Role of Magnetic Resonance Imaging in Visualizing Coronary Arteries

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ABSTRACT
Ischemic heart disease is the leading cause of death worldwide. At present, coronary angiography is the gold standard for the diagnosis of coronary artery disease. Conventional coronary angiography is an invasive procedure with a small, yet inherent risk of myocardial infarction, stroke, potential arrhythmias, and death. Other noninvasive diagnostic tools, such as electrocardiography, echocardiography, and nuclear imaging are now widely available but are limited by their inability to directly visualize and quantify coronary artery stenoses and predict the stability of plaques. Coronary magnetic resonance angiography (MRA) is a technique that allows visualization of the coronary arteries by noninvasive means; however, it has not yet reached a stage where it can be used in routine clinical practice. Although coronary MRA is a potentially useful diagnostic tool, it has limitations. Further research should focus on improving the diagnostic resolution and accuracy of coronary MRA. This review summarizes results from several studies comparing coronary MRA with conventional coronary angiography. Current two-dimensional and three-dimensional coronary MRA techniques and their limitations are also discussed.
INTRODUCTION

Ischemic heart disease is the leading cause of death worldwide. For patients with coronary artery disease (CAD), treatment consists of medical therapy, percutaneous intervention, or coronary artery bypass grafting. The most essential diagnostic tool to evaluate graft disease is coronary angiography. This technique provides rapid and accurate delineation of the entire coronary anatomy including the graft, and the native non-grafted coronary arteries, and it is generally used as a prelude to revascularization procedures.

Coronary magnetic resonance angiography (MRA) is a technique that allows the visualization of coronary arteries by non-invasive means. Since it was first reported by Paulin et al. in 1987, coronary MRA has gained considerable importance as a method that could be used to diagnose coronary artery stenoses. The potential benefit of coronary MRA is not only the visualization of coronary arteries, but also the visualization of the cardiac morphology, acquired diseases of the great vessels, and cardiac function at rest and under stress. Other benefits of MRA include assessment of the patency of aorto-coronary bypass grafts, anomalous coronary arteries, and possible stability of plaques without significant exposure of ionizing radiation. However, further studies are needed to corroborate these findings.

Conventional coronary angiography is considered the gold standard for the visualization of CAD. Nevertheless, conventional coronary angiography is an invasive procedure. It involves a small but significant risk of acute myocardial infarction, and potential arrhythmias. It is also the visualization of coronary arteries, but also the visualization of the cardiac morphology, acquired diseases of the great vessels, and cardiac function at rest and under stress. Other benefits of MRA include assessment of the patency of aorto-coronary bypass grafts, anomalous coronary arteries, and possible stability of plaques without significant exposure of ionizing radiation. However, further studies are needed to corroborate these findings.

CURRENT CORONARY MRA TECHNIQUES AND TECHNICAL LIMITATIONS

Coronary MRA has evolved as a promising non-invasive modality for the imaging of the coronary arteries. It is also useful in the evaluation of coronary artery stenoses.

Images obtained during coronary MRA can be visualized in 2-dimensional (2D) or 3-dimensional (3D) views. The cardiac contractions and the motion of the diaphragm limit the quality of images. Different techniques, such as a breath hold technique versus a free breathing with navigator echo-based technique, have been employed to overcome these limitations. For a 2D coronary MRA utilizing the breath hold technique, the patient may be required to do 30 or more breath holds for 16-20 seconds, and may be even longer for a 3D coronary MRA. On the other hand, the free breathing with navigator technique enables respiratory synchronization of image acquisition to a specific phase and spatial location of the diaphragm with prospective or retrospective gating (figure 1).

Two main approaches have been developed to visualize the endovascular lumen. In the conventional spin-echo approach, the areas of the vessel with turbulent flow (non-stenosed segments) appear black, whereas in the commonly used gradient-echo approach, the vessels with laminar flow appear dark in color, and those with turbulent flow secondary to stenoses appear bright. Other technical impediments include a relatively small coronary artery diameter (2.7 to 3.5 mm), tortuous course of the vessel, and the surrounding epicardial fat. Furthermore, the interpretation of the imaging of a left circumflex coronary artery in MRA is limited by difficulty to distinguish the artery from parallel running cardiac veins.

Several studies have assessed the diagnostic accuracy of 2D and 3D coronary MRA in comparison to conventional coronary angiography. Although not yet standardized, the current method for coronary MRA combines fast imaging 3D techniques with respiratory gated coronary MRA using navigator echo that improves its diagnostic accuracy. The navigator echo technique seems to have more application in clinical practice, as the breath hold technique is not always possible for patients with congestive heart failure, CAD, and chronic obstructive pulmonary disease. However, in those cases the quality of images may be degraded due to inconsistent breathing patterns and patient movements.

The other alternative techniques include magnetic resonance subtraction methods, which include selective tagging of blood in the aortic root and suppression of the background tissue. This method holds potential for visualization of the proximal portion of the coronary artery, but the length of the vessel can only be visualized if there is blood flow throughout the coronary artery. Thus, if the blood flow is impaired in the presence of coronary artery stenoses, visualization of the entire artery is not possible. Other techniques, such as spiral acquisition echo planar imaging and segment echo planar imaging techniques, provide a complete 3D data set encompassing the entire heart and can be acquired in one or two breath holds.
TWO-DIMENSIONAL CORONARY MRA

Edelman et al.17 published the first report of a clinical application of 2D coronary MRA to visualize the coronary arteries in 1991, though the first comparison of the results of 2D coronary MRA with conventional coronary angiography was done by Manning et al.18 in 1993. Overall, the sensitivity and specificity of the 2D coronary MRA technique for correctly identifying the significant stenoses in the coronary artery (>50%) based upon coronary angiography was 90% and 92%, respectively. Studies by Duerinckx and Urman,19 Pennell et al.,20 and Post et al.21 failed to reproduce Manning’s results.

One of the few studies in which a large number of patients were evaluated with 2D coronary MRA utilizing the breath hold technique was performed by Watanuki et al.22 involving 108 patients. When compared with coronary angiography, this technique was very sensitive (85%) and specific (80%) for diagnosing severe coronary artery stenoses (90% to 100%), but for moderate stenoses (more than 50%), the sensitivity was as low as 38%, while the specificity was 83%. The low sensitivity was attributed to the method of detecting the stenoses. The detection of stenoses was dependent upon the presence of a decrease in the signal intensity secondary to a decrease in the blood flow. The rate of blood flow can be significantly affected by the tortuous course of the artery, as well as the characteristics of stenoses. The quality of images was distorted by the inability of the patient to hold his or her breath for 15 seconds and/or the slight movements of the diaphragm.

It should be noted that 2D gradient-echo breath-hold coronary MRA has several drawbacks:

1. Relatively thick sections (4-6 mm in most studies) may preclude an exact grading of focal stenoses.18,20 This probably also explains the limited evaluation of tortuous vessels and the distal portions of major coronary arteries, especially the left circumflex coronary artery.20,23,24

2. Different oblique planes are required for different patients and for the visualization of different arteries.23,24

3. Multiple breath holds can be a practical problem in certain patient populations with a history of congestive heart failure, chronic obstructive pulmonary disease, and severe CAD.11,12

4. Inconsistent breath-holds and misregistration between breath holds may lead to inadequate vessel assessment.24-26

THREE-DIMENSIONAL CORONARY MRA

The first 3D coronary MRAs were used by Paschal et al.27 and Li et al.28 in 1993. However, these studies did not employ the use of the navigator-based echo technique; they used the method of averaging multiple acquisitions without respiratory synchronization. Significant blurring has been reported with those techniques.29 Hofman et al.30 used the navigator echo techniques for the first time and compared
the results of 2D breath holding with 3D respiratory gating technique. Post et al.31 studied 20 patients who had undergone respiratory gated 3D coronary MRA and conventional coronary angiography. The studies concluded that even though these techniques provide a good view of proximal, as well as middle segments of the coronary arteries, the sensitivity for detecting coronary artery stenoses was decreased to 38%, however, the specificity remained as high as 95%. The low sensitivity was likely due to the differences in the techniques relating to relatively poor temporal resolution, shorter echo time, poor patient cooperation with breath holding, or irregular rhythms, all of which attribute to image degradation.12

The study by Kim et al.32 was the first multicenter trial where 109 subjects were evaluated for CAD by the free-breathing 3D technique. However, this technique was limited to evaluation of proximal and middle segments only. In this study a total of 636 of 759 proximal and middle segments of coronary arteries were interpretable. A sensitivity of 83% was reported for this technique. However, lesions in the left main coronary artery in patients with three vessel disease could be identified with some certainty in a limited number of patients.33 The study also stated that major limitations with the 3D technique are the relatively longer time (average 70 minutes), low specificity (42%), and low overall diagnostic accuracy (72%).

Muller et al.33 conducted a study in which 35 patients underwent coronary MRA with single slab, three dimensional gradient-echo sequences employing a spin-echo navigator echo measurement and conventional angiography. The sensitivity, specificity, and positive and negative predictive values of coronary MRA in detecting significant stenoses (>50%) were 83%, 94%, 87%, and 93%, respectively. The high sensitivity and specificity reported from this study was never reproduced in other studies. A major limitation in this study was that only proximal and middle segments of the main coronary arteries were considered and the number of subjects was small. Kessler et al.34 conducted a similar study in 73 patients who had undergone cardiac catheterization as well as 3D respiratory-gated coronary MRA. The sensitivity and specificity for the diagnosis of stenoses in the proximal and middle coronary arteries was 65% and 88%, respectively. Sandstede et al.35 reproduced similar results in a study of 30 patients determining the sensitivity and specificity of detecting coronary artery stenoses in the four main coronary arteries at 81% and 89%, respectively. The small number of subjects and evaluation of only the proximal and middle portions of the coronary arteries were limitations of this study.

Sardenelli et al.36 tried to identify the sensitivity of 3D navigator echo coronary MRA in detecting stenoses of the coronary arteries in a group of 42 patients. They concluded that coronary MRA has a sensitivity of 82% and specificity of 89%, and that 3D coronary MRA has increased sensitivity for the detection of stenoses in the proximal segment of the coronary artery. The sensitivity was 90% for proximal and middle segments, but dropped to 68% when distal segments were included.

Weber et al.37 conducted a blinded study of the respiratory motion compensated technique (motion-adapted gating) for visualization of the coronary arteries in 15 subjects (11 patients and 4 volunteers).10 Results revealed that the coronary MRA correlated with coronary angiography. They used the electrocardiography-triggered respiratory motion gated 3D turbo field echo sequence technique defining a sensitivity of 88% and a specificity of 94%, with positive and negative predictive values of 83% and 96%, respectively. However, the motion-adapted gating concept has substantial limitations. It assigns more importance to the contrast than to the edge definition. Edge definition and sharpness are the prerequisites for stenosis detection and quantification. This results in high false positive values (e.g., in this study, five patients and two volunteers received high false positive values) and still remains a technical problem to be solved.

Watanabe et al.38 performed a study involving 12 patients. All 12 patients had undergone conventional coronary angiography, as well as high resolution selective 3D coronary MRA by orienting the 3D slab along the major axis of the right coronary artery, left circumflex or left main, or the left anterior descending group. On retrospective analysis, the sensitivity, specificity, and accuracy of identification of significant coronary artery stenoses was 80%, 85%, and 84%, respectively. Even though high resolution selective coronary MRA can provide information on segmental anatomy in detail, this technique has low sensitivity for the left circumflex artery. The other major problem with this method is its lengthy examination time that may cause degradation in image quality due to body motion.

Two studies have been performed where the use of the 3D coronary MRA with free breathing respiratory gating technique was used with some other techniques. Regenfus et al.39 compared the results of the contrast enhanced breath holding technique with the free breathing respiratory gating technique in 38 patients. The sensitivity using the breath holding technique was 86.7%, and significantly higher than the free breathing respiratory gating technique (60%). The higher sensitivity of the breath holding technique than the free breathing respiratory gating technique can be attributed to improvement in the imaging quality secondary to the use of contrast media. Contrast enhanced image relies on anatomic enhancement of stenoses rather than on flow effect.39,40 Moreover, it can be assumed that respiratory gating may be an ineffective technique in improving image quality.

Nikolaou et al.41 studied 20 patients who had undergone contrast enhanced computed tomography (EBCT) and
navigator echo-based coronary MRA with retrospective gating. The results were compared with conventional coronary angiography. The sensitivity and specificity for detecting significant stenoses with coronary MRA were 79% and 70%, respectively, and with EBCT the sensitivity and specificity were 85% and 77%, respectively. The low sensitivity with 3D coronary MRA was attributed to inadequate synchronization during the end-expiration phase. EBCT has the advantage of better image quality and less need for patient cooperation, but it also has certain disadvantages, for example, the patient is required to hold his/her breath for approximately 35 seconds. Furthermore, not much progress has been made in the technology, and EBCT is not commonly available in many facilities. Nevertheless, 3D coronary MRA also has several limitations:

1. Some images may not be obtained during the desired end expiratory phase.41
2. Patient cooperation is essential with regular, rhythmic respiration and no movement for the whole acquisition time of approximately 35 minutes.41
3. Temporal and spatial resolutions are critical factors for image quality in coronary MRA.29,42

ADDITIONAL APPLICATION OF CORONARY MRA

Coronary MRA is a diagnostic modality with excellent soft tissue contrast and, therefore, permits visualization and analysis of plaques and the components of the arteries. This has been shown in the atherosclerotic lesions in vitro and in vivo in large arteries such as the carotid arteries.43,44

Coronary MRA is highly effective in detecting coronary artery anomalies and can be regarded as a definite tool for diagnosis.45 Conventional coronary MRA is an important diagnostic tool for the diagnosis of patency of coronary artery bypass grafts, as the arteries have lesser mobility with cardiac and respiratory motion and also have a larger lumen (5-10 mm).46

Nagel et al.3 compared high dose dobutamine stress magnetic resonance imaging (DMRI) with dobutamine stress echocardiography and found that DMRI was more sensitive and more specific than dobutamine stress echocardiography in the detection of myocardial ischemia using coronary stenosis by arteriography as the gold standard. Hundley et al.47 reported that DMRI provides excellent diagnostic information as well as prognostic information. Cardiac MRI is ideally suited for the detection of myocardial viability because of its ability to assess the transmurality of myocardial scar, as well as myocardial performance.48 At the present state of technical development, the sensitivity and specificity of coronary MRA with retrospective navigator echo respiratory triggering is only modest. The technique is poor and not useful as a screening method for CAD.49

CONCLUSION

Coronary MRA is a rapidly evolving, new non-invasive technique. Although coronary MRA presently has limited clinical utility, it has the potential to aid in the diagnosis of coronary artery stenoses with a high degree of accuracy, especially in the proximal and middle segments, but remains challenging for distal coronary arteries. Magnetic resonance technology has some limitations, which makes it difficult to have better visualization of the coronary arteries. These limitations are secondary to the tortuous course of the coronary arteries, coronary arteries of smaller diameter (2.7 to 3.5 mm), rapid movement caused by respiratory and cardiac contractions, and the surrounding epicardial fat.5,50 It may also be difficult to distinguish the coronary arteries from the parallel running coronary veins during the interpretation of coronary MRA, especially for the left circumflex coronary artery.12,18,20,24,25

Even though coronary MRA is a potentially useful clinical application, especially in patients with a low probability of CAD, it does not allow visualization of smaller vessels, such as side branches or the distal segments of large epicardial arteries.10 Several approaches to coronary MRA have been described, but no one technique can be universally applied.11

Future research should focus on the development of optimal respiratory compensation strategies by improving the diagnostic and spatial resolution to visualize greater lengths of coronary arteries and faster acquisition of the data. New strategies are being investigated to improve the diagnostic accuracy, especially with the use of intravenous contrast media, and also to decrease the acquisition time with volume target imaging.51 It is conceivable that advances in technology will help in achieving this goal in the not too distant future.

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