NEW HIGH-RESOLUTION IMAGING TECHNOLOGIES HAVE ENHANCED OUR UNDERSTANDING OF THE CORONARY atherosclerotic disease process, and this atlas provides a multimodality pictorial review of the development of histologically verified coronary atherosclerosis. A modified American Heart Association classification scheme system based on morphological plaque features and the propensity of plaque for thrombosis or cause of sudden cardiac death has recently been proposed. This classification scheme incorporates 5 categories of coronary atherosclerotic lesions (Table 1) (1,2). These categories include nonatherosclerotic lesions (intimal thickening and intimal xanthoma) and progressive atherosclerotic lesions (pathological intimal thickening, fibroatheroma, thin fibrous cap atheroma, rupture, erosion, calcified nodule, and fibrocalcific plaque). The description of these categories is based on the accretion of lipid in relationship to fibrous cap formation, lipid pool transition into necrotic core, the thinning or thickening of fibrous cap, and presence of thrombosis. Furthermore, plaque characteristics such as angiogenesis, intraplaque hemorrhage, inflammation, calcification, cell death, and proteolysis are presented as descriptive terms along with features like culprit lesion associated with thrombus. This multimodality imaging atlas of ex vivo human hearts illustrates this morphological classification through computed tomography (CT), intravascular ultrasound (IVUS), optical frequency domain imaging (OFDI) and corresponding histological characteristics (Figs. 1 to 7) (3–8).
Figure 1. Adaptive Intimal Thickening With Focal Loss of Media

The earliest change in the arterial wall that can be detected by current imaging technologies is intimal thickening. These lesions can be detected soon after birth, consisting mainly of proteoglycan-rich matrix and smooth muscle cells. Histopathology (A) demonstrates three distinct layers: intima (I), media (M), and adventitia (A). The intima is asymmetrically thickened (black arrowheads), the normal media is seen between the external elastic membrane (EEM) and internal elastic membrane (IEM) while a focal loss of media is indicated with black *. Optical frequency domain imaging (OFDI) (B) provides the best correlation with the histopathology findings and demonstrates asymmetric intimal thickening and a focal loss of media (white *). Intravascular ultrasound (IVUS) (C) depicts the collagen rich adventitia as bright echos (white arrowheads), however, the distinction between the intima and media can not be easily appreciated. Coronary CT angiography (CTA) (D) demonstrates a thickened coronary wall. The black arrows indicate the inner border of the vessel wall, while the white arrows indicate the outer border of the vessel wall. Further characterization of the coronary wall layers is not possible. IC = imaging catheter; L = coronary lumen; W = guide wire.

Table 1. Correlation of AHA Plaque Nomenclature With Descriptive Scheme

<table>
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<tr>
<th>AHA Classification (2)</th>
<th>Descriptive Scheme (1)</th>
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<tr>
<td>Type III</td>
<td>Pathologic intimal thickening</td>
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<tr>
<td>Type IV</td>
<td>Fibrous cap atheroma</td>
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<tr>
<td>Type Va, Vb, Vc</td>
<td>Healed plaque rupture with or without calcification</td>
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<tr>
<td>Type VI</td>
<td>Thin cap fibroatheroma</td>
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<tr>
<td>Type VI</td>
<td>Plaque hemorrhage/plaque rupture</td>
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AHA = American Heart Association.

Figure 2. Pathologic Intimal Thickening

Pathologic Intimal Thickening is thought to represent the building block for atherosclerotic plaque development and it is sometimes referred to as an “intermediate lesion.” The thickened intima often contains deposits of lipid in a proteoglycan rich matrix called lipid pools that are devoid of smooth muscle cells and macrophages close to the media, but without evidence of a necrotic core. Histopathology (A) demonstrates minimal luminal obstruction, a thickened intima with lipid accumulation close to the media (light green areas, white arrowheads). The lipid pool is visualized by both OFDI (signal loss) and IVUS (echolucent area) although the differentiation is difficult (B and C, white arrowheads). The outer boundary of the plaque is not visualized by OFDI, whereas the side branch is partially shadowed by the guide wire. In IVUS artifacts (nonuniform rotational distortion) limit the boundary recognition between intima and media and allow only partial plaque characterization. CTA clearly demonstrates a thicker noncalcified plaque (plaque depth is approximately 1.5 mm) but further differentiation of plaque composition is not possible. SB = coronary artery side branch.
Figure 3. Pathologic Intimal Thickening With Calcification

Histopathology (A) demonstrates a thickened intima which contains lipid pools close to the media (white arrowheads) and spotty calcification (Ca). OFDI (B) demonstrates the intimal thickening, the lipid pool and the spotty calcification (low density area with sharp boundary indicated by “Ca”). In IVUS (C), acoustic shadowing limits assessment of plaque properties, the lipid pool is not visualized. CTA (D) demonstrates the calcification with significant blooming artifact (about 4 times overestimation of calcified area) (3) as well as the noncalcified plaque component but without further characterization. SB — coronary artery side branch.

Figure 4. Late Fibroatheroma

The American Heart Association differentiates between Type IV and V fibrous cap atheroma lesions on the basis of the thickness of the fibrous cap and the presence of a lipid or necrotic core, whereas Virmani et al. (1) defined these lesions as fibrous cap atheroma (Table 1) (4). The fibrous cap is composed of smooth muscle cells in a proteoglycan rich matrix. As the plaque matures the lipid core consolidates and accrues necrotic debris and cholesterol crystals. Histopathology (A) demonstrates a fibroatheroma with a thick fibrous cap (black arrows) and a large necrotic core (*). It is known that the size of the necrotic core is significantly associated with its likelihood to rupture (5,6). OFDI (B) also depicts a thick fibrous cap (white arrows) and the large necrotic core with typical low intensity appearance (*). IVUS (C) demonstrates a narrowed coronary lumen with an eccentric plaque. The plaque is heterogeneous with an echolucent core and an overlying echodense fibrous layer (white arrows). There is signal drop out due to the plaque thickness (*). CTA (D) reveals a large noncalcified plaque segment. In this case, however, the plaque can be further characterized based on differences in CT attenuation. Specifically, there is a difference in attenuation between a central low attenuation area (corresponding to the lipid-rich necrotic core, *) and rim of high CT attenuation (corresponding to fibrous plaque tissue). This CT attenuation pattern has been described as the napkin-ring sign, the CT signature of high-risk coronary atherosclerotic plaque (7).

Figure 5. Fibrocalcific Plaque With Sheet Calcification

If the calcium area exceeds 10% in the absence of a necrotic core it constitutes a fibrocalcific plaque. In contrast to the fibroatheroma, the dominant component of a fibrocalcific plaque is calcification and not necrotic core. Both histology and OFDI (A and B) demonstrate extensive sheet calcification (Ca) with a shallow intimal layer between the calcification and the lumen (white arrowheads). The sharp delineation of the calcification against the intima can be appreciated in OFDI. IVUS (C) permits visualization of the calcification (Ca) as an echo bright area with acoustic shadowing. CTA (D) demonstrates a calcified plaque that appears much larger than in OFDI or histology as a result of extensive blooming artifact. As a result, the thickened intima cannot be distinguished as an underlying noncalcified plaque. This is an example that plaque that appears as calcified in CTA images, usually also has significant noncalcified portion. Thus, current differentiation between mixed and calcified plaques based on CTA images may be artificial.
Conclusions

We demonstrate that the core in vivo imaging strategies are promising but remain limited by their invasive nature (IVUS, OCT), poor penetration (OCT), limited spatial resolution (IVUS, CT), and ionizing radiation (CT). Advanced reconstruction and post-processing techniques and the development of hybrid technologies (near infrared spectroscopy, IVUS-OCT, PET-CT) may usher in a new era in plaque imaging.
REFERENCES