Coronary MR Angiography: Current Status

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Abstract
Since first described in the early 1990s, coronary magnetic resonance angiography (MRA) has evolved as a promising noninvasive modality for imaging of the coronary arteries and evaluation of coronary artery disease. Despite technical limitations, coronary MRA has established value for imaging of anomalous coronary arteries and assessment of bypass graft patency. Current research focuses on the development of optimal respiratory compensation strategies, improved spatial and temporal resolution and faster acquisition of image data. The accurate detection of stenoses and assessment of the severity of coronary atherosclerosis is presently being evaluated with large multicenter studies. With further technique enhancements and more clinical experience, coronary MRA is likely to become the dominant noninvasive modality in clinical cardiology.

Key Words: Magnetic resonance angiography · Coronary artery imaging

Aktueller Stand der koronaren MR-Angiographie

Zusammenfassung

Schlüsselwörter: Magnetresonanztomographie · Darstellung von Koronararterien

Introduction
Despite improvements in both prevention and treatment, coronary artery disease remains the leading cause of morbidity and mortality in industrialized nations [1]. While numerous noninvasive tests are available to detect regional ischemia, direct assessment of coronary artery integrity would represent a major advance in clinical care. Over the past decade, clinical magnetic resonance angiography (MRA) of large vessels such as the aorta and carotid arteries has been widely accepted. MRA of the coronary arteries, however, offers particular challenges. Early attempts to image the proximal coronary arteries with conventional ECG-gated spin-echo sequences were only occasionally able to identify the coronary ostia [30, 42], but did not succeed in visualizing longer coronary artery segments or focal stenoses. The main obstacles to coronary MRA include: a) the small diameter (3 to 4 mm) of coronary vessels; b) motion artifacts from cardiac contraction and respiration-related bulk cardiac motion; c) the presence of high signal from the surrounding epicardial fat; and d) the tortuous course of the vessels, which results in luminal discontinuities on tomographic imaging due to vessel deviation outside the image plane. Despite these limita-

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tions, the potential to obtain images with high spatial and temporal resolution, the absence of associated exposure to ionizing radiation and the ability to image in any orientation have been attractive advantages of MRA, in particular for coronary artery imaging. Other noninvasive modalities, including echocardiography and computerized tomography, have additional limitations, such as the poor penetration and resolution (for echocardiography) and the need for X-ray exposure, iodinated contrast administration and prolonged breath-holding (for computed tomography). Accordingly, coronary MRA has emerged as the most promising noninvasive test for assessment of coronary artery integrity. Over the last 10 years, the field of coronary MRA has progressed rapidly, with research advances in several parallel areas, as described in the following discussion.

**Methods for Respiratory Compensation**

In addition to ECG-gating, all current coronary MRA approaches utilize some form of respiratory compensation, including breath-hold and free-breathing techniques. Although breath-holding is attractive because it offers the potential to quickly obtain image data, it also carries significant limitations due to breath-hold duration and frequent need for breath-hold repetition. Breath-holding requires detailed patient instruction/coaching and considerable motivation and cooperation. The breath-hold duration also limits spatial and temporal resolution as well as the use of signal enhancements (such as averaging). Many patients, especially those with cardiac or pulmonary disease, have difficulty sustaining adequate breath-holds. Although breath-holding ability can be augmented with the use of respiratory maneuvers such as supplemental oxygen and hyperventilation [9, 34], such maneuvers still require significant patient involvement and are not practical for the general population. Furthermore, there is significant variability of the breath-hold level even in motivated subjects, which may account for varying cardiac position among serial breath-holds and poor slice registration. The result may be gaps between the coronary segments, which could be misinterpreted as signal voids from coronary stenoses. Finally, during prolonged breath-holds, the diaphragm (and heart) drifts towards a more cephalad position [9], thereby contributing to blurring and image degradation. Although alternative suspended respiration techniques, including multiple brief breath-holds [14] and coached breath-holding with visual or audible feedback [31, 64], have been used to minimize respiratory motion artifacts and patient inconvenience, these approaches are only appropriate for highly motivated subjects. Thus, while multiple breath-hold strategies are often successful with motivated healthy volunteers, their applicability to the broad range of patients with cardiovascular disease is more limited.

To overcome the limitations of breath-hold imaging, free-breathing, respiratory-compensated coronary MRA methods have been developed. The respiratory cycle may be easily monitored with the use of respiratory belts to track chest wall expansion. Image acquisition can thus be gated to a certain part of the respiratory cycle (commonly to the end-expiratory – minimal expansion position). Coronary MRA using such devices has been shown to be both feasible and practical [6, 23, 36, 40, 64]. However, external respiratory bellows-gating is not robust, possibly due to temporal dissociation between chest wall expansion and cardiac motion.

A more direct and elegant method of monitoring diaphragmatic and resultant cardiac displacement during free breathing is with the use of MR navigators, a technique that provides real-time positional data about moving structures. If, for example, the navigator beam is positioned at the base of the left ventricle, in close proximity to the coronary artery ostia, the respiration-related basal cardiac motion can be monitored, and image acquisition can be gated to effectively “freeze” the respiratory motion of the proximal epicardial coronary vessels. Because of limitations of the navigator implementation on certain vendor hardware platforms (related to local signal loss – spin-echo navigators) and because of relatively complicated navigator positioning at the cardiac base, a vertical navigator is commonly positioned on the dome of the right hemidiaphragm. Assuming a good correlation between coronary and diaphragmatic position during the respiratory cycle, diaphragmatic positional information can be used to gate coronary MRA acquisitions. The use of prone imaging appears to be particularly beneficial (Stuber M, unpublished data). Although there is significant individual variability in the respiratory kinematics of the heart (coronaries) and the diaphragm, recent approaches have been shown to consistently provide sufficient image quality for major coronary artery visualization. Several navigator implementations have been described