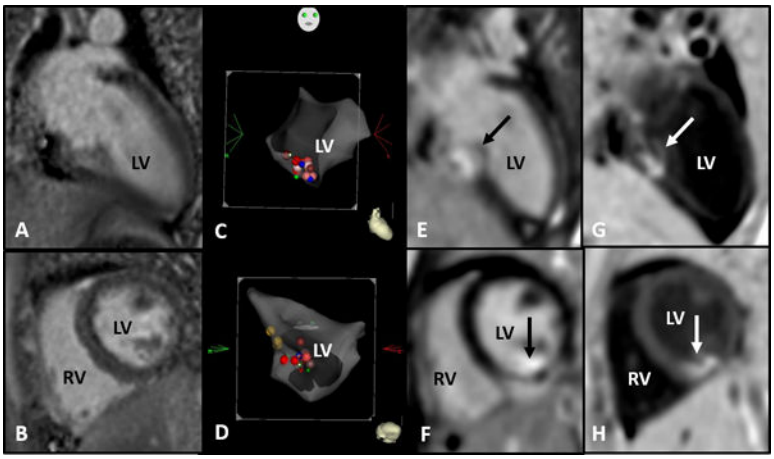

Figure 1.

(Case 2) Two-year-old male with normal cardiac anatomy and history of ventricular tachycardia. Radiofrequency ablation performed at the mid-septal left ventricle with pre- and post- ablation cardiac MRI. Abbreviations: RV, right ventricle; LV left ventricle.

a&b. Baseline cardiac MRI with no late gadolinium enhancement in long axis (a) and short axis (b)

c&d. 3D electroanatomic map, long axis (c) and short axis (d) with red and pink dots indicating ablation lesion sites in the mid-septal left ventricle

e&f. Immediate post-ablation cardiac MRI with late gadolinium enhancement (black arrows) corresponding to the reported ablation lesion site in the long axis (e) and short axis (f)

g&h. Dark blood shows late gadolinium enhancement (white arrow) with increased contrast between the blood pool, soft tissue and the ablation lesion in the long axis (g) and short axis (h)

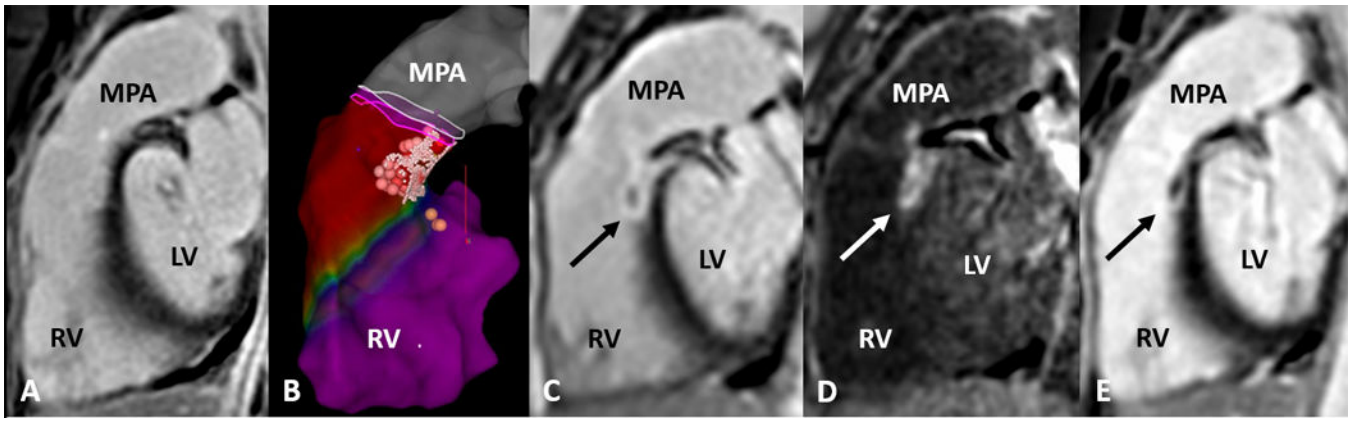

Figure 2.

(Case 10) Eighteen-year-old female with normal cardiac anatomy and history of ventricular tachycardia. Radiofrequency ablation performed at the post-septal right ventricular outflow tract with pre- and post-ablation cardiac MRI. Abbreviations: MPA, main pulmonary artery; RV, right ventricle; LV left ventricle.

a. Baseline cardiac MRI, sagittal right ventricular outflow tract view, with no late gadolinium enhancement

b. 3D electroanatomic map with red and pink dots indicating ablation lesion sites and yellow dots indicated the bundle of His location

c. Immediate post-ablation late gadolinium enhancement (black arrow) corresponding to the reported ablation lesion site

d. Dark blood shows late gadolinium enhancement (white arrow) with increased contrast between the blood pool, soft tissue and the ablation lesion

e. Late gadolinium enhancement (black arrow) still present on follow up imaging one month post ablation

Table 1

Case	Age (years)	Cardiac Anatomy	Pre-procedure arrhythmia	Arrhythmia during electrophysiology case	Mapping Type	Ablation site	Catheter tip (mm)	Irrigated	Number of RF ablation lesions	Post-ablation CMR LGE visible	Arrhythmia recurrence at last follow up
1	1.8	D-TGA s/p arterial switch	VT	PVCs	Activation & PaSo	Anterior RVOT	4	No	10	Yes	No
2	2	Normal	VT	VT	PaSo	Mid-septal LV	4	No	8	Yes	No
3	5	D-TGA s/p arterial switch	VT	VT	Activation & PaSo	High septal RVOT	4	Yes	17	Yes	No
4	11	Normal	VT	PVCs	Activation & PaSo	RV inflow	3.5	Yes	42	Yes	No
5	13	Normal	VT	PVCs	Activation & PaSo	Anterior septal RVOT	3.5	No	11	**No**	**Yes**
6	14	Cardiac rhabdomyomas	VT	PVCs	PaSo	Posterior septal LV	3.5	Yes	13	Yes	No
7	15	Normal	VT	PVCs	Activation & PaSo	Anterior RV	4	No	15	Yes	No
8	16	Normal	VT	None	PaSo with finding of abnormal diastolic potentials	LV apex	3.5	Yes	27	Yes	No
9	17	s/p Unroofing of RCA arising from the left sinus of Valsava	Frequent PVCs	PVCs	Activation & PaSo	RVOT and right aortic cusp	3.5	Yes	16	Yes	No
10	18	Normal	VT	PVCs	Activation and PaSo	Septal RVOT	3.5	Yes	13	Yes	No

Abbreviations: CMR, cardiac magnetic resonance; LGE, late gadolinium enhancement; D-TGA, D-transposition of the great arteries; RCA, right coronary artery; VT, ventricular tachycardia; PVCs, premature ventricular contractions; PaSo (PaSo Module of CARTO system; Biosense Webster, Diamond Bar, CA, USA); RV, right ventricle; LV, left ventricle; RVOT, right ventricular outflow tract