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Characterization of Acute and Subacute Radiofrequency Ablation Lesions with Non-enhanced Magnetic Resonance Imaging

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Abstract

Background—MRI has the potential to visualize radiofrequency ablations (RFA), which have become the preferred treatment strategy for many arrhythmias. However, MRI patterns after RFA have not been well investigated.

Objective—This study sought to define the characteristic appearance and the effect of time and energy on non-contrast-enhanced MR imaging of RFA.

Methods—Using a power-controlled, cooled tip ablation system, RFA (5W–50W for 45s) were created on the right ventricular epicardium in 10 mongrel dogs. T1- and T2-weighted MR images were obtained during a 12-hours follow-up and compared to gross anatomy and histopathology.

Results—Lesions were successfully visualized with T2- and T1-weighted images 30min to 12 hours after RFA. T2 images were more consistent and displayed a characteristic elliptical, high-signal core (Contrast-to-noise-ratio [CNR] = 18.9 ± 8.4) with a surrounding 0.5 mm low-intensity rim, which corresponded on histopathology to the central tissue necrosis and the transition zone, respectively. T1 images showed a less remarked increase in signal intensity (CNR = 9.6 ± 7.4) without surrounding rim. Lesion size and appearance were well defined and unchanged during the 12 hours follow-up (ANOVA). CNR was independent of applied RF energy and allowed accurate assessment of the RFA at all time points ($r=0.87$ and $r=0.83$ for T2/T1 images, respectively). Transmural lesions, interlesional gaps and intralesional pathology could be reliably predicted in >90%.

Conclusion—Non-contrast-enhanced MRI allows accurate assessment of RFA and its intra-lesional pathology during a 12h follow-up. This confirms a possible role for MRI in guiding and evaluating RF application during electrophysiological ablation procedures.

CONDENSED ABSTRACT—MRI can visualize heat-induced tissue damage and its associated histological changes such as interstitial edema or protein necrosis through changes in T1- and T2-relaxation parameters. This study demonstrates that the characteristics of radiofrequency ablations can be reliably assessed in acute and subacute RF lesions. This may allow a novel use of MRI to guide and improve complex clinical ablation procedures allowing peri-procedural assessment and potentially real-time MR guidance.

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Keywords

Catheter ablation; magnetic resonance imaging; ablation lesion; electrophysiology; arrhythmia

INTRODUCTION

Over the last two decades radiofrequency ablation (RFA) has become the first line therapy for many cardiac arrhythmias including atrioventricular nodal reentrant tachycardia, atrial flutter, and accessory pathway mediated arrhythmias.[5]

As ablation protocols have become increasingly complex and anatomically based such as for ablation of atrial fibrillation and non-mappable ventricular tachycardia[13;18], the need for newer imaging technology, which can assess the anatomic location and extent of the ablation lesion became evident.[11;18] However, the currently used guiding tools such as fluoroscopy and 3-D-mapping devices are limited in their ability to confirm the exact location, presence, and extent of ablation lesions, which are indicators of the procedural success.[18;22]

While over the last 10 years cardiac magnetic resonance imaging (MRI) has evolved as a standard diagnostic tool in the evaluation of ischemic heart disease[7;9] and has been successfully used to guide cardiac interventions, such as right heart catheterization,[19] its application in electrophysiology has been very limited. As heat-related changes in T1-and T2 parameters should allow to visualize the location and extent of ablation lesions within the myocardium[11] MRI has the potential to guide RF ablation, evaluate treatment progress, and reduce radiation exposure. Therefore, the purpose of the study was to establish the role of non-contrast enhanced MR imaging in the assessment of acute and subacute RF lesions.

METHODS

Animal Preparation

Ten mongrel dogs (35 to 40 kg) were injected with 10mg of ketamine i.m. and maintained on 1–2% isoflurane gas (Narkomed Draegar, Telford, Pennsylvania). End-tidal CO₂ as well as ECG leads I, II, and III were monitored throughout the experiment. Vascular access was obtained by percutaneous puncture or cutdown of the right jugular vein. Midline thoracotomy was performed with clinical grade surgical equipment and the pericardium removed. Using a 4mm tip, 7F ablation catheter with an open irrigation system (0.9% normal saline at a flow rate of 5ml/min) single RF lesions were created along the epicardial surface of the right ventricle (RV) using a clinical RF generator (Atakr, Medtronic, Minneapolis, Minnesota). Ablation lesions were created in a linear interrupted fashion using a power-controlled mode at 5, 10, 20, 30, 40 and 50W for 45s each. All ablation sites were at >2.5cm distance to any epicardial fat deposits. After the ablation the animals were closely monitored hemodynamically and the live animals were transported to the MRI scanner without closing the thoracotomy. All animal protocols were reviewed and approved by the Animal Care and Use Committee at the Johns Hopkins University and conformed to the guidelines published in the “Position of the American Heart Association on Research Animal Use”.

Imaging Protocol

MR imaging was performed with a 1.5 Tesla MR scanner (Signa XL, GE, Waukesha, Wisconsin) using a standard surface phase-array coil. First, the correct imaging plane of the ablation lesions was identified with standard T1 and T2-weighted scout images. Continuous long-axis images were obtained in the area of RF ablations with a 3mm slice thickness at 30min, 1h, 2h, 3h, 4h, 5h, 6h and 12h after RFA with a T2-weighted fast spin-echo (FSE) sequence

(TR=1200ms, TE=68ms, echo train length=32, field of view=18cm, readout bandwidth=62.5kHz, 512x256 matrix, nexus=5, slice thickness=3mm). For comparison, imaging was repeated using an intrathoracic, 3-inch high-resolution coil, which was placed directly over the RV wall.

Similarly, T1-weighted images were acquired along this slice prescription at the same time intervals using a spoiled gradient recall acquisition (SPGR) protocol (TR=9ms, TE=4.3ms, readout bandwidth=31.25kHz, field of view=20cm, 256x192 matrix, flip angle=20°, nexus=1, slice thickness=3mm). Animals were monitored and alive during all follow-up imaging sequences. All images were visually inspected to rule out the presence of susceptibility artifacts caused by the air-tissue interface of the open chest preparation.

Postmortem Examination

After the experiment, the animals were sacrificed with an intravenous injection of 3molar KCL-solution, the hearts were excised and sectioned through the right ventricular lesions into slices corresponding to the tomographic MR images. Lesion size, diameter, location, morphology, and transmural extent were measured at autopsy and photographed for later comparison with the MR images. Histological staining with Masson's trichrome and hematoxylin-eosin was performed on sections of the thermally damaged tissues and analyzed for global morphological changes using light microscopy.

Data Analysis

Using an off-line quantitative analysis package (version 1.53; e-film, Merge Technology, Milwaukee, Wisconsin) lesion size, characteristics, and signal intensity were measured directly from the corresponding MR images. The signal-to-noise ratio (SNR) was calculated as the signal intensity (SI) of the lesion divided by the standard deviation (SD) of the background noise. The contrast-to-noise ratio (CNR) was measured as the SI of lesion minus the SI of the adjacent myocardium over the SD of the background noise.

Lesion parameters at gross examination were measured independently of MR lesions parameters and compared.

Statistical Analysis

Changes in lesion size, signal intensity, and heterogeneity during the time course were analyzed and compared between the various energy groups. Differences were considered significant at a level of $p < 0.05$ in a paired t-test (analysis of variance [ANOVA]). Comparisons of the pathological specimens and the ablation lesions assessed by MRI were performed using linear regression after an adjusted analysis with a generalized estimating equation approach (GEE) to control for a potential cluster effect. P-values of $p < 0.05$ were considered statistical significant. Unless noted otherwise, results are reported as arithmetic mean $\pm$ SD.

RESULTS

Lesion characteristics and lesion size

In T2-weighted images the lesions appeared as conus- or oval-shaped areas of high signal intensity (signal-to-noise ratio [SNR] 73.4 ± 29.6), which were well demarcated compared to the surrounding myocardium (contrast-to-noise ratio [CNR] of 18.9 ± 8.4). Identification was further facilitated by the existence of a small rim of low signal intensity (~ 0.5 mm wide) in $>80\%$ of the lesions (Figure 1). In the pathological specimen the center with increased signal corresponded to a macroscopically darker inner zone demonstrating coagulation necrosis and an adjacent lighter zone displaying contraction band necrosis. The low intensity rim seen on MRI correlated to a macroscopically small and darker outward rim that showed interstitial

edema and hemorrhage. Lesion size as assessed with MRI increased with the amount of RF energy applied and correlated well with the tissue specimen ($r=0.87$, $p<0.05$; Figure 3). T2-weighted images overestimated the lesion size by $0.2 \pm 1.5\text{mm}$.

In T1-weighted images RF lesions had a similar cone- or oval-like shape. They appeared as areas of high signal intensity compared to the adjacent myocardium ($\text{SNR } 34.5 \pm 26.0$), but image quality was less consistent than in the T2-weighted images (Figure 2). The ablation lesions showed a CNR of 9.6 ± 7.4 compared to the adjacent myocardium. This high signal area corresponded to the two central concentric zones on the pathological specimen with coagulation- and contractionband necrosis. No surrounding rim of low density was seen using the T1 protocols. The lesion size on T1-weighted MR images correlated well with the gross specimen ($r=0.83$, $p<0.05$; Figure 3). Using the SPGR imaging protocol the lesion size was underestimated by $1.1 \pm 1.4\text{mm}$.

Slice acquisition in T2-weighted protocols required more time (32s vs. 13s, $p<0.01$), but the higher CNR allowed a better and more consistent visualization in the individual experiments.

Use of the 3-inch high-resolution MR coil increased the SNR by 46% to 107.5 ± 45.7 ($p<0.001$) and the CNR by 44% to 27.3 ± 20.7 ($p<0.001$) in the T2-weighted images. During the T1-weighted protocols SNR and CNR increased by 42% and 44% to 48.9 ± 22.8 and 13.8 ± 10.6 , respectively ($p<0.001$). No changes in imaging characteristics or lesion size were seen when comparing the standard surface phase-array coil and the intrathoracic high-resolution coil.

Time-course

Over the course of the 12h follow-up the typical appearance of the RF lesions in T2-weighted images remained unchanged displaying a core of high-signal intensity and an adjacent low-intensity rim (Figure 1). The CNR and SNR decreased non-significantly to 17.4 ± 12.4 (-7.9%) and 68.8 ± 35.9 (-6.2%), respectively (Figure 4). RF lesion size on the MRI did not significantly change over the time-course (Figure 5; ANOVA $p=\text{n.s.}$).

Similar observations were made for the T1-weighted sequences. The characteristic appearance of RF lesions did not change (Figure 2) and assessment of the lesion size did not vary significantly during the follow-up (Figure 5; ANOVA $p=\text{n.s.}$). However, the SNR decreased to 29.6 (-14%) and CNR diminished to 8.1 (-16%), which represented a non-significant trend with $p=0.08$ and $p=0.06$, respectively (Figure 4).

Energy-dependency and intralesional pathology

As expected the RF lesion size increased with the amount of applied RF energy ($p<0.05$) (Figure 5). However, the SNR and CNR within the RF lesion did not depend on the energy used to create the lesion in either the T2 or T1-weighted protocols (Figure 4; ANOVA, $p=\text{n.s.}$). However, with higher RF energy the lesion appearance became increasingly heterogeneous displaying adjacent areas of high and low signal intensity, which was a significant change in the T2-weighted images and showed a trend for the T1-weighted protocols (Figure 6). Heterogeneous areas corresponded at the pathological and histological examination to regions of necrotic cavity formation and/or intralesional hemorrhage (Figure 7). Location and size of intralesional necrotic cavities correlated well with the pathological specimen and appeared as areas of increased signal intensity in T2 and decreased signal intensity in T1-weighted images.

Assessment of transmural extent or intralesional gaps

Transmural extent was assessed with T2-weighted and T1-weighted images in 39 and 27 RF lesions, respectively. All ten transmural lesions were correctly identified in T2-weighted images, but two non-transmural lesions appeared transmural on the MR image (sensitivity:

100%, specificity: 93%). SPGR images correctly identified all 20 non-transmural lesions, but did not accurately describe two transmural lesions (sensitivity: 71%, specificity: 100%).

29 intralesional gaps were assessed with T2-weighted images, which underestimated the gap by $0.8 \pm 1.3\text{mm}$ compared to the pathological specimen. T1-weighted images were used to evaluate 23 intralesional gaps and overestimated the gap sized by $0.3 \pm 1.9\text{mm}$.

DISCUSSION

Main findings

The findings of this study suggest that 1) RF lesions have a characteristic appearance and can be visualized with non-contrast enhanced MRI over a time course of at least 12 hours using T2- and T1-weighted images; 2) ablation size, intralesional gaps, and degree of transmurality can be predicted using T2- and T1-weighted protocols; 3) CNR is independent of applied energy allowing visualization over a wide energy spectrum; and 4) MRI can successfully visualize changes in intralesional morphology.

Non-contrast enhanced MR Imaging of Cardiac RF Lesions

RF lesions could be visualized with non-contrast enhanced MRI during the entire 12 hours of follow-up. This is due to specific changes in the T1 and T2-relaxation parameters, which result from a variety of heat-induced biophysical changes in cardiac tissue, such as interstitial edema, hyperemia, conformational changes, and tissue coagulation.[11] In T2-weighted images the area of increased signal intensity correlated with the histological picture of coagulation and contraction band necrosis and is predominantly caused by an increase in unbound proteins representing interstitial edema after tissue damage and hyperemic response. While not statistically significant, the decrease of signal intensity at the end of the observation period may indicate a gradual resolution of the edema after the acute phase of injury. Heat-related products of hemoglobin such as deoxyhemoglobin, display a decreased signal intensity in T2-weighted images[12;21] and might be responsible for the low signal-intensity rim frequently observed in the transition zone.

These findings extend the observations of the only previously published study, in which T2-weighted imaging of RF lesions in the right ventricular apex of 6 mongrel dogs were limited to the first ~20min of the acute phase.[11] Ablation lesions could be visualized after 2 minutes and demonstrated a linear increase in signal intensity up to 1.9 ± 0.4 times greater than baseline after $12 \pm 2.1\text{min}$. [11] In the current study T2-weighted MRI allowed to accurately assess the RF lesion size at any time point during the follow-up, which did not significantly change during the course of the study. This is consistent with the findings of Lardo et al., in which the lesion size by MRI ~20min post ablation correlated well with the actual postmortem size.[11]

While two canine series reported MR imaging of ablations using contrast agents like gadolinium[2;11], the current study is the first to evaluate the visualization of RF lesions using T1-weighted, non-contrast-enhanced MRI. This is of interest because imaging times were significantly less when compared to the T2-weighted protocols. Ablations appeared as homogenous areas of increased signal intensity, which correlated well with the pathological lesion size and did not significantly change during the follow-up duration of 12 hours. The increased signal intensity in T1-weighted images likely reflects changes in the T1-relaxation parameters due to configuration changes of the denaturated proteins in the necrotic areas[1] as well as the heat-induced formation of methemoglobin from deoxyhemoglobin.[4] However, CNR was decreased in comparison to the T2-weighted images and image quality was less consistent between individual experiments.

Both imaging protocols were able to accurately assess the transmural extent of the lesions and to identify non-ablated gaps between the ablation lesions, which might be useful for a non-invasively assessment of complex RF lesions. This would be facilitated by the observation that RF energy over a wide range resulted in the same, characteristic appearance in both imaging protocols enabling its use in a wide variety of ablation procedures.

MRI slightly overestimated the pathological lesion size in T2-weighted images. This would be consistent with the hypothesis that the unbound protein in the interstitial edema are responsible for the signal increase as the edema extends beyond the actual necrosis borders in the adjacent, heat-injured, but still viable myocardium.[8] As such, some of the peripheral, ablated tissue visualized with T2-protocols may be able to regain electrical conductivity after the healing process is complete. T1 weighted images, on the other hand, slightly underestimated the lesion size. As the increased signal intensity is likely due to denaturized protein within the ablation lesion, this may more accurately describe the truly necrotic area of the RF lesion.[1] This difference of the imaging protocols was also reflected in the transmural and gap measurements and resulted in either a high sensitivity or specificity, respectively. This raises the intriguing question, if specific MRI protocols might be able to differentiate different histological properties of the myocardium (such as reversible edema vs. permanent necrosis), providing a potential tool to evaluate the procedural success and enabling a future application of “MR histology”.

Already, MRI was able to identify and characterize intralesional pathology in this study. When applying higher energy above 30–40W the creation of necrotic cavities was frequently noted on the pathological specimen, which corresponded to areas of heterogeneous signal intensities on the MRI (Figure 6, 7). With sufficiently high energy delivery, intracellular and interstitial fluid is heated beyond its boiling point resulting in the creation of gas and steam, which can create intramyocardial cavities and may even suddenly evaporate out of the myocardium. This phenomenon has been previously described in ultrasound-guided ablation series as “bubbles formation”[14] and may correlate to occasionally audible “pops” during RF delivery in our experiments. Post-ablation interstitial edema develops leaving these holes fluid-filled.[8]

Consistent with those findings, we found that these intralesional cavities displayed an increased signal intensity in T2-weighted images as the unbound protons in water would be mostly responsible for the increased T2 signal intensity.[6] Correspondingly, we observed in the T1 protocols that those areas appeared as islets of less signal intensity. As the higher T1 signal of the RF lesion is likely due to the denaturized proteins in the ablated area,[1] fluid filled cavities would be expected to display little or less T1 signal.

MR Imaging of non-cardiac RF lesions

Multiple studies have examined the MR imaging characteristics of RF ablations in non-cardiac tissue. However, reports on the appearance of ablation lesions using T1 protocols vary. Naour et al. report a decreased signal intensity of 2h old RF ablations in tongue muscle of 10 swine [16], while Oyama described isodense properties in 69 lung lesions after one day with slight signal increase after 1 week.[17] On the other hand, several other studies report an increased signal intensity,[15;20] which is similarly thought to be due to hemorrhage or a proteinaceous material within the RF lesion.[20] Comparison of the MRI with the pathological preparation demonstrated that T1 images correlated reasonably well with histology ($r=0.69-0.85$).[16; 17]

Different imaging characteristics have also been described for imaging of ablation lesions with T2-weighted studies. Kim et al. described ablations of VX2 carcinomas in rabbit muscle, which appeared as hyperintense on T2-weighted MR images and were surrounded by a 1–2-mm-thick rim of higher signal intensity.[10] In RF treatment of liver cancer Dromain et al. reported that

most of the areas were hypointense on T2-weighted images possibly representing a dehydrating effect of RF-induced thermal damage.[3] However, a marked hyperintensity found in 14% of the successful ablations might have been due to bilomas or liquefying necrosis.[3] Several other studies report the appearance of a low signal center with a high signal border.[15–17] Similarly, T2 images correlated reasonably well with pathology ($r=0.62\text{--}0.83$).[15;16]

MR Imaging of Contrast-Enhanced RF Lesions

Two studies have reported the visualization of RF lesions using delayed enhancement with gadolinium. Lardo et al. reported a hyperenhancement of the ablation site occurring as early as 1min during a 12min follow-up of RF lesions in the right ventricle of 6 mongrel dogs.[11] Lesions correlated well with the pathological lesion size and achieved a signal intensity of 1.55 ± 0.16 times the pre-injection values. In a recent study, we found a characteristic 4-phase enhancement pattern reflecting the prolonged wash-in kinetics of gadolinium.[2] While the CNR allowed to well delineate the ablation lesions, contrast-enhanced imaging was unable to further describe the intralesional pathology. Although the contrast-enhanced area likely represents cell necrosis as well, the post-injection change of T1 and T2 parameters renders a visualization of histological processes, such as edema vs. necrosis unreliable.

Limitations

Several limitations should be considered in regard to this study. While clinical RF lesions are usually delivered endocardially, ablations in this study were created on the epicardium to allow a controlled delivery of a wide range of RF energy and guarantee lesion development. While the macroscopic and histological appearance of the ablation lesions was similar to the lesions described for endocardial ablations[8] and included over 50% of the myocardial wall thickness, differences related to e.g. blood supply and cooling effects cannot be excluded.

Due to the experimental design, which included post-RFA animal transport and scanner setup, the MRI follow-up did not start until 30min after ablation. While previous work has suggested that RF lesions can be visualized already minutes after the ablation in T2-weighted images [11], no experience exists with non-enhanced T1-weighted protocols. However, given that MRI might be used to evaluate the procedural progress of complex and prolonged procedures, a post-procedure imaging time frame of several hours appears realistic.

CONCLUSION

The results of the study demonstrate that acute and subacute RF ablation lesions can be reliably evaluated with non-contrast enhanced MRI. While 3D mapping devices and image integration have been a significant improvement, none of the currently used modality is able to visualize the RF lesions and to potentially allow the assessment of procedural success. As RF ablations have become increasingly complex and anatomically based, such as for ablation of atrial fibrillation or non-ischemic ventricular tachycardia,[13;18] imaging of ablation lesions may shorten the procedure times, increase safety and treatment success. Different MRI protocols might be able to differentiate between acute ablation results due to reversible surrounding edema and long-term success due to tissue necrosis, as well as assess transmural extent, interlesional gaps and intralesional characteristics. With further progress in the emerging field of real-time MR guidance, these assessments could potentially be performed during the ablation procedure.

Additional studies will now have to delineate its clinical applicability in electrophysiology and will possibly open another application of MRI in the field of cardiology.

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ABBREVIATION LIST

MRI	magnet resonance imaging
RFA	radiofrequency ablation
FSE	fast spin-echo
SPGR	spoiled gradient recall acquisition
SNR	Signal-to-Noise Ratio
CNR	Contrast-to-Noise Ratio
KCL	potassium chloride

Figure 1.

Time-course of RF lesions. Shown are 30W, 40W and 50W epicardial ablation lesions after 30min, 1h, 3h, 6h, and 12h of follow-up using T2-weighted MR imaging and the corresponding pathological specimen (EP-epicardium, EN-endocardium, RV-right ventricular wall).

Figure 2.

Time-course of RF lesions. Shown are 30W, 40W and 50W epicardial ablation lesions at 30min, 1h, 3h, 6h, and 12h of follow-up using T1-weighted MR imaging and the corresponding pathological specimen (EP-epicardium, EN-endocardium, RV-right ventricular wall).

Figure 3.

Correlation of RF lesion size. Comparison of the ablation size in the pathological specimen and the corresponding MRI using T2-weighted and T1-weighted imaging protocols.

Figure 4.

Influence of time and applied RF energy on Contrast-to-Noise Ratio (CNR) of RF Lesions. Twelve hours of follow-up of CNR on RF lesions created with an increasing amount of RF energy using T2-weighted (fast spin-echo or FSE) and T1-weighted (spoiled gradient recall acquisition or SPGR) MR imaging protocols.

T2-weighted Protocol

T1-weighted Protocol

Figure 5.

Size of RF ablations during 12h follow-up. Lesion size of individual RF energy group over 12h follow-up as determined by T2-weighted and T1-weighted MR images.

T2-weighted Protocol

T1-weighted Protocol

Figure 6. Heterogeneity of RF lesion. Increasing heterogeneity of RF ablations (measured as the standard deviation of the signal intensities over the lesion area) with increasing amount of applied RF energy assessed with T2-weighted and T1-weighted MR images.

Figure 7.

Intralesional Pathology. Necrotic cavities within high-energy RF ablation lesions and corresponding pathological specimen. Typical appearance of intralesional necrotic cavities as (a) areas of increased signal intensity in T2-weighted MRI, and (b) areas of decreased signal intensities in T1-weighted MR images, (c) corresponding gross pathology, and (d) histology (Masson's Trichrome stain).