INTRODUCTION—IMAGING OF ATHEROSCLEROTIC DISEASE

Reliable noninvasive imaging tools that can detect various stages of atherothrombotic disease in different vessel regions and characterize the composition of the plaques are clinically desirable (1). Such imaging tools would improve our understanding of the pathophysiological mechanisms underlying atherothrombotic processes and allow us to better risk-stratify the disease. Future goals are optimal tailoring of treatment and direct monitoring of the vascular response. Currently available imaging techniques for the diagnosis of coronary artery disease (CAD) are subject to several limitations. Conventional coronary angiography, widely accepted as the gold standard for the detection of coronary artery disease, demonstrates the degree of luminal narrowing, but fails to visualize the coronary artery wall. It has been shown that plaque composition rather than the severity of an actual stenosis predicts the risk of plaque rupture and acute clinical complications of coronary artery disease (2–4). Thus, new imaging techniques that can image the artery wall and characterize different lesion types may allow for identification and follow-up of patients at risk and for selecting appropriate therapeutic strategies (5).

Presently, a number of imaging modalities are employed to study atherosclerosis and to assess luminal diameter, wall thickness, and plaque volume (6). Two noninvasive imaging modalities, computed tomography (CT) and magnetic resonance imaging (MRI), have been introduced for the study of atherothrombosis. Both have been shown to be capable of imaging vessel wall structures and differentiating various stages of atherosclerotic wall changes. The latest generation of multidetector-row computed tomography (MDCT) scanners allow for sufficiently reliable detection of significant proximal coronary stenoses (7), quantitative measurement of atherosclerotic burden including calcified and noncalcified plaques (8), and characterization of the plaque components (1). MRI has been applied in various in-vivo human studies to image atherosclerotic plaques in carotid (9,10) and aortic (11) arterial disease. In vivo imaging of the coronary artery wall is challenging because of a combination of cardiac and respiratory motion artifacts, and the tortuous course, small size, and location of the vessels. Initial in vivo studies in human coronary arteries have used noninvasive black-blood spin-echo techniques with breath-holding (12) or a real-time navigator for respiratory gating (13).

By possibly combining the advantages of both techniques, detecting significant stenoses and describing the plaque composition at the same time, information could be provided that may predict cardiovascular risk, facilitate further study of atherothrombosis progression and its response to therapy, and provide for assessment of subclinical disease.

PLAQUE IMAGING—METHODS

METHODS OF CT PLAQUE IMAGING

In 2002, newly developed 16-row CT systems were clinically introduced, allowing for faster data acquisition with improved spatial resolution (14). Primary requisites for a sufficient delineation and depiction of atherosclerotic calcified and noncalcified plaques are similar to the requirements for a high-quality CT angiography (CTA) of the coronaries—i.e., a high spatial and high temporal resolution at the same time. There are several advantages of a 16-row CT system over a 4-row CT system concerning the depiction of coronary artery plaques. A direct comparison of a 4-row CT and a 16-row CT image clearly demonstrates this advantage (Fig. 1). First, the gantry rotation time in 16-row CT for cardiac investigations is 420 ms, allowing a temporal resolution of =210 ms. This is a gain of about 20% over the temporal resolution of a 4-row CT system. With higher heart rates and multisegment-reconstruction algorithms, the exposure time varies between 105 and 210 ms, depending on the actual heart rate (15). Second, the slice thickness is reduced from 1.25 mm to 0.75 mm, allowing for an improved spatial resolution along the z axis. This way, using 16-row CT, almost isotropic voxels can now be acquired. Based on the improved spatial resolution, “blooming” artifacts of calcium deposits in the vessel wall are reduced as a result of decreased partial-volume effects. This allows for improved depiction and delineation of calcified and noncalcified plaques.
Third, and probably most important, the complete heart can now be covered in a significantly shorter breath-hold time of less than 20 s, compared to 35- to 40-s breath-hold time on a 4-row CT. This results in a considerable reduction of motion artifacts and allows for a substantial reduction in contrast volume compared to previously published protocols on 4-row CT. Compared to low-pressure arterial systems such as the pulmonary arteries, where calcifications are absent and the injection rate can be increased to visualize the smallest arterial branches, in coronary arteries the opacification must not exceed approx 300 Hounsfield units (HU) for a reliable depiction and judgment of calcifications. Optimization of vessel contrast-to-noise ratio (CNR) is also mandatory for sufficient visualization of noncalcified plaques, and can be performed either by a test bolus setting (20 mL + 50 mL NaCl) or a bolus tracking. Because nonenhanced blood on CT has attenuation similar (50–70 HU) to that of noncalcified plaques, this type of lesion can be detected only after administration of contrast medium. Therefore, a vessel enhancement significantly above the CT values of noncalcified lesions (150 HU) must be achieved to allow for reliable detection. A target attenuation of 200 HU seems best suited to fulfill this requirement. With this vessel enhancement, calcified coronary lesions remain detectable because their attenuation is significantly higher (16).

METHODS OF MR PLAQUE IMAGING

High-resolution MR has emerged as the potential leading noninvasive in-vivo imaging modality for atherosclerotic plaque characterization. MR differentiates plaque components on the basis of biophysical and biochemical parameters such as chemical composition and concentration, water content, physical state, molecular motion, or diffusion (17). MR provides imaging without ionizing radiation and can be repeated over time. In-vivo MR plaque imaging and characterization have been performed utilizing a multicontrast approach with high-resolution black-blood spin-echo and fast spin echo (FSE) based MR sequences. The signal from the blood flow is rendered black through preparatory pulses (e.g., radiofrequency spatial saturation or inversion recovery pulses) to better image the adjacent vessel wall (18). However, bright blood imaging (i.e., 3D fast time of flight) can be employed in assessing fibrous cap thickness and morphological integrity of the carotid artery plaques (19). This sequence enhances the signal from flowing blood, and a mixture of T2 and proton density contrast weighting highlights the fibrous cap. Atherosclerotic plaque characterization by MR is generally based on the signal intensities and morphological appearance of the plaque on T1-weighted, proton density–weighted, and T2-weighted images as previously validated (see references in recent reviews by Fayad et al. [6] and Yuan et al. [20]).

PLAQUE IMAGING—APPLICATIONS

APPLICATIONS OF CT PLAQUE IMAGING

Noncoronary Plaque Imaging With CT

Several precedent studies in animals and humans in other vascular territories than the coronary arteries have demonstrated the ability of CT to differentiate calcified, fibrous, and lipid-rich plaque components based on CT attenuation (HU). CT is described as an accurate, noninvasive means for studying detailed plaque morphology and composition in the carotid arteries. According to Estes et al. (21), CT accurately defined plaque features containing calcium, fibrous stroma, and lipids in carotid arteries. Using tissue attenuation values, CT distinguished between lipid and fibrous stroma (means 39 ± 12 HU and 90 ± 24 HU, respectively, p < 0.001). Oliver et al. (22) tried to assess whether features seen at CTA might be used to predict carotid plaque stability by comparing CT angiograms with histopathologic examinations of the carotid artery bifurcation.