MRI of the Coronary Arteries

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Introduction

Magnetic resonance angiography (MRA) of the coronary arteries has shown advances in both spatial and temporal resolution since its development in the early 1990’s. Coronary MRA may also be combined with other imaging techniques for cardiac function and structure. This review will discuss technical issues and implementations of MRI of the coronary arteries.

Technical issues for coronary MRA

The critical issue for coronary MRA is to account for multiple sources of motion while maintaining a high spatial resolution and high temporal resolution acquisition. Under optimal circumstances, the spatial resolution of coronary MRA is 700-900 microns for in plane resolution, but slice thickness (z-axis) remains at 2-3 mm. This is considerably greater than the 300 micron resolution available from invasive angiography. Besides bulk cardiac motion that is commonly observed with functional studies of the left ventricle, the right and left coronary arteries have complex motion paths influenced by the atria as well as ventricles. Because the heart rests on the diaphragm, bulk cardiac motion related to respiration must be eliminated during the acquisition. Technical factors related to coronary acquisitions are discussed further below.

Coronary artery motion.

Coronary artery imaging is typically performed in mid diastole, during a relatively quiescent period of coronary artery motion. Although algorithms to predict the period of decreased motion have been developed based on heart rate, there is considerable variation between individuals. In general, however, with increasing heart rate, the duration of quiescent motion decreases or in some patients cannot be identified with certainty at high heart rates. A simple approach is to determine the period of mid diastole when there is decreased motion by studying a horizontal long axis view containing the right coronary artery. The left coronary artery may be studied separately, or assumed quiescent at a similar time. For these cine images, we usually obtain 50 cine phases throughout the cardiac cycle using a retrospectively gated steady state free precession (SSFP) acquisition with 25-50 msec temporal resolution.

Respiratory Motion.

Respiratory motion can be controlled either by breath-holding or using navigator echoes to account of the position of the diaphragm. For simple studies directed to a portion of the coronary tree, breath holding is usually sufficient. Note that during an inspiratory breath-hold, there is usually considerable drift of the diaphragm of at least 1 cm. Therefore, breath-hold imaging for coronary MRA should be performed at resting lung volume. Breath-hold coronary MRA may be used, for example, for anomalous coronary artery imaging.

Free breathing navigator echoes allow the motion of the diaphragm to be tracked over time, with image acquisition occurring when the diaphragm is within a prespecified distance of the average position. Typically, limits of 2-3 mm of the mean diaphragm position are specified for coronary MRA. Navigator echoes are usually positioned to intersect with the dome of the right hemidiaphragm to monitor cranio caudal motion of the diaphragm (and heart). In our experience, this approach works well for volunteers and patients who are cooperative without significant co-morbidity. However, 10-30% of patients will have considerable “drift” of the diaphragm during the acquisition out of the predefined limits for acceptance of the position of the
diaphragm. Optimally, the user could reposition the navigator window during the image acquisition. Unfortunately, this option is not typically implemented by MR vendors at this time. In optimal circumstances, the navigator efficiency approaches 50%, so that scan times for 3D navigated coronary MRA approach 5-8 minutes per arterial segment.\(^7\) However, many circumstances may be encountered where navigator gating efficiency is only 30-40%.

**Contrast enhanced coronary MRA.** Contrast agents are likely to be necessary before there is routine use of coronary MRA for diagnostic purposes. The goal of contrast enhanced coronary MRA is to improve both the signal to noise and contrast to noise ratio of the vessels compared to the adjacent background signal. Unfortunately, in the United States, only extravascular contrast agents are approved by the FDA. In addition, none of these is currently approved for imaging of the heart. These gadolinium based extravascular agents rapid leak from the vessel lumen to adjacent tissues, and may actually decrease contrast to noise ratio depending on the MR pulse sequence. Thus, unless breath-hold techniques are applied, the routine use of gadolinium based extravascular contrast agents for coronary artery visualization is not performed.

Intravascular, or blood pool, contrast agents for MRI are under evaluation for coronary MRA. Example of these include MS-325 (Epix Medical) and B22956 (Bracco). These agents should optimally increased vascular contrast to noise ratio over prolonged periods suitable for navigator coronary MRA.\(^8\)-\(^10\) Improved vessel sharpness as well as increased vascular signal was seen using the contrast agent SH L 643A (Schering, Berlin, Germany).\(^11\)

In order to improve the relative contrast of coronary vascular signal compared to adjacent myocardium and epicardial fat, fat suppression sequences are required.\(^12\) In addition, magnetization transfer contrast pre-pulses (MTC)\(^13\) or more recently T2 preparatory pulses (T2Prep)\(^14,\)\(^15\) have been used to demonstrate vascular signal relative to the lower signal intensity adjacent myocardium.

**MRA Technique**

**Steady state with free-precession (SSFP) coronary MRA:** Conventional fast gradient echo pulse sequences with fat suppression rely on flowing blood to generate vascular signal. Using SSFP pulse sequences, the vascular signal remains high due to the relative T2 weighting of this technique. This approach is the primary method used currently for 3D coronary MRA with navigator gating.\(^16\) The same technique can also be used for breath-hold imaging, although the spatial resolution may need to be lower in order to acquire the entire dataset within a breath-hold acquisition.\(^17\)

**Whole-heart Coronary MRA.** Recent success with coronary CT angiography based on axial imaging has led to revisiting of strategies to perform coronary MRA. Instead of imaging each coronary arterial tree separately,\(^18\) recent approaches have involved imaging a stack of axial images using navigator imaging and SSFP pulse sequences. The advantage of this approach is simplicity for technologist prescription of the coronary MRA. In addition, post-processing tools developed for CTA may be adapted for coronary visualization by MRA. The results of this approach demonstrated coronary angiograms that are very visually appealing.

There are also several disadvantages of the whole heart approach. First, it is difficult to achieve isotropic resolution with MRA, as opposed to coronary CTA. Slice thickness of the coronary MRA for the whole heart approach is approximately 1 mm, while in plane resolution is 700-900 microns. Thus, reformations of the coronary arteries in certain territories may be suboptimal. In addition, in order to achieve 1mm slice thickness for the entire heart, imaging times are prolonged, and may be about 15 minutes. Significant patient motion during that time will be propagated throughout the entire 3D acquisition, as opposed to CTA where only a subset of slices are affected. This approach may benefit by the addition of intravascular contrast agents.
so that scan time could potentially reduced. Despite these drawbacks, the whole heart approach appears to be currently preferred at a number of centers and awaits larger scale trials to determine its utility for coronary artery disease evaluation.

**Clinical Applications of Coronary MRA**

**Anomalous Coronary Artery.** Several series have demonstrated good results for coronary MRA relative to x-ray angiography for the evaluation of anomalous coronary artery. In practice, most clinically significant anomalies can be identified using routine axial imaging, so that either 2D or 3D fast gradient echo MRA with fat suppression or SSFP coronary artery pulse sequences are acceptable. Particularly in young patients for whom radiation exposure is a concern, coronary MRA is preferred for the evaluation of anomalous coronary artery disease.

**Coronary Artery Aneurysms/Kawasaki’s disease.** Kawasaki’s disease is a vasculitis of unknown origin that is prone to affect the coronary arterial tree. Patients with active Kawasaki’s disease are young, often less than 5 years old, and nearly 20% develop coronary artery aneurysms. These patients, as well as young adults with coronary artery ectasia have been reported to be accurately depicted using coronary MRA techniques.

**Coronary artery atherosclerosis.** The largest experience to date is from a multi-center trial conducted exclusively on Philips magnets. These results, which used free breathing targeted coronary MRA technique showed high sensitivity but only modest specificity for >50% diameter stenosis by quantitative coronary angiography. The sensitivity and negative predictive value were high for the identification of left main or multivessel disease. Thus, in some circumstances, it may be feasible to perform coronary MRA, for example, in patients with congestive heart failure or dilated cardiomyopathy in the absence of prior known coronary artery disease. In this setting, it may be feasible to determine if the cardiac disease is ischemic or nonischemic in origin. Clinical trials for this indication have not yet been performed.

Using SSFP whole heart coronary technique, single center studies have reported sensitivities of 80-90% and specificity exceeding 90%. To date, however, this method has not been the subject of large and/or multi-center trials.

**Coronary Artery Bypass Graft Assessment.** Axial coronary MRA has been used to assess bypass graft patency. In addition, both 3D acquisitions and contrast enhanced gadolinium MRA have been described for bypass graft assessment. In our experience, the presence of sternal wires, metal artifacts from hemostatic clips or graft markers results in significant loss of signal in portions of the bypass graft, limiting clinical acceptance.

**Non-Calcific Plaque Detection with MRI**

Angiographic studies with intravascular ultrasound correlation have shown that most myocardial infarctions result from rupture of vulnerable plaque without a significant luminal stenosis. The so-called “vulnerable plaque” is much more likely to cause arterial wall disruption and myocardial infarction than more severe calcified plaques. Thus, there has been considerable focus on MRI techniques to evaluate the coronary arterial wall.

The tendency for plaque to rupture is thought to be related to plaque composition. In particular, a plaque with a large lipid core and associated thin fibrous cap overlying the lipid core is thought to represent a vulnerable plaque. While MRI has been useful to assess plaque composition in the carotid arteries, the likelihood of plaque characterization for coronary arterial lesions is less clear due to resolution limits. Since the thickness of the coronary fibrous cap is on the order of 70 microns, this is well beyond the spatial resolution of coronary MRA (700-900...
microns). Plaque characterization also relies on T2 weighted imaging; these images have much less signal to noise ratio than T1 weighted images and are particularly difficult to acquire of the coronary arteries. Thus, using inherent T1 and T2 contrast of plaque is not likely to be successful. The use of contrast agents that either bind to plaque or plaque components may present greater opportunity for vulnerable plaque detection by MRI.

Currently, the degree of coronary atherosclerosis can be directly identified using “black-blood” magnetic resonance (MR) imaging or CT angiography. CT angiography imaging of “soft plaque” requires the use of iodinated contrast media that is associated with contrast induced nephropathy and allergic reaction. The radiation dose of coronary CT angiography in male patients is 6.7–10.9 mSv for male patients and 8.1–13.0 mSv for female patients. CT angiography radiation dose is 3-6 times higher than invasive x-ray coronary angiography (dose of 2.1 and 2.5 mSv for male and female patients, respectively). Thus coronary CT angiography currently has several major disadvantages as a screening test in the general population, and for assessment of subclinical disease in asymptomatic individuals.

Black blood MRI does not require iodinated contrast media nor ionizing radiation to image coronary artery wall disease. The method is similar to that used for carotid MRI wall evaluation in MESA and other studies. Coronary wall MRI is novel, as technical challenges have only recently been overcome to allow this approach. In particular, motion from both a) breathing and b) cardiac contraction must be eliminated by the MRI pulse sequence (i.e., software program). These methods have been rapidly improved at Johns Hopkins, and images of the coronary wall are obtained in the long axis of the vessel (Figure 1) or a cross-sectional view. Maximum resolution of the method is currently 500-780 µm.

The “wall thickness” in MRI (for both coronary and carotid MRI black blood wall imaging) corresponds to intima, media and adventitial layers, with increased wall thickening in atherosclerosis occurring primarily in the media. Coronary wall MRI has been validated in vivo in animal models and in human coronary artery specimens demonstrating accurate correlation (r=0.94, slope 0.81) between MRI measured wall thickness and matched histopathology sections.

In patient studies, coronary wall MRI identified increased coronary artery wall thickness with preservation of lumen size in patients with nonsignificant coronary artery disease, consistent with a “Glagov-type” outward arterial remodeling. MRI of coronary arteries in patients with >40% stenosis as assessed by x-ray angiography showed localized wall thickening; the difference in maximum wall thickness between the normal subjects and patients was statistically significant (p=0.0001). Individuals with mild, yet angiographically detectable coronary artery disease had a wall thickness by MRI of 1.7 +/- 0.3 mm. Healthy subjects had a wall thickness of 1.0 +/- 0.2 mm.

References


