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CMR is well suited to assess several aspects of renal arterial disease (any condition which results in irregularity, stenosis, dissection, or aneurysmal dilatation of the renal arteries). Specifically, CMR can be used to determine the following:

1. The number and location of renal arteries. Multiple renal arteries are common and occur in approximately 24% of cases with bilateral multiple renal arteries in 5% of the population (351).

2. The severity of renal artery stenosis, including the presence of fibromuscular dysplasia.

3. The configuration of the renal blood supply. The incidence of horseshoe kidney at necropsy is estimated at 1:666 (352). Furthermore, only in 30% of cases is the horseshoe kidney supplied by a single renal artery to each side, the majority of cases receiving multiple renal arteries bilaterally, as well as variable arterial supply of the midline isthmus (353).

4. The presence of renal or adrenal parenchymal mass lesions.

Recent studies have estimated the sensitivity and specificity of 3.0-T MRA in the detection of intra-abdominal arterial stenosis as 100% and greater than 92%, respectively (354,355).

3.15.1. Potential Advantages of CMR Relative to Other Imaging Modalities

The absence of associated ionizing radiation and nonionic contrast medium injection reduces potential toxicities related to ionic contrast materials, particularly in patients with renal insufficiency (356). CMR offers the opportunity to perform both morphological renal arterial assessment as well as derive complementary flow-related data by means of PC flow quantification of individual renal arteries. This combined approach to renal imaging may provide insight into which patients would most benefit from endovascular intervention (357,358). In addition to high-resolution 3D large field-of-view data acquisition, renal arterial MRA also allows assessment of the renal and adrenal parenchymal tissue for the presence of congenital anomalies or potentially causative occult tumors. Time-resolved first-pass perfusion imaging of the kidneys may be valuable in identifying significant renovascular lesions (359).

3.15.2. Summary of Existing Guidelines and Appropriate Use Criteria

The writing committee recognizes that few guidelines for appropriate use criteria are available for the use of CMR for assessing the renal arteries. The ACC/AHA 2005 Practice Guidelines for the Management of Patients With Peripheral Arterial Disease (lower extremity, renal, mesenteric, and abdominal aortic) designates CMR a Class I recommendation as a screening test to establish the diagnosis of renal arterial stenosis (Level of Evidence: B) (305).

4. CMR Safety

4.1. Introduction

CMR is generally considered safe, but there are important safety concerns that fall into 3 general categories: potential projectiles in the MR scanner room, implanted cardiovascular devices, and issues related to contrast administration. In regard to potential projectiles, it is important to remember that the magnet is always “on.” Therefore, ferromagnetic materials entering the MR room are a hazard and can be drawn into the bore of the scanner with unopposable and unstoppable force. This produces an immediate lethal danger to anyone in the scanner or in the path of ferromagnetic material attracted to the scanner bore. For this reason, local guidelines and safety policies are developed to guard against ferromagnetic material entering the MR environment.

This section will explore the issues related to implanted devices and MR contrast and present an overview of the types of devices that are of concern, as well as the underlying safety considerations for patients with these devices. Since device specifications change frequently, a comprehensive list of CMR compatible or incompatible devices is not possible, and information on specific devices will need to be obtained either from the manufacturer’s package inserts or CMR safety Web sites or handbooks. After reviewing devices, issues related to Gd contrast will be presented.

4.2. General Safety Considerations for Implanted Devices

There are several reasons that implanted devices may pose safety considerations for patients undergoing CMR. First, the CMR scanner generates a very powerful static magnetic field. Ferromagnetic objects (i.e., those that contain iron) will interact with the static field and may move in the patient’s body. Nearly all implanted devices, however, are nonferromagnetic or only weakly ferromagnetic. Each device must undergo separate testing to determine whether it is likely to translate or rotate in the magnetic field. Besides the static magnetic field, additional smaller and changing magnetic fields, termed gradients, are generated during CMR scanning. These gradient fields may change very rapidly during CMR scanning. Gradient fields can produce electric currents in wires or leads that can potentially result in arrhythmia.

In addition to magnetic fields, radiofrequency waves are transmitted into the patient by the CMR scanner. These radiofrequency waves are absorbed by the body and can produce slight (less than 1°C) heating of the patient. With respect to implanted devices, these radiowaves may potentially interfere with certain electronic components as well as cause heating at the tips of implanted wires.
Besides the type of devices, there are many variables that affect the likelihood that a CMR device could be affected by the CMR scanner. These include the location of the device, the strength of the CMR scanner and, potentially, whether the device has been acutely placed or is firmly fixed in position. Because of these factors, experts in CMR safety and physics should be consulted when presented with an unfamiliar device prior to undergoing CMR. This applies to individuals with implanted devices receiving any type of magnetic resonance procedure including the heart, brain, extremities, or other body/organ/structure/part. If the type of device is unknown, alternatives to performing CMR should be evaluated. In general, the benefits of undergoing CMR must be weighed against the potential risk of injury to the patient or device failure.

Prior to undergoing CMR, patients are screened for both implanted cardiovascular devices as well as other types of implants. Patients are screened by licensed MR technologists with supervision by a CMR-knowledgeable physician. Standardized screen forms are available (360–362) that should be completed prior to undergoing CMR.

Medical devices are classified by the American Society for Testing and Materials as “MR safe,” “MR conditional,” and “MR unsafe” (Table 10) (363).

### 4.3. CMR Scanning Post Device Implantation

Devices that are manufactured from nonferromagnetic material (300 series stainless steel, titanium, titanium alloy, nitinol) that have no electrical or magnetic components and that have no concern for heating due to CMR may undergo CMR scanning immediately after implantation.

For devices that are weakly ferromagnetic, CMR safety has not been established for every device, and in some cases, the CMR scanner could potentially dislodge or move such a device immediately after implantation. Devices that are firmly implanted into a vessel wall or adjacent tissues are less likely to undergo motion. In the case of heart valves in particular, the forces of the heart on the valve are often much greater than the CMR forces due to weak ferromagnetism. In general, waiting after implantation (e.g., for 6 weeks) may be considered if this is an option for the patient. For weakly ferromagnetic devices, the risks and benefits of CMR immediately after implantation need to be considered to determine whether it is necessary or possible to defer the CMR scan.

### 4.4. Coronary Artery and Peripheral Vascular Stents

Most coronary artery and peripheral vascular stents exhibit weak ferromagnetism or are nonferromagnetic. Anchoring in the vascular wall likely provides protection against movement, and further anchoring of the stent may occur due to tissue ingrowth at 6 to 8 weeks after implantation. However, for nonferromagnetic coronary stents, there is no good rationale or clinical data to suggest that a delay is necessary after implantation. Data on specific coronary stents suggest that many of these could be considered CMR safe (364–367) but not necessarily at the highest (3.0-T) magnetic fields (366,368,369). There have been no reports of increased risk of stent subacute or late thrombosis following CMR scans (367,370–373).

Drug-eluting stents have the same considerations as conventional stents regarding ferromagnetism (374). Slight heating of the stent (less than 1°C or less than 2°C for overlapping stents) has been reported, but the effect of this on the drug-eluting properties of the stent is unknown. It is possible that stent heating may be mitigated by a heat-sink effect of flowing blood in the vessel. A small study of patients after myocardial infarction who underwent MR within 2 weeks of stent implantation detected no increased incidence of adverse events at 30 days and 6-month follow-up compared with patients who did not undergo CMR (375).

### 4.5. Aortic Stent Grafts

Most aortic stent grafts that have been tested have been labeled as MR safe with the exception of the Zenith AAA Endovascular Graft Stent, which has been labeled as MR unsafe (362,376). The Zenith stent has significant deflection and torque of the stainless steel component of the graft in the magnetic field. Although no adverse events have been reported with the Zenith stent, there remains a potential for device migration or vessel damage so that the risks and benefits of CMR examination should be considered in these patients (377). With other aortic stent grafts (e.g., Endologic AAA or Lifepath AA), there may be significant associated artifact around the stent or obscuring of the vascular lumen due to the metallic components.

### 4.6. Intracardiac Devices

The majority of prosthetic heart valves and annuloplasty rings that have been tested have been labeled as MR safe, with a lesser number labeled as MR conditional. In general, the presence of a prosthetic heart valve or annuloplasty ring is not considered a contraindication to CMR examination up to 3.0-T at any time after implantation (376,378–382). The forces exerted on valve prosthesis are substantially less than those exerted by the beating heart and pulsatile flow (383). The forces required to pull a suture through the valve annulus tissue have been shown to be greater than magnetically induced forces up to a field strength of 4.7-T (384). Thus, patients with valve prosthesis are unlikely to be at risk for valve dehiscence during clinical

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**Table 10. Safety Terminology for Implanted Devices**

<table>
<thead>
<tr>
<th>Classification</th>
<th>Definition</th>
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<tr>
<td>MR safe</td>
<td>A device that poses no hazards in the MR environment.</td>
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<tr>
<td>MR conditional</td>
<td>A device that poses no known hazards in a specific MR imaging environment with constraints on the conditions of use. These constraints may include, e.g., the magnetic field strength or specific absorption rate.</td>
</tr>
<tr>
<td>MR unsafe</td>
<td>An item that is known to pose hazards in all MR environments.</td>
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</table>

MR indicates magnetic resonance.
CMR examinations. Associated CMR-related heating has been determined to be less than 1°C in ex vivo studies (378,380,381,385,386); this is likely to be less due to the heat-sink effect of flowing blood. Valve dysfunction due to interaction with the magnetic field has not been reported.

Cardiac closure and left atrial appendage occluder devices are either weakly ferromagnetic or nonferromagnetic depending on the materials used (376,387,388). The majority of cardiac closure and occluder devices that have been tested have been labeled as MR safe; several that have been tested are labeled as MR conditional (362). Patients with nonferromagnetic cardiac closure and occluder devices may undergo CMR procedures at any time after implantation. The timing of CMR examination at 3.0-T or less in patients with cardiac closure or occluder devices that are weakly ferromagnetic should be weighed on a case-by-case basis. For cases in which there is a clear potential clinical benefit of scanning in the days to weeks after implantation, the benefits of the MR examination will likely outweigh the risks of the examination.

Sternal wires associated with cardiac surgery/valve replacement are not considered to be a contraindication to CMR examination.

4.7. Inferior Vena Cava Filters
CMR examinations of both animals and humans with implanted inferior vena cava (IVC) filters have thus far not reported complications or symptomatic filter displacement (389–394). Most IVC filters that have been tested have been labeled as MR safe; the remainder of IVC filters that have been tested are classified as MR conditional (362). In patients who have a weakly ferromagnetic IVC filter (Gianturco bird nest IVC filter [Cook, Bloomington, Ind], stainless steel Greenfield vena cava filter [Boston Scientific, Watertown, Mass]), consideration should be made to wait at least 6 weeks before performing CMR examination to allow firm implantation of the device. In cases where there is a strong clinical indication for CMR and the device is firmly anchored, the benefits of performing the CMR prior to 6 weeks may outweigh the potential risks.

4.8. Embolization Coils
Commonly utilized embolization coils are either nonferromagnetic or weakly ferromagnetic. Although there is theoretical potential for coil heating during a CMR examination, no significant effects were found on the Guglielmi detachable coil (GDC) (Boston Scientific) ex vivo (395) or in patient studies (396). Embolization coils made from nitinol, platinum, or platinum and iridium have been evaluated and found to be safe for CMR performed at magnetic field strengths of 3.0-T or less (376,397–400). Platinum coils implanted in the CNS have not been reported to cause complications for patients undergoing MR. Most embolization coils that have been tested have been labeled as MR safe; the remainder of embolization coils that have been tested have been labeled as MR conditional (362). For weakly ferromagnetic devices, the risks of performing CMR prior to 6 weeks after coil placement must be considered relative to the benefits of CMR on a case-by-case basis.

4.9. Hemodynamic Monitoring and Temporary Pacing Devices
Retained temporary epicardial pacing leads are relatively short in length without large loops. These are felt not to pose a significant risk during CMR. No complications have been reported as a result of MR scanning for a patient with retained leads (401).

Hemodynamic catheters that contain conducting wires and those few temporary transvenous pacing wires that have been tested have been labeled as MR unsafe (362). Patients with pulmonary artery hemodynamic monitoring/thermodilution catheters (such as the Swan-Ganz catheter) should not undergo CMR examinations because of the possible associated risks unless labeling information or instructions for use are provided that permit CMR examinations to be performed safely. Nonferromagnetic pulmonary artery catheters without electrically conductive pathways in the catheter are safe for CMR examination.

CMR of patients with temporary pacemaker external pulse generators is not recommended as CMR can alter the operation of an external pulse generator or damage it. Pacing of the patient during the CMR may also be unreliable with a temporary transvenous lead.

4.10. Permanent Cardiac Pacemakers and Implantable Cardioverter Defibrillators
Due to the wide prevalence of cardiovascular diseases, a significant proportion of patients who would normally be referred for CMR examinations will have permanent cardiac pacemakers or implantable cardioverter defibrillators (ICDs). Pacemakers and ICDs contain metal with ferromagnetic properties, as well as complex electrical systems with 1 or several leads implanted into the myocardium. Potential complications of CMR under these circumstances include damage or movement of the device, inhibition of the pacing output, activation of the tachyarrhythmia therapy of the device, cardiac stimulation, and heating of the electrode tips (402–408). These factors may lead to clinical sequelae including changes in pacing/defibrillation thresholds, pacemaker ICD dysfunction or damage (including battery depletion), arrhythmia, or death (404,409,410).

A few small clinical trials have been conducted to assess conditions under which MR examination with these devices could be conducted safely. Pacemaker-dependent patients were excluded from these studies, and the heart rhythm was monitored during the exam. No episodes of pacing above the upper rate limit or arrhythmias were noted (410), though 1 patient had a change in device programming (411). Another study suggested that ICDs and pacemakers manufactured after the year 2000 are more resistant to the electrical and magnetic fields associated with MR examination at 1.5-T (412). To date, it is likely that several hundred
patients have undergone MR examination with either pacemakers or ICDs (413–419), and strategies and protocols for safe pacemaker/ICD scanning during CMR have been proposed (420,421). As of this writing, no deaths have been reported under conditions in which patients were deliberately scanned and monitored during the MR examination, although changes in pacing threshold, programming changes, need for device reprogramming, and possibly battery depletion have been reported.

Currently, pacemakers available in the United States are labeled as MR unsafe (362). At present, CMR examination of patients with pacemakers is discouraged and should only be considered at highly experienced centers in cases in which there is a strong clinical indication and where the benefits clearly outweigh the risks. CMR examination of patients with ICDs should not be performed unless the center is highly experienced in both the operation of these devices and in complex CMR procedures in the setting of highly compelling circumstances where the benefits clearly outweigh the risks.

4.11. Retained Transvenous Pacemaker and Defibrillator Leads

There are no clinical studies that have specifically addressed the risk for CMR associated with retained pacemaker or ICD leads. Since no radiofrequency chokes are present on these leads, significant heating of the lead tips may occur. CMR in these circumstances is discouraged, and CMR examination should only be considered in centers with expertise in electrophysiology and CMR when there are no alternatives to the CMR examination under compelling clinical circumstances. Similarly, CMR examination should not be performed in patients with known retained transvenous leads that have fractures.

4.12. Hemodynamic Support Devices

Hemodynamic support devices such as ventricular assist devices and intra-aortic balloon pumps are complex electromagnetic devices containing ferromagnetic materials. Formal CMR testing of these devices has not been conducted. However, it is believed that these hemodynamic support devices represent absolute contraindications to CMR examination.

4.13. Gadolinium Contrast Agents

Gadolinium contrast agents are frequently used for CEMRA as well as for imaging the heart for LGE, perfusion, or masses. Currently the use of Gd contrast agents for these purposes is off-label in the United States. Unlike iodinated contrast materials used with radiographic techniques, there are different safety issues relating to underlying renal function that need to be considered prior to their administration.

Mild-to-moderate reactions to Gd contrast agents (e.g., hives, shortness of breath) have been reported to occur in approximately 1 in 5000 patients. Severe anaphylactic reactions occur in 1 in 250 000 to 300 000 patients. Nephrogenic systemic fibrosis (NSF) is an extremely rare but important complication of Gd administration associated with acute renal failure or severe renal failure due to advanced chronic kidney disease (National Kidney Foundation Stage 4 or 5 renal failure). NSF is a scleroderma-like fibrosing entity of the skin (422). The disease has systemic features that include involvement of pleura, pericardium, lungs, joints, and striated muscle (including diaphragm and myocardium) (359,423). Besides acute renal failure or severe renal failure due to advanced chronic kidney disease (glomerular filtration rate less than 30 mL/min/1.73 m²), other characteristics that have been implicated with an increased risk for NSF include severe liver failure or liver transplant, kidney transplant, hypercoagulability, deep vein thrombosis, and tissue injury secondary to surgical procedures (424). The 1-year incidence of NSF in the presence of all recognized risk factors (end-stage renal disease [ESRD], use of Gd contrast, dialysis, and proinflammatory events) has been estimated to be between 1% (unpublished data, Mayo Clinic Experience; ISMRM proceedings, Toronto, 2008) and 4.6% (425). Over 200 cases have been reported to the Food and Drug Administration as of May 2007, but not all are confirmed. Given the total number of Gd contrast applications, the overall risk of NSF in other groups is considered very low. Because of the risk of NSF, screening for reduced renal function prior to CMR should be considered in most individuals and particularly in at-risk groups, for example, older patients, individuals with history of renal disease or dysfunction, or patients with a prior renal transplant. Patients with hepatorenal syndrome in association with severe liver disease, periliver transplant patients, and patients with acute renal failure are typically poor candidates for Gd contrast administration. Patients undergoing peritoneal dialysis have prolonged retention of Gd contrast agents and their use is discouraged. The use of Gd in patients with ESRD must be balanced by the significant risk of NSF (3% to 5%). Once informed consent is obtained, using a macrocyclic chelate (like gadoteridol) in the lowest possible dose and avoiding repeat exposure appear reasonable measures, based on available evidence (426). Postprocedure hemodialysis of all patients with ESRD should be considered.

5. Summary

With its advantages in studying patients with cardiovascular disease and ability to provide high-resolution images, CMR offers a suitable mechanism for assessment in various clinical and research applications. Table 11 summarizes the writing committee’s potential indications for the use of CMR in clinical practice situations.
### Table 11. Summary of Potential Indications for the Use of Cardiovascular Magnetic Resonance

<table>
<thead>
<tr>
<th>Disease/Condition</th>
<th>Recommendations for Use in Clinical Practice</th>
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<tbody>
<tr>
<td><strong>Heart failure</strong></td>
<td>CMR may be used for assessment of LV and RV size and morphology, systolic and diastolic function, and for characterizing myocardial tissue for the purpose of understanding the etiology of LV systolic or diastolic dysfunction. The writing committee recognizes the potential capabilities of spectroscopic techniques for acquiring metabolic information of the heart when evaluating individuals with heart failure.</td>
</tr>
<tr>
<td><strong>Coronary artery disease</strong></td>
<td>CMR may be used for identifying coronary artery anomalies and aneurysms and for determining coronary artery patency. In specialized centers, CMR may be uniquely useful in identifying patients with multivessel coronary artery disease without exposure to ionizing radiation or iodinated contrast medium.</td>
</tr>
<tr>
<td><strong>Ischemic heart disease</strong></td>
<td>The combination of CMR stress perfusion, function, and LGE allows the use of CMR as a primary form of testing for identifying patients with ischemic heart disease when there are resting ECG abnormalities or an inability to exercise, defining patients with large vessel coronary artery disease and its distribution who are candidates for interventional procedures, or determining patients who are appropriate candidates for interventional procedures. Assessment of LV wall motion after low-dose dobutamine in patients with resting akinetic LV wall segments is useful for identifying patients who will develop improvement in LV systolic function after coronary arterial revascularization. The writing committee recognizes the potential advantages of spectroscopic techniques for identifying early evidence of myocardial ischemia that may or may not be evident using existing non-CMR methods.</td>
</tr>
<tr>
<td><strong>Myocardial infarction/scar</strong></td>
<td>LGE-CMR may be used for identifying the extent and location of myocardial necrosis in individuals suspected of having or possessing chronic or acute ischemic heart disease.</td>
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<tr>
<td><strong>Nonischemic cardiomyopathy/myocarditis</strong></td>
<td>CMR may be used for assessment of patients with LV dysfunction or hypertrophy or suspected forms of cardiac injury not related to ischemic heart disease. When the diagnosis is unclear, CMR may be considered to identify the etiology of cardiac dysfunction in patients presenting with heart failure including evaluation of dilated cardiomyopathy in the setting of normal coronary arteries, patients with positive cardiac enzymes without obstructive atherosclerosis on angiography, patients suspected of amyloidosis or other infiltrative diseases, hypertrophic cardiomyopathy, arrhythmogenic right ventricular dysplasia, or syncope or ventricular arrhythmia.</td>
</tr>
<tr>
<td><strong>Assessment of valvular heart disease</strong></td>
<td>CMR may be used for assessing individuals with valvular heart disease in which evaluation of valvular stenosis, regurgitation, para- or perivalvular masses, perivalvular complications of infectious processes, or prosthetic valve disease are needed. CMR may be useful in identifying serial changes in LV volumes or mass in patients with valvular dysfunction.</td>
</tr>
<tr>
<td><strong>Cardiac masses</strong></td>
<td>CMR may be used for clinical evaluation of cardiac masses, extracardiac structures, and involvement and characterization of masses in the differentiation of tumors from thrombi.</td>
</tr>
<tr>
<td><strong>Pericardial disease (constrictive pericarditis)</strong></td>
<td>CMR may be used as a noninvasive imaging modality to diagnose patients with suspected pericardial disease. CMR can provide a comprehensive structural and functional assessment of the pericardium as well as evaluate the physiological consequences of pericardial constriction.</td>
</tr>
<tr>
<td><strong>Congenital heart disease</strong></td>
<td>CMR may be used for assessing cardiac structure and function, blood flow, and cardiac and extracardiac conduits in individuals with simple and complex congenital heart disease. Specifically, CMR can be used to identify and characterize congenital heart disease, to assess the magnitude or quantify the severity of intracardiac shunts or extracardiac conduit blood flow to evaluate the aorta, and to assess the pathological and physiologic consequences of congenital heart disease on left and right atrial and ventricular function and anatomy.</td>
</tr>
<tr>
<td><strong>Pulmonary angiography</strong></td>
<td>CE-MRA may be used in patients with a strong suspicion of pulmonary embolism in whom the results of other tests are equivocal or for whom iodinated contrast material or ionizing radiation are relatively contraindicated (255). The writing committee agrees that data in the literature are insufficient to recommend where pulmonary CE-MRA should fit into a diagnostic pathway for pulmonary embolism.</td>
</tr>
<tr>
<td><strong>Atrial fibrillation</strong></td>
<td>CMR may be used for assessing left atrial structure and function in patients with atrial fibrillation. The writing committee recognizes that evolving techniques utilizing LGE may have high utility for identifying evidence of fibrotic tissue within the atrial wall or an adjoining structure. Standardization of protocols and further studies are needed to determine if CMR provides a reliable effective method for detecting thrombi in the left atrial appendage in patients with atrial fibrillation. CMR is recommended for identifying pulmonary vein anatomy prior to or after electrophysiology procedures without need for patient exposure to ionizing radiation.</td>
</tr>
<tr>
<td><strong>Peripheral arterial disease</strong></td>
<td>CMR recommendations for PAD are in agreement with current guidelines and appropriate use criteria. CMR for PAD 1. is recommended to diagnose anatomic location and degree of stenosis of PAD (Class I, Level of Evidence: A); 2. should be performed with gadolinium enhancement (Class I, Level of Evidence: B); and 3. is useful in selecting patients with lower extremity PAD as candidates for endovascular intervention (Class I, Level of Evidence: A). CMR of the extremities may be considered 1. to select patients with lower extremity PAD as candidates for surgical bypass and to select the sites of surgical anastomosis (Class IIb, Level of Evidence: B); and 2. for post-revascularization (endovascular and surgical bypass) surveillance in patients with lower extremity PAD (Class IIb, Level of Evidence: B) (288). Additionally, MRA of the lower extremities is appropriate for patients with claudication.</td>
</tr>
<tr>
<td><strong>Carotid arterial disease</strong></td>
<td>CMR may be used for defining the location and extent of carotid arterial stenoses.</td>
</tr>
<tr>
<td><strong>CMR of thoracic aortic disease</strong></td>
<td>CMR may be used for defining the location and extent of aortic aneurysms, erosions, ulcers, dissections; evaluating postsurgical processes involving the aorta and surrounding structures, and aortic size blood flow and cardiac cycle-dependent changes in area.</td>
</tr>
<tr>
<td><strong>Renal arterial disease</strong></td>
<td>CMR may be used for evaluating renal arterial stenoses and quantifying renal arterial blood flow.</td>
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REFERENCES


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