Coronary Magnetic Resonance Angiography – 1.5T Techniques

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Introduction

The current gold standard for the diagnosis of coronary artery disease is x-ray coronary angiography. Both in the United States and in Europe, approximately 1 million cardiac catheterizations are performed each year. However, x-ray coronary angiography is expensive, invasive, ionizing radiation exposure for the patient and the operator has to be taken into account, and a small risk of serious complications exists. Thus, there is a strong need for a more cost-effective, non-invasive, and patient friendlier technique. Coronary magnetic resonance angiography (MRA) combines several advantages and great potential: Due to its non-invasiveness it is patient friendly, it is cost effective, a high spatial resolution can be obtained, it can survey in any image plane, and no exposure to potentially harmful ionizing radiation has to be taken into account. Therefore, the utility of coronary MRA has been investigated since the late 1980s (1,2). Although no coronary stenoses were identified in these early studies, the potential of MR imaging to assess the anatomy of the coronary vessels was demonstrated, and triggered further interest in this field. For successful coronary MRA data acquisition, a series of major ***technical*** obstacles have to be overcome. The heart is subject to ***intrinsic*** and ***extrinsic motion*** due to its natural periodic contraction and due to breathing. Both of these motion components exceed the coronary artery dimensions multiple times and therefore, coronary MRA data acquisition in the sub-millimeter range is technically very challenging. In addition, an ***enhanced contrast*** between the coronary lumen blood pool and the surrounding tissue is mandatory for a successful visualization of the coronary anatomy.

Spatial Resolution

The spatial resolution achievable with MR imaging (>700µm in plane resolution) is inferior to that obtainable with x-ray coronary angiography (<300 µm) (3). For MR imaging, improvement in spatial resolution is accompanied by a trade-off in terms of reduced signal-to-noise ratio (SNR). As the voxel size approaches that of x-ray angiography, methods to reduce extrinsic and intrinsic motion of the coronary arteries become increasingly important (4).

Motion suppression in coronary MRA

Using ECG triggering for coronary MRA data acquisition in conjunction with ***segmented diastolic k-space acquisition*** and a ***short acquisition interval*** (5), adverse effects of natural myocardial contraction and relaxation on image quality can be minimized. In fact, and in order to limit the residual coronary motion of all the coronary segments to <1mm simultaneously, an acquisition interval of 30ms only would be necessary(4). To compensate for respiratory motion, ***breath-holding*** was implemented early to allow for suppression of respiratory motion. Two-dimensional (2D) breath-hold coronary MRA relied on acquiring contiguous images, with the goal of surveying the proximal segments of the coronary arteries during serial breath-holds. Three-dimensional (3D) breath-hold techniques for coronary MRA have also been implemented (6-10). Breath-hold approaches offer the advantage of rapid imaging and are technically easy to implement in compliant subjects. However, breath-holding strategies have several limitations. Some patients may have difficulty sustaining adequate breath-holds, particularly when the duration exceeds a few seconds. Additionally, it has been shown that during a sustained breath-hold there is cranial diaphragmatic drift (11), which is substantial in many cases (~1cm). Among serial breath-holds, the diaphragmatic and cardiac positions frequently vary by up to 1 cm, resulting in registration errors (6,12). Misregistration results in apparent gaps between the segments of the visualized coronary arteries, which could be misinterpreted as signal voids from coronary stenoses. Finally, the use of signal enhancement techniques, such as signal averaging or fold-over suppression is significantly restricted by the duration of the applicable breath-hold duration. Using breath-holding techniques, the spatial resolution of the images is also governed by the patient's ability to hold his/her breath. Thus, while breath-hold strategies are often successful with motivated volunteers, their applicability to the broad range of patients with cardiovascular disease is still limited.

To overcome limitations associated with breath-holding, methods have been developed to allow for free-breathing coronary MRA. ***MR navigators*** (13), have been implemented for coronary MRA. With vertical positioning of the navigator at the dome of the right hemidiaphragm (lung-liver interface), the diaphragmatic craniocaudal displacement can be monitored. These data can be used to gate coronary MRA acquisitions. The gating process can be either prospective (i.e. before data acquisition) or retrospective (i.e.

following data acquisition, but before image reconstruction). Although navigator approaches greatly improve patient comfort and do not require significant subject motivation, their use prolongs the scan duration by a factor of ~2 since coronary MRA data are collected on average during 50% of the RR intervals (14). Typical examination times with free-breathing 3D real-time navigator approaches are ~7min for targeted approaches and up to 15min for whole heart data acquisition (15,16). While disadvantages of navigators include prolonged scanning times and inability to complete scans in cases of excessive patient motion or severe diaphragmatic drift, more recent developments in the area of ***self navigation*** (17) (18) and related techniques (19) may provide powerful solutions.

Contrast enhancement in coronary MRA

Using MRI, the contrast between the coronary blood-pool and the surrounding tissue can be manipulated using the ***in-flow effect*** (20) or by the application of ***MR pre-pulses***. Non-exogenous contrast enhancement between the coronary arteries and the surrounding tissue has been obtained by the use of fat-saturation pre-pulses (20), magnetization transfer contrast pre-pulses (MTC) (21) or more recently T2 preparatory pulses (T2Prep) (22,23) that take advantage of natural T2 differences between blood and surrounding myocardium. With these techniques, the coronary lumen appears bright and the surrounding tissue including fat and myocardium appear with reduced signal intensity.

Alternatively, with the use of ***MR contrast agents***, the T1 relaxation of blood can be shortened, allowing for increased contrast-to-noise ratio (CNR) for coronary MRA (24,25). Since ***extracellular agents*** quickly extravasate into the extravascular space, their use traditionally required rapid first-pass imaging, and thus breath-holding (8). The use of ***intravascular agents*** has the inherent advantage of allowing image acquisition over longer time periods after intravenous administration of the contrast agent. Thus, non-breath-hold schemes can be employed, and repeated scans have similar CNRs without the need for repeated injections (24). More recent progress including the use of higher magnetic field strength, slow infusion of extracellular contrast agents, and parallel imaging also led to a considerable contrast enhancement in free-breathing navigator gated whole heart coronary MRA (26). In comparison to contemporary steady state with free precession coronary MRA at 1.5T, this advanced technique leads to a reduced acquisition time, higher CNR, and better depiction of coronary segments (27).

Imaging sequences used for coronary MRA

In general, coronary MRA consists of a motion suppression module (ECG triggering, short acquisition interval, navigators…), a magnetization preparation module (fat saturation, T2Prep…), and an imaging module. This imaging module of the sequence typically quite short (<100ms per RR interval), it follows magnetization preparation pre-pulses and navigators, and it is typically performed in mid-diastole, a period of minimal myocardial motion. Currently, this imaging module mainly consists of the imaging techniques that are listed below.

Segmented k-space gradient echo coronary MRA: With the advent of segmented k-space gradient echo techniques, coronary MRA data collection during a short acquisition interval within a single breath-hold of ~15sec became technically feasible (20). Advantages of segmented k-space gradient echo imaging include the relative low sensitivity to flow or motion artifacts and to off resonance effects. This makes it a very robust and reliable technique. For these reasons, many of the earlier 2D and 3D studies were conducted using this imaging approach. However, it does not provide intrinsic blood-muscle contrast. In comparison with steady-state with free precession (SSFP) methods, both SNR and CNR are reduced but imaging at a higher spatial resolution is currently less challenging. Multicenter experience exists with segmented k-space gradient echo coronary MRA (5).

Steady-state with free-precession (SSFP) coronary MRA: With this method, high signal in the coronary arteries and very high contrast between the ventricular blood-pool and the myocardium can be obtained without the need for exogenous contrast enhancement (28). SSFP imaging permits high quality coronary MRA during free breathing with improvements in SNR, CNR and vessel conspicuity when compared with standard T2-prepared segmented k-space gradient-echo imaging, albeit at the expense of a slightly reduced in-plane spatial resolution. Therefore, the utility of SSFP for the identification of significant luminal proximal coronary artery disease is currently being investigated by many clinical and research centers. In many centers, 1.5T 3D SSFP is currently the method of choice and the majority of the whole heart studies (29) are conducted with SSFP (15). Currently, no multicenter experience has been reported.

Spiral coronary MRA: While early attempts for coronary MRA data acquisition in the sub-millimeter range included 2D spiral acquisitions with outstanding image quality (30), this technique has not been widely applied. Advantages of spiral techniques include a most efficient way to sample k-space with high SNR, while adverse effects of flow artifacts can be minimized. Therefore, the extension of spiral coronary MRA with a 3D acquisition strategy (31,32), an interleaved segmented approach (32), and real-time navigator technology for free-breathing coronary MRA data acquisition has shown to be a very valuable alternative for high-resolution coronary MRA (33). However, spiral imaging is not readily available on all MRI platforms and challenges include fat suppression and off-resonance artifacts. No multicenter experience has been reported using spiral coronary MRA.

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