Journal of Visualized Experiments

Cardiac Magnetic Resonance for the Evaluation of Suspected Cardiac Thrombus: Conventional and Emerging Techniques

--Manuscript Draft--

Article Type:	Invited Methods Article - JoVE Produced Video
Manuscript Number:	JoVE58808R3
Full Title:	Cardiac Magnetic Resonance for the Evaluation of Suspected Cardiac Thrombus: Conventional and Emerging Techniques
Keywords:	cardiac magnetic resonance; cardiac magnetic resonance; thrombus; thrombus; T1 mapping; T1 mapping; Magnetic resonance imaging; Magnetic resonance imaging; cardiac mass; cardiac mass; Tumor; Tumor
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Additional Information:	
Question	**Response**
Please indicate whether this article will be Standard Access or Open Access.	Standard Access (US$2,400)
Please indicate the **city, state/province, and country** where this article will be **filmed**. Please do not use abbreviations.	Tampa, Florida, USA

TITLE:

Cardiac Magnetic Resonance for the Evaluation of Suspected Cardiac Thrombus: Conventional and Emerging Techniques

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KEYWORDS:

Cardiac magnetic resonance, screening, cardiac mass, cardiac thrombus, first pass perfusion, late gadolinium enhancement, T1 mapping, tissue characterization, post processing

SUMMARY:

The goal of this article is to describe how cardiac magnetic resonance can be used for the evaluation and diagnosis of a suspected cardiac thrombus. The method presented will describe data acquisition as well as the pre-procedure and post-procedure protocol.

ABSTRACT:

We present the conventional cardiac magnetic resonance (CMR) protocol for evaluating a suspected thrombus and highlight emerging techniques. The appearance of a mass on certain magnetic resonance (MR) sequences can help differentiate a thrombus from competing diagnoses such as a tumor. T1 and T2 signal characteristics of a thrombus are related to the evolution of hemoglobin properties. A thrombus typically does not enhance following contrast administration, which also helps differentiation from a tumor. We also highlight the emerging role of T1 mapping in the evaluation of a thrombus, which can add another level of support in diagnosis. Prior to any CMR exam, patient screening and interviews are critical to ensure safety and to optimize patient comfort. Effective communication during the exam between the technologist and the patient promotes proper breath holding technique and higher quality images. Volumetric post processing and structured reporting are helpful to ensure that the radiologist answers the ordering services' question and communicates these results effectively. Optimal pre-MR safety evaluation, CMR exam execution, and post exam processing and reporting allow for delivery of high quality radiological service in the evaluation of a suspected cardiac thrombus.

INTRODUCTION:

Cardiac magnetic resonance (CMR) imaging is an important diagnostic modality for the evaluation of cardiovascular function and pathology. Technological advances allow for reduced acquisition time, improved spatial and temporal resolution, as well as higher quality tissue characterization. These advances are particularly useful in the evaluation of cardiac masses.

Echocardiography remains the first line imaging modality for the initial evaluation of cardiac masses, specifically with respect to mass location, morphology, and physiologic impact. However, echocardiography is limited by poor tissue characterization, a restricted field of view, and operator dependent image quality. Cardiac computed tomography (CT) is often utilized as a second-line imaging modality for assessing cardiac masses. Advantages of cardiac CT over other modalities include excellent spatial resolution and a superior ability in detecting calcifications. The main disadvantage of cardiac CT is patient exposure to ionizing radiation. Additional limitations include decreased temporal resolution and soft tissue contrast resolution. CMR is emerging as a valuable tool in the characterization of cardiac masses detected on echocardiography or CT. Compared to CT, CMR does not expose patients to ionizing radiation. In addition, CMR can be useful in treatment and surgical planning[1,2].

A thrombus is the most common cardiac mass. The most common locations for cardiac thrombi are the left atrium and left atrial appendage, especially in the setting of atrial fibrillation or a dysfunctional left ventricle[1,3]. The diagnosis of thrombus is important for the prevention of embolic events as well as establishing the need for anticoagulation. CMR can aide in determining the acuity of a thrombus. Acute thrombus typically demonstrates intermediate T1- and T2-weighted signal intensity relative to the myocardium due to high amounts of oxygenated hemoglobin. Increased methemoglobin content in the subacute thrombus results in lower T1-weighted signal intensity and intermediate or increased T2-weighted signal intensity. With a chronic thrombus, methemoglobin and water are replaced with fibrous tissue leading to decreased T1- and T2-weighted signal intensity[1-3].

The avascular composition gives a cardiac thrombus intrinsic tissue characteristics that can be exploited by contrast enhanced CMR, to aide in the differentiation of a thrombus from other cardiac tumors[4]. An organized thrombus does not enhance while true cardiac lesions enhance on post contrast imaging due to the presence of intratumoral vascularity[3]. Arterial perfusion imaging allows real time assessment of vascularity within a mass and is critical to differentiate a thrombus from a tumor. Perfusion within a mass can also be useful in the delineation of a bland thrombus from a tumor thrombus. Cine imaging provides advantages over other modalities that can be subject to motion artifact, and the temporal resolution provided by real time gated perfusion imaging increases sensitivity in detecting enhancement[5].

T1 mapping is a MR technique that allows pre-contrast native T1 relaxation times and post-contrast extracellular volume calculation to detect pathologic alterations in tissue. By adding a quantitative dimension to CMR, T1 mapping can help differentiate various disease processes from the normal myocardium. An emerging application is the characterization of cardiac

masses and delineation of masses from cardiac thrombi. Previous studies performed on a 1.5 T Aera XQ scanner have reported native T1 relaxation times of a recent thrombus (911 ± 177 ms) and a chronic thrombus (1169 ± 107 ms)[6]. Other pertinent native T1 relaxation times include lipoma (278 ± 29 ms), calcifications (621 ± 218 ms), melanoma (736 ms), and normal myocardium (950 ± 21 ms). This data suggests that T1 mapping can add quantitative information to a non-contrast exam which in the setting of contraindication to IV gadolinium could be extremely useful[6,7].

Contrast-enhanced CMR has been well validated for the detection of a left ventricular thrombus. It has been shown to provide the highest sensitivity and specificity (88% and 99%, respectively) for detection of a left ventricular thrombus compared to transthoracic (23% and 96%, respectively) and transesophageal (40% and 96%, respectively) echocardiography[8]. Currently, there are no large-scale studies validating the utility of CMR for assessing a thrombus in other chambers of the heart[3].

Despite the many advantages of CMR over other imaging modalities for evaluating cardiac masses, there are also limitations. CMR, like cardiac CT, relies on electrocardiographic gating. This can cause artifact and image degradation in patients with significant arrhythmias. Image quality can also be degraded when scanning patients who have difficulty complying with breath hold requirements. However, faster acquisition times and respiratory gating techniques allow for quality images during free breathing. The presence of certain implanted devices is a contraindication for CMR and poses as a major disadvantage, although the number of MR compatible implantable devices is increasing[1,2].

In summary, specific CMR sequences can be utilized to develop a dedicated MR imaging protocol for the evaluation of a suspected cardiac thrombus. The method presented here will provide instructions for the acquisition of CMR data for evaluation of a suspected thrombus. Pre-procedure screening, sequence selection, troubleshooting, post-processing, volumetric analysis, and report generation will be discussed.

PROTOCOL:

The following protocol follows the departmental clinical guidelines and is adherent to the institution's human research ethics guidelines.

1. **Prepare for MRI data acquisition**

1.1. Conduct a safety screening.

1.1.1. Evaluate for renal impairment[8].

1.1.1.1. Avoid gadolinium contrast in patients with stage 4 or 5 chronic kidney disease (estimated glomerular filtration rate <30 mL/min/1.71 m^2) not on chronic dialysis, patients with

end-stage renal disease on chronic dialysis, and patients with known or suspected acute kidney injury due to concerns for NSF.

1.1.2. Determine necessity for sedation[9].

NOTE: Moderate sedation or general anesthesia allows completion of the examination for patients suffering from anxiety or claustrophobia or pediatric patients.

1.1.2.1. Administer a lorazepam tablet up to 1 mg orally prior to scanning for patients with claustrophobia. Driving or machinery operation after medication administration is contraindicated.

1.1.3. Evaluate for implanted devices[9].

1.1.3.1. Perform a careful review of the patient's history and safety to identify implanted devices that may be hazardous in the CMR environment or create image artifact.

1.1.3.2. Determine MR compatibility of patient implanted devices. Each case is reviewed for risks and benefits. The proper personnel are required to be present during the examination if CMR is to be performed in patients with non-MR safe devices.

1.1.3.3. Obtain radiographs to assist with screening, particularly orbit radiographs when there is possible history of metal fragments within the eye. Perform posterior-anterior radiographs with eyes up, eyes down, and a lateral view.

1.2. Provide patient instructions.

1.2.1. Deliver breathing instructions[10].

1.2.1.1. Perform breath holding at end expiration as reproducibility is higher compared to inspiratory breath holds. For CMR, use the typical breath hold command: "breathe in, breathe out, stop breathing".

1.2.1.2. Provide patient with headphones connected to the technologist microphone so commands can be efficiently conveyed.

1.2.1.3. Perform free-breathing protocol when patient is unable to hold-breath for the exam due to sedation or medical condition. Free breathing protocols increase the number of averages (excitations) up to 4 and allow adequate free breathing image acquisition. Free breathing protocols can be selected from typical scanner exam libraries.

1.3. Setup physiological monitoring[10].

1.3.1. Place electrocardiogram (ECG) leads in optimal positions on the left chest, and confirm adequate ECG signal.

1.4. Position the patient on the MRI scanner.

1.4.1. Ensure an appropriate surface coil size is chosen to maximize the signal-to-noise ratio over the heart. Often a dedicated cardiac coil is selected for optimal performance. Signal to noise correlates directly with image quality and is visually evident during scanning

1.4.2. Reduce field of view to maintain adequate spatial resolution. FOV is changed in the scanner settings directly and is dependent on patient size

2. **Acquire the MRI data [cardiac MR without and with IV contrast limited] focused scan to evaluated potential cardiac thrombus**

NOTE: Basic scan sequences are often loaded by the MRI technologist from scan libraries that are present on each MRI scanner. Standard cardiac scan prescription and orientations are also considered routine operating tasks for MRI technologists.

2.1. Obtain the Scout T1-weighted fast spin-echo including the trans-axial localizing stack[1].

NOTE: This constitutes the first scan for each MRI exam and allows further sequences to be prescribed using spatial localization.

2.2. Obtain the Bright-blood, cine SSFP gradient-echo – axial stack with full heart coverage. This sequence offers the most consistent mass delineation and correlation with other radiology studies.

2.2.1. Obtain short axis, 2 chamber, 3 chamber, and 4-chamber planes as needed depending on clinical indications. Scan plane prescriptions are discussed in detail in Boegart[11].

NOTE: These acquisitions are non-dependent on flow effects which allow for short TR, improve temporal resolution, and permit determination of mobility of a thrombus. SSFP provides high SNR and CNR due to intrinsic contrast properties between myocardium and blood pool.

2.3. Perform the tissue characterization module[1-3,11-12].

2.3.1. Obtain the black-blood triple inversion recovery.

NOTE: This provides excellent contrast resolution for determining the size and the extent of the mass. It is useful for characterizing myocardial edema associated with mass or cystic component of mass and in detecting fat within the mass.

2.3.1.1. Obtain the black-blood double inversion recovery if there is a benefit of a bright fat signal. This is run as a separate sequence available in most CMR scanner sequence libraries where blood pool and myocardium signal are nulled while fat remains bright.

2.4. Perform the first-pass arterial perfusion module[1-3,11-12].

2.4.1. Obtain T1-weighted fat-saturated volumetric contrast-enhanced images; the axial plane is often most universal for mass visualization.

2.4.1.1. Begin imaging during contrast administration of 0.05 – 0.1 mmol/kg injected at 3-4 mL/s.

2.4.1.2. Image until the contrast passes through the LV myocardium (40-50 heart beats).

NOTE: A vascular tumor enhances during perfusion sequences while a thrombus does not enhance.

2.5. Perform the post gadolinium delayed viability module[1-3,11-12].

2.5.1. Obtain phase sensitive inversion recovery (PSIR), (~10 min post injection) 6-8 mm slices with inversion time set to null thrombus, to differentiate the thrombus from the tumor or delineate the thrombus surrounding or associated with the tumor.

2.5.1.1. Set the scan "time to inversion" (TI time) which changes in real time based on gadolinium kinetics and is typically set at 200– 450 ms at 1.5 T; 300-550 ms at 3 T. Set a new TI time into the scanner for each PSIR sequence run, which is usually higher than the previous time based on gadolinium kinetics.

NOTE: Serial imaging can be performed to distinguish hypo-perfused tumor necrotic core from thrombus. This is performed by repeating the PSIR sequence at multiple time points to evaluate gadolinium kinetics with the region of concern.

2.6. Consider obtaining emerging sequences[13-19].

2.6.1. Obtain native T1 mapping (multiple protocols available).

NOTE: For example, use a single shot inversion recovery readout with a 5(3)3 scheme: inversion followed by 5 acquisition heartbeats, 3 recovery heartbeats, an additional inversion followed by 3 heartbeats.

2.6.2. Obtain post contrast T1 mapping (extracellular volume fraction).

NOTE: Post contrast Extracellular volume (ECV) represents a gadolinium-based measurement of the size of the extracellular space which primarily reflects interstitial disease. ECV is calculated

by comparing the changes in relaxivity of myocardium and blood pool prior to and following the administration of the IV contrast agent. Serum hematocrit is necessary to calculate ECV.

2.6.3. Obtain T2 mapping.

NOTE: T2 mapping can be derived from bright-blood T2 prepped SSFP sequence. Accurate application of T2 mapping requires a reference range for normal T2w signal; however, large interpatient variability of myocardial T2 signal can affect interpretation of results.

2.6.4. Obtain a cardiac triggered 3D spoiled gradient echo acquisition named 3D-QALAS (3D quantification).

NOTE: This sequence uses an interleaved look-locker acquisition sequence with T2-preparation and has been shown to be a feasible option for myocardial T1 and T2 mapping in a single breath hold.

3. **Analysis of the MRI data**

3.1. Perform post-processing[2,20].

3.1.1. Use an FDA-approved software for processing data either as part of the MRI system or on a separate workstation.

NOTE: Post-processing is performed or supervised by the cardiac MRI physician and appropriately documented in the report.

3.2. Assess ventricular chambers.

3.2.1. Perform visual analysis of global and segmental function and wall motion. Look for any wall motion abnormalities in all obtained planes.

3.2.2. Perform quantitative analysis of ventricular volumes and wall thicknesses. Ensure there is no abnormal thickening (>13 mm) or thinning of the left ventricular myocardium, which could suggest underlying pathology.

3.3. Evaluate T2-weighted imaging.

3.3.1. Visually analyze to detect or exclude regions of increased myocardial signal intensity indicating edema. For cardiac thrombus evaluation, the thrombus can have increased T2w signal intensity in the subacute time period and low T2w signal intensity in the chronic time period.

3.3.2. Perform semi-quantitative analysis of T2 signal intensity ratios, if needed. Using Picture Archiving and Communication Software (PACS), draw an ROI over a portion of the LV

myocardium and compare the LV T2 signal to skeletal muscle ROI signal. This can be useful in ruling out myocarditis.

3.4. Evaluate perfusion imaging.

3.4.1. Perform visual analysis to identify regions of relative hypoperfusion. In cardiac thrombus evaluation, the mass in question is carefully analyzed for any internal post contrast increased signal, which would suggest against thrombus and signify the presence of vascular tumor.

3.5. Evaluate late gadolinium enhancement (LGE) imaging within myocardium and any suspected masses.

3.5.1. Perform visual analysis to assess for the presence and the pattern of LGE. No solid regions of internal LGE are expected within a thrombus. However, a thin linear component of LGE can be seen along the outer margin of thrombus.

3.5.2. Perform visual analysis of location and extent of LGE.

3.5.3. Perform quantitative analysis with T1 mapping. Post processing software is used. Motion corrected sequences are used for analysis. Draw a region of interest over the mass of interest and over the myocardial regions of concern and record the pertinent T1 relaxation times.

NOTE: This is potentially helpful in distinguishing a thrombus from a tumor by providing quantitative assessment of pre-contrast T1 relaxation times.

3.6. Generate the report[20-21].

3.6.1. Include general study information.

3.6.1.1. Document the study site, scanner information including the manufacturer and the model, the field strength, and the software platform.

3.6.1.2. Document patient demographics.

3.6.1.3. Document the patient ID, gender, and date of birth.

3.6.1.4. Document the referring physician and service.

3.6.2. Include study performance information.

3.6.2.1. Document the date and time of examination, the personnel involved, the indication for examination, and the list of sequences used.

3.6.2.2. Document the patient history and risk factors.

3.6.2.3. Document the height, the weight, the heart rate, and the electrocardiogram interpretation.

3.6.2.4. Document the contrast agent administered, the route, and the dose.

3.6.2.5. Document the amount, the type, the route, and the dose of sedation, if applicable.

3.6.3. Report the cardiovascular imaging features.

3.6.3.1. Describe the cardiac size and function based on qualitative and quantitative assessment.

3.6.3.1.1. Report the cardiac mass and describe the location, the anatomic relationships, the 3-dimensional size, and the morphology.

3.6.3.1.2. Report the mass T1- and T2-weighted signal characteristics of the mass. Classically, a thrombus will have low T1 and T2 signals. However, the T2w signal can vary with the age of blood products.

3.6.3.1.3. Report the first pass perfusion pattern of the mass. The thrombus should have no internal perfusion.

3.6.3.1.4. Report the late gadolinium enhancement pattern of the mass. Thrombus generally has no internal LGE but may have thin linear LGE signal around the periphery.

3.6.3.1.5. Report the mass motion on cine imaging and its effect on myocardial contractility.

3.6.3.1.6. Provide concluding statements synthesizing the findings into a comprehensive impression

REPRESENTATIVE RESULTS:

The CMR protocol designed for the evaluation and diagnosis of cardiac thrombus encompasses patient screening and preparation, data acquisition utilizing specific sequences, data post-processing, and report generation. Specific signal characteristics on given sequences can infer with high accuracy the diagnosis of a cardiac thrombus and differentiate these from the competing diagnosis of a cardiac tumor. **Table 1** highlights the conventional and emerging CMR sequences that are commonly used to evaluate for cardiac thrombus.

A cardiac thrombus has a low SSFP signal with absent internal perfusion and absent delayed enhancement (**Figure 1 and Figure 3**). The T2 signal on dark blood imaging can vary depending

on the age of the blood products within the thrombus. In subacute thrombi, mildly increased T2w signal can be encountered (**Figure 3B**); whereas in chronic thrombus, low T2w signal is expected. Alterations in native T1 signal are also expected with chronic thrombus having elevated T1 relaxation times (**Figure 1D,E** and **Figure 3F**).

Pazos-Lopez et al. showed that CMR can differentiate a thrombus from other cardiac tumors with excellent accuracy[22]. Cardiac thrombi were smaller, more homogenous, and less mobile than tumors[22]. Higher or isointense signals compared to normal myocardium on T2w, first pass perfusion, and LGE sequences were more common in tumors vs. thrombi (85% vs. 42%, 70% vs. 4%, and 71% vs. 5%), respectively[22].

FIGURE AND TABLE LEGENDS:

Figure 1: A 71-year-old male with history of prostate cancer and a left ventricular mass seen on CT. CMR demonstrates an intraluminal LV mass compatible with thrombus within an LV apical aneurysm with associated chronic LV infarct (A) Axial SSFP demonstrates LV apical wall thinning with an aneurysmal configuration at the apex. There is a low signal intraluminal structure within the LV apex. **(B)** Axial first pass arterial perfusion image: There is no perfusion within the LV apical structure. **(C)** 3 chamber LGE image: no LGE within the LV apex mass. LGE within the apical wall is >50% wall thickness compatible with previous infarct. **(D)** Color native T1 map demonstrates native T1 relaxation time within the LV apex mass of 1105 ms suggesting chronic bland thrombus. **(E)** Enlarged color native T1 map at LV apex: There is a thinned LV apex wall with the blue-green ROI T1 relaxation time measuring 1268 ms which is compatible with a prior infarct.

Figure 2: A 70-year-old male with hepatocellular carcinoma metastatic to the IVC and right atrium. This right atrial intraluminal metastasis is shown to provide comparison to intraluminal thrombus in other figures (A) Axial SSFP: A cavoatrial junction mass demonstrates low signal. **(B)** T2 dark blood: The high T2 signal within the mass (arrow) is nearly iso-intense to nearby hepatic tumors seen on the same image. **(C)** Axial Native T1 map color image (Siemens myomaps, Erlangen, Germany): the mass (arrow) demonstrates a native T1 relaxation time of 724 ms. **(D)** Coronal MRA: the mass is contiguous with adjacent hepatic tumor extending through the IVC into the right atrium (arrow).

Figure 3: A 61-year-old male with metastatic urothelial carcinoma with a right ventricular mass seen on CT which is compatible with thrombus on CMR. (A) Axial SSFP: A low signal mass near the RV apex is noted. **(B)** Axial T2 dark blood: there is isointense to mildly hyperintense T2 signal within the mass related to the presence of subacute blood products. **(C)** Axial dynamic arterial perfusion: no perfusion is seen within RV mass. **(D)** Axial post contrast CT: there is no enhancement within the RV mass. **(E)** Axial LGE: the non-enhancing RV mass is compatible with thrombus. **(F)** Grayscale pre-contrast native T1 Map demonstrates an elevated T1 relaxation time within the mass of 1094ms, which is compatible with thrombus.

DISCUSSION:

With the increasing quality and frequency of diagnostic imaging, it is not uncommon to discover incidental cardiac masses when performing imaging for unrelated indications. Patients with cardiac masses are often asymptomatic, and if present, symptoms are typically nonspecific.

The diagnosis of cardiac thrombus is important not only for differentiating thrombus from benign or malignant cardiac tumors, but also for determining the need for anticoagulation and prevention of embolic events[1]. In patients with a suspected cardiac thrombus, the option for a single imaging modality with a specific protocol can provide for accurate and efficient diagnosis.

The protocol described includes specific CMR sequences designed for optimal localization and characterization of a suspected cardiac thrombus. For structural and functional evaluation, cine SSFP images are acquired in two-chamber, three-chamber, four-chamber, and short-axis views. SSFP imaging provides high spatial resolution and is not dependent on flow effects. This allows for a short time to repetition (TR), which improves temporal resolution. This is particularly useful for patients with breath-holding difficulty, and it aids in assessing for any mobility of a suspected thrombus. SSFP also provides a high signal to noise ratio (SNR) and contrast to noise ratio (CNR) due to intrinsic contrast properties between the myocardium and blood pool. For tissue characterization, black blood T1-weighted and T2-weighted double and triple inversion recovery FSE images are acquired with and without fat saturation. The T1-weighted images provide excellent contrast resolution for determining size and extent of the thrombus, as well as providing information on the presence or absence of recent hemorrhage or melanin due to T1 shortening. T1-weighted images also serve as a basis for comparison to post-contrast images. The fat-saturated images are useful for determining the presence of fat in a cardiac mass. The T2-weighted images are useful for characterizing myocardial edema associated with a mass, or to assess for a cystic component. Post gadolinium enhancement images are acquired during the injection of contrast (first pass perfusion) and repeated at approximately 10 minutes post-injection (LGE). The perfusion images are useful for distinguishing vascular tumor from a thrombus. For LGE, a phase-sensitive inversion recovery sequence is utilized, and the inversion time is set to null thrombus. This aids in differentiating a thrombus from a tumor. If there is a known tumor, this aids in delineating a thrombus surrounding or associated with a tumor[1-4].

We also highlight the emerging role of T1 mapping in the evaluation of thrombus which can add another level of support in diagnosis. T1 mapping is potentially helpful in distinguishing a thrombus from a tumor by providing quantitative assessment of pre-contrast T1 relaxation times. T1 mapping can also potentially differentiate between an acute and a chronic thrombus. More recent (<1 week) thrombi have been shown to have shorter T1 values compared to older (>1 month) thrombi[6]. Additionally, T1 mapping in addition to T2 mapping have shown to be useful for differentiating masses such as cardiac myxomas from myocardium[23].

Multiple imaging modalities can be employed to comprehensively evaluate cardiac masses, each possessing strengths and weaknesses. CMR is emerging as the imaging modality of choice for evaluating cardiac masses. CMR allows for the qualitative and quantitative assessment of cardiac anatomy, function, perfusion, and tissue characteristics in a single examination. Unlike CT, CMR does not expose patients to ionizing radiation. In contrast to echocardiography which

suffers from poor tissue characterization and limited field of view, CMR offers superior tissue characterization, high spatial and temporal resolution, multiplanar imaging capabilities, and a larger field of view[1-3].

Prior to any CMR exam, patient screening and interviews are critical to ensure safety and to optimize patient comfort. Effective communication during the exam, between the technologist and the patient, promotes proper breath holding technique and high quality images. Volumetric post processing and structured reporting are helpful to ensure the radiologist answers the ordering services' question and communicates these results effectively. Optimal safety screening evaluation, CMR exam execution, exam post-processing, and reporting allow for delivery of high quality radiological service in the evaluation of suspected cardiac thrombus.

ACKNOWLEDGMENTS:

The authors acknowledge support from the Department of Diagnostic Imaging at the H. Lee Moffitt Cancer Center and Research Institute.

DISCLOSURES:

The authors have nothing to disclose.

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Figure 1

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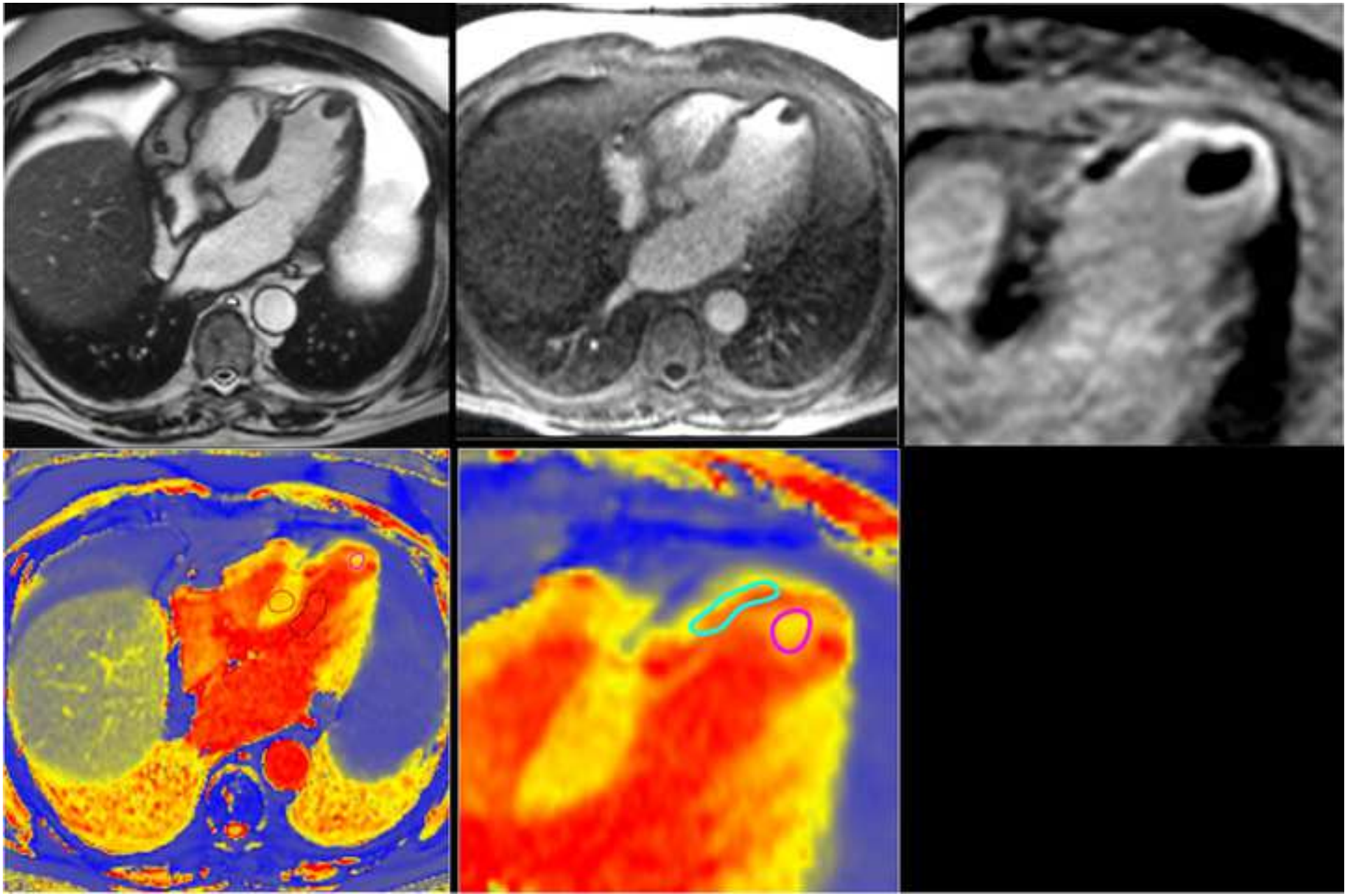

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Table 1: CMR sequences for thrombus evaluation

Conventional CMR Sequences	**Indications**	**Comments**
Cine SSFP	Bright blood structure and function evaluation	Mass delineation and mobility evaluation. Axial plane is often helpful to correlate with previous radiological imaging.
T2w - Triple IR	Saturated blood, fat, and myocardium	Helpful to distinguish thrombus from avidly T2w hyperintense masses such as myxomas.
1st pass arterial perfusion	Mass characterization, ischemia evaluation	Thrombus will have no perfusion while vascular masses will perfuse
Delayed Viability	Myocardial ischemia/disease characterization	Thrombus may have subtle delayed rim enhancement but no internal enhancement
Emerging CMR sequences		
T1 Mapping (pre contrast native T1 and post contrast extracellular volume)	Quantification of T1 relaxation times within myocardium and masses.	T1 values are dependent on field strength and scanner/prescription.
T2 Mapping	Quantification of T2 relaxation times. Myocardial and mass characterization.	T2 signal is sensitive to mild stressors such as viral illness. Large inter-patient T2w signal variability limiting widespread utility

CMR – cardiac magnetic resonance; SSFP – steady state free precession; T2w – T2 weighted; IR – inversion recovery;

Table of Materials

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Name of Material/ Equipment	Company
MRI Scanner	Siemens Healthcare
Post processing software	Medis
Scanner processing software	Siemens Healthcare

Location	Catalog Number
Erlangen, Germany	Magnetom Aera 1.5 Tesla
The Netherlands	Qmass software
Erlangen, Germany	Myomaps

Comments/Description

MRI scanner that will be used for the demonstration

post processing software for ventricular volumetric and T1 mapping analysis

Scanner sequence package and post processing software

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Author(s):	Elizabeth M. Johnson, Kenneth Gage, Sebastian Feuerlein, Daniel Jeong

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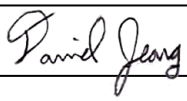
Signature:	
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We highly appreciate the suggestions from the editors regarding the changes to improve the writing and we have implemented all suggested changes. We have also employed two additional expert editors to carefully review the manuscript for any additional grammatical improvements. I have assembled the corrections from the copy editors into the marked version provided by JoVE which are visualized in blue font.

In addition to the JoVE editor changes which were implemented, additional changes from our copy editors are noted in the following lines:

55, 66, 71, 76, 90, 207-208, 235, 263, 266, 271, 331-332, 335, 373, 380, 383, 394, 405, 412, 414, 417-418, 421-422, 424-431, 433-434, 437-438, 440, 457, 463-464, 468, 483, 489-490, 492, 494, 497.

Additionally, minor changes to the references section were made to assure compliance with JoVE formatting.

We hope that you will find the changes acceptable and we appreciate your time and effort with the review process.

Sincerely,

Daniel Jeong