Abstract—The process of coronary artery disease progression is infrequently visualized. Intravascular ultrasound has been used to gain important insights but is invasive and therefore limited to high-risk patients. For low-to-moderate risk patients, noninvasive methods may be useful to quantitatively monitor plaque progression or regression and to understand and personalize atherosclerosis therapy. This review discusses the potential for coronary computed tomography angiography to evaluate the extent and subtypes of coronary plaque. Computed tomographic technology is evolving and image quality of the method approaches the level required for plaque progression monitoring. Methods to quantify plaque on computed tomography angiography are reviewed as well as a discussion of their use in clinical trials. Limitations of coronary computed tomography angiography compared with competing modalities include limited evaluation of plaque subcomponents and incomplete knowledge of the value of the method especially in patients with low-to-moderate cardiovascular risk. (Circ Cardiovasc Imaging. 2015;8:e003316. DOI: 10.1161/CIRCIMAGING.115.003316.)

Key Words: atherosclerosis ■ coronary artery disease ■ inflammation ■ myocardial infarction ■ plaque, atherosclerotic

I

Ischemic heart disease is the most common cause of death and disability worldwide. The underlying process of atherosclerosis in the coronary vessel wall may progress to stenosis or plaque rupture, often leading to myocardial damage. The evolution of early changes in the vessel wall leading to pathological lesions is conceptualized as a sequential progression from minimal to severe plaque (Figure 1). However the temporal evolution of processes that contribute to plaque formation (e.g., inflammation, lipid accumulation, calcification or plaque rupture, healing) have rarely been serially monitored in humans. Direct visualization of the disease process in the vessels may help guide patient management and understand the effects of therapy.

A current limitation in the understanding of coronary atherosclerotic disease in vivo is our ability to noninvasively track and monitor the disease process over time. On a population level, HMG-CoA reductase (statin) medications are effective in reducing cardiovascular disease event rates presumably through the stabilization and perhaps regression of atherosclerotic plaque. At present, individualized assessment of plaque response to therapy is inferred by cholesterol monitoring. However, cholesterol targets are derived based on a population; their relationship to a single individual’s disease status is often less clear. In other disciplines such as cancer therapy or infection, imaging of treatment response is critical to assess the success of medical treatments. For atherosclerosis, noninvasive imaging methods that can accurately assess change in coronary plaque burden over time hold the promise to personalize medical therapy as well as accelerate drug development. At present, the response of atherosclerosis to medical therapy has been demonstrated conclusively only using invasive techniques including catheter coronary angiography and intravascular ultrasound (IVUS). IVUS in particular has been shown to be useful for this purpose.

The purpose of this review is to provide an overview of recent developments in coronary computed tomography angiography (CCTA) with respect to other imaging methods for defining the extent and subtypes of coronary atherosclerosis. A prior limiting factor of serial CCTA examination has been the relatively high radiation dose. Dramatic developments in CCTA techniques have reduced radiation exposure from CCTA from 15 to 20 mSv to below 1 mSv in selected patients. For plaque characterization and quantification, high image quality is necessary, so that higher radiation doses are likely needed than ultralow doses used for detection of coronary stenosis. The limitations and potential areas of development of CCTA technologies are emphasized in the discussion below.

Background

Pathology: Dynamics of Coronary Artery Disease

The initial course of atherosclerotic disease is thought to begin in early adulthood. In young adults lesions in the arterial vessel wall have been observed surprisingly frequently but the prognostic relevance of early, adaptive, or reversible changes...
such as fatty streak or intimal thickening remains a matter of debate. Pathology studies seek to integrate autopsy findings from various stages of atherosclerosis to provide a putative sequence of events. In brief, intimal thickening is observed early in the disease process. The early atherosclerotic lesion is composed of smooth muscle cells and is affected by increased macrophage and lipid influx. If this process continues, a necrotic core is formed and the lesion progresses to a fibrous cap atheroma. The necrotic core contains lipids and apoptotic macrophages. A stable fibrous cap may prevent rupture of the lesion. If the fibrous cap loses matrix proteins and smooth muscle cells, a thin cap atheroma can result. Intraplaque hemorrhage is also seen frequently in this entity, leading to further enlargement of the lipid core. The risk of plaque rupture is increased as the fibrous cap thins and the lipid core enlarges. The fibrocalcific plaque is considered to be more stable, although the processes involved in calcification are not fully understood.

Subclinical Coronary Disease

It is generally conceived that therapeutic intervention for atherosclerosis is most effective when started at an early stage of the progressive disease process. Imaging tools have provided a substantial database of knowledge on disease burden. Imaging of the larger surface vessels (carotid or femoral arteries) has been extensively used to detect early systemic vascular pathology. Calcium detection using non–contrast CT provides a direct approach to assessing coronary atherosclerosis burden. The coronary artery calcium score has strong predictive power for cardiovascular events in asymptomatic subjects. However, calcium deposition is felt to be a late event in the formation of atherosclerotic plaque. The relevance of noncalcified plaque is emphasized by prospective IVUS studies that show coronary fibroatheroma without significant calcification confers an elevated risk for myocardial infarction. Noncalcified plaque is more common than calcified plaque in asymptomatic individuals aged <45 years. The ability to noninvasively image noncalcified plaque or wall thickening of the coronary arteries using MRI or CT enables the detection of earlier stages of atherosclerotic disease.

Imaging of Atherosclerotic Plaque Burden and Progression

Invasive Coronary Imaging

Intravascular Ultrasound

Invasive coronary angiography delineates the vessel lumen with high quality, but the amount and composition of atherosclerotic plaque are not shown. The additional
step of IVUS\textsuperscript{21} constitutes the current gold standard for plaque quantification. Multiple studies using IVUS and other techniques have revealed a robust relation between statin therapy and plaque regression\textsuperscript{11,22–35} (Table 1). In the ASTEROID trial coronary atheroma volume regressed by 6.8\% during 24 months of high-intensity lipid therapy.\textsuperscript{23} A meta-analysis of IVUS trials including 7864 patients showed an association between plaque regression and decreased cardiovascular events.\textsuperscript{56}

**Optical Coherence Tomography**

Optical coherence tomography provides an order of magnitude higher resolution when compared with IVUS but lacks delineation of the outer vessel boundary because of weaker penetration. Optical coherence tomography has the unique ability to directly visualize thin cap fibroatheroma (cap diameter <65 μm; resolution of optical coherence tomography, 10 μm).\textsuperscript{37} Using serial optical coherence tomography imaging, Habara et al\textsuperscript{24} recently showed that the fibrous cap thickness of lipid-rich plaque increased after 9 months of lipid treatment.

**Near Infrared Spectroscopy**

Near infrared spectroscopy is able to image the lipid content of plaques. A short-term follow-up study showed a significant reduction in plaque lipid content as early as 7 weeks after starting intensive statin treatment.\textsuperscript{25}

### Table 1. Examples of Longitudinal Atherosclerosis Imaging Trials

<table>
<thead>
<tr>
<th>Authors</th>
<th>Modality</th>
<th>Design</th>
<th>Main Imaging Finding</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lichtlen et al\textsuperscript{22}</td>
<td>Invasive angiography</td>
<td>Prospective, randomized</td>
<td>Severity and number of stenoses increases over time</td>
<td>230</td>
</tr>
<tr>
<td>Nissen et al\textsuperscript{11}</td>
<td>Coronary IVUS</td>
<td>Prospective</td>
<td>Change in percent atheroma volume 1.6 ((\text{atorvastatin})) vs 0.3 ((\text{pravastatin}))</td>
<td>502</td>
</tr>
<tr>
<td>Nissen et al\textsuperscript{22}</td>
<td>Coronary IVUS</td>
<td>Prospective</td>
<td>6.8% plaque volume regression using statin</td>
<td>349</td>
</tr>
<tr>
<td>Habara et al\textsuperscript{24}</td>
<td>Coronary OCT</td>
<td>Prospective</td>
<td>Fibrous-cap thickness increased after 9 mo statin/ezetimibe</td>
<td>63</td>
</tr>
<tr>
<td>Kini et al\textsuperscript{23}</td>
<td>Coronary NIRS</td>
<td>Prospective</td>
<td>Short-term reduction of plaque lipid content with high-intensity lipid therapy</td>
<td>87</td>
</tr>
<tr>
<td>Corti et al\textsuperscript{26}</td>
<td>Carotid MRI</td>
<td>Prospective</td>
<td>18% wall volume regression in statin therapy</td>
<td>29</td>
</tr>
<tr>
<td>Sibley et al\textsuperscript{27}</td>
<td>Carotid MRI</td>
<td>Prospective, randomized</td>
<td>10% wall volume regression in statin therapy</td>
<td>145</td>
</tr>
<tr>
<td>Arad et al\textsuperscript{28}</td>
<td>Coronary calcium score</td>
<td>Prospective, randomized</td>
<td>No effect of statin treatment on (\text{CAC}) progression</td>
<td>2005</td>
</tr>
<tr>
<td>Hoffmann et al\textsuperscript{29}</td>
<td>CCTA, volume (CP, NCP, mixed plaque)</td>
<td>Retrospective observational</td>
<td>Noncalcified plaque increased from 21 to 29 mm(^3) ((38%))</td>
<td>63</td>
</tr>
<tr>
<td>Tardif et al\textsuperscript{30}</td>
<td>CCTA, volume (NCP), number of plaques, plaque CT numbers</td>
<td>Prospective, randomized</td>
<td>Volume of noncalcified plaque Placebo: 6% increase VIA-2291: −4.9% decrease</td>
<td>28</td>
</tr>
<tr>
<td>Burgstahler et al\textsuperscript{31}</td>
<td>CCTA, volume (NCP, CP)</td>
<td>Prospective, atorvastatin</td>
<td>Noncalcified plaque decreased by 24%</td>
<td>20</td>
</tr>
<tr>
<td>Papadopoulou et al\textsuperscript{32}</td>
<td>CCTA, lumen diameter and area, total plaque volume, remodeling index (...)</td>
<td>Prospective, observational</td>
<td>Normalized atheroma volume increased by 47 mm(^3) ((6.7%))</td>
<td>32</td>
</tr>
<tr>
<td>Zeb et al\textsuperscript{33}</td>
<td>CCTA, volume (NCP, CP, low attenuation plaque), remodeling index</td>
<td>Retrospective</td>
<td>28% decrease in noncalcified plaque volume</td>
<td>60</td>
</tr>
<tr>
<td>Lehman et al\textsuperscript{34}</td>
<td>CCTA, number of slices with plaque (NCP, CP)</td>
<td>Prospective</td>
<td>12.7% increase in number of slices with plaque.</td>
<td>69</td>
</tr>
<tr>
<td>Lo et al\textsuperscript{35}</td>
<td>CCTA, lumen stenosis, volume (NCP, total), high risk plaque features</td>
<td>Prospective, randomized, atorvastatin</td>
<td>Plaque volume Placebo: +18.2%, Atorvastatin: −4.7%</td>
<td>37</td>
</tr>
</tbody>
</table>

The lower part of the table shows a selection of CCTA plaque progression trials. Design, sample size, patient population, follow-up time, and CT scanner technology are heterogeneous among these examples. \(\text{CAC}\) indicates non–contrast calcium score; CCTA, coronary CT angiography; CP, calcified plaque; CT, computed tomography; IVUS, intravascular ultrasound; MP, mixed (partially calcified) plaque; NCP, noncalcified plaque; NIRS, near infrared spectroscopy; and OCT, optical coherence tomography.
better predictor of subsequent CVD events than carotid IMT.\textsuperscript{43} Thus, direct imaging of the coronary vessels promises better predictive power for cardiovascular events when compared with carotid imaging.

**Computed Tomography**

**Non–Contrast CT Calcium Score**

Non–contrast CT calcium score scoring is extensively used for risk stratification in clinical practice. The most common method to quantify calcium is the Agatston calcium score. The method exclusively focuses on the calcified plaque component and is unable to quantify vascular stenosis. Nevertheless, there exists a tremendous amount of data indicating a strong and robust predictive power of this test.\textsuperscript{44} Data from the MESA show an incremental predictive value for cardiovascular events of the calcium score when added to traditional risk factors.\textsuperscript{17}

Despite the extensive research support for non–contrast CT calcium score as a tool for risk stratification, data on the ability of the calcium score to reflect treatment effects are inconclusive. Several nonrandomized studies showed evidence of a slower progression of coronary calcifications in patients treated with statins when compared with untreated patients\textsuperscript{45–47} as reviewed by Priester et al.\textsuperscript{48} However, in the prospective randomized St. Francis heart study,\textsuperscript{28} the baseline calcium score was the only significant predictor for cardiovascular events; change of coronary calcium after 2 and 4 years was not affected by treatment with atorvastatin or placebo. Change of calcium score did not predict cardiovascular events after adjusting for baseline calcium score. The prospective randomized Beyond Endorsed Lipid Lowering With EBT Scanning (BELLES) trial reported by Raggi et al\textsuperscript{49} compared atorvastatin 80 mg with pravastatin 40 mg and found no significant difference in progression of coronary calcium volume after 1 year (15.1\% and 14.3\%, respectively). IVUS studies have shown that calcified lesions are less likely to be influenced by medical therapies.\textsuperscript{50} Thus, calcium score does not seem to be useful for assessing plaque regression for either clinical purposes or research studies.

**Contrast-Enhanced CT Coronary Angiography**

In clinical practice, CCTA is mainly used in symptomatic subjects at moderate risk according to the Appropriate Use Criteria.\textsuperscript{51} CCTA can characterize not only lumen stenosis but also plaque subcomponents (calcified, noncalcified) and arterial remodeling. The degree and characteristics of atherosclerosis are highly relevant to the concept of overall coronary plaque burden. The importance of overall plaque burden was emphasized by a study showing that patients with widespread nonobstructive CAD had similar event rates when compared with patients with localized obstructive disease\textsuperscript{52} using qualitative assessment. Moreover, quantitative analysis of overall coronary plaque volume is now available. Studies showing increased noncalcified plaque volumes in acute coronary syndrome (ACS) patients\textsuperscript{53} or in obese diabetics\textsuperscript{54} as well as response to statin therapy\textsuperscript{34} suggest that overall coronary plaque burden may have clinical relevance.

CCTA has been extensively compared with IVUS\textsuperscript{55–65} (reviewed in 66 and 67; overview in Table 2). A meta-analysis concluded that overall plaque volumes measured using CCTA and IVUS do not differ significantly on a study sample basis.\textsuperscript{67} A recent study showed an excellent correlation of individual plaque measurements ($r=0.94$ for expert-assisted

### Table 2. Overview of Selected Studies Comparing CCTA With Intravascular Ultrasound

<table>
<thead>
<tr>
<th>Authors</th>
<th>Number</th>
<th>CT Technology</th>
<th>Method</th>
<th>Mean Difference, mm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brodoefel et al\textsuperscript{55}</td>
<td>14</td>
<td>64 slice 120 kVp</td>
<td>Automatic (Vitrea SurePlaque, Toshiba)</td>
<td>+7.7</td>
</tr>
<tr>
<td>Dey et al\textsuperscript{56}</td>
<td>20</td>
<td>64 slice 120 kVp</td>
<td>Automatic (Autoplaq, Cedars-Sinai Medical Center) and manual</td>
<td>10.7 (automatic NCP) –5.1 (manual NCP)</td>
</tr>
<tr>
<td>Harada et al\textsuperscript{57}</td>
<td>17</td>
<td>64 slice 120/135 kVp</td>
<td>Automatic</td>
<td>+58 (total) –16 (fibrous)</td>
</tr>
<tr>
<td>Bruining et al\textsuperscript{58}</td>
<td>48</td>
<td>16 slice 120 kVp</td>
<td>Semiautomatic (CURAD)</td>
<td>+32.75 (total)</td>
</tr>
<tr>
<td>Akutagawa et al\textsuperscript{59}</td>
<td>21</td>
<td>64 slice</td>
<td>Automatic (Vitrea SurePlaque, Toshiba)</td>
<td>–46.7 (total)</td>
</tr>
<tr>
<td>Pedrazzini et al\textsuperscript{60}</td>
<td>57</td>
<td>64 slice 100/120 kVp</td>
<td>Automatic (CardIQ Xpress Pro, GE)</td>
<td>+1.9 (total)</td>
</tr>
<tr>
<td>Park et al\textsuperscript{61}</td>
<td>151</td>
<td>64 slice 100/120 kVp</td>
<td>Automatic and semiautomatic (QAngio CT, Medis, NL)</td>
<td>Total: –22.28 (automatic) +12 (expert) NCP: –27 (automatic) –3.6 (expert)</td>
</tr>
<tr>
<td>de Graaf et al\textsuperscript{62}</td>
<td>57</td>
<td>64 slice (16) 320 slice (41) 120 kVp</td>
<td>Automatic (QAngio CT, Medis, NL)</td>
<td>+36.5</td>
</tr>
<tr>
<td>Nakazato et al\textsuperscript{63}</td>
<td>27</td>
<td>64 slice 100/120 kVp</td>
<td>Manual</td>
<td>–4.4 (total)</td>
</tr>
<tr>
<td>Schepis et al\textsuperscript{64}</td>
<td>70</td>
<td>64 slice 120 kVp</td>
<td>Manual</td>
<td>–1 (total)</td>
</tr>
<tr>
<td>Otsuka et al\textsuperscript{65}</td>
<td>47</td>
<td>64 slice 120 kVp</td>
<td>Manual</td>
<td>–2 (total) –9 (NCP) –4 (CP)</td>
</tr>
</tbody>
</table>

CCTA indicates coronary computed tomography angiography; CP, calcified plaque; NCP, noncalcified plaque, and positive mean difference, overestimation of volume by CCTA.
Coronary CT Angiography Assessment of Plaque Burden and Progression

CCTA has matured to a routine clinical tool with excellent sensitivity (≥80%) and specificity (99%) for coronary artery stenosis.76,77 Besides the assessment of stenosis, CCTA can measure overall plaque burden. A key issue that remains to be determined is the capability of CCTA to track changes in plaque burden over time (Figure 2). This section addresses the current state of the art of CCTA for quantitative measurement of plaque burden with respect to image acquisition and processing.

CT Acquisition

Based on IVUS data, the change in extent of coronary plaque seems to be small for a timeframe of 1 or 2 years. Thus, serial imaging of the coronary arteries by CCTA requires consistent and high-quality CT acquisitions using the same CCTA instrument for many years. An example of technical change of CCTA is reflected by radiation dose data: a median dose of 12.5 mSv for CTA was reported in a multicenter analysis 200973 but third generation CCTA scanners achieve comparable image quality with a dose of <1 mSv12,75 (Figure 3). Faster acquisition speeds have been achieved by faster rotation, larger detectors, and dual source systems. This also results in reduced artifacts which may provide increased reproducibility and improved plaque quantification and characterization.74

Recently, complex image reconstruction (iterative reconstruction) has been introduced in commercial CT systems, which improves image quality with regard to noise, resolution, artifacts, and most importantly diagnostic accuracy.75

Quantification of Plaque by CCTA

For the assessment of plaque progression, the quantification and characterization of plaque are key issues. For semiquantitative methods, the location of coronary segments is determined by the American Heart Association nomenclature adapted for CCTA.78 Methods for scoring the degree of plaque in coronary segments are described below.

Segment Involvement Score

A simple and highly reproducible semiquantitative measurement is the segment involvement score which describes the number of segments affected by any plaque as seen on CCTA77,78 (Figure 4). A score ≥5 has been shown to have additional prognostic value for overall survival independent of clinical risk factors.79 Because the individual lesion severity is not taken into account, the use of a categorical score for monitoring small changes in plaque progression seems limited.

Segment Stenosis Score

The segment stenosis score (SSS) assigns a number from 0 to 3 to each segment based on maximum diameter stenosis in each segment (0 for <30%, 1 for 30%–49%, 2 for 50%–69%; and 3 for ≥70%). Segments are then added to yield the SSS. Incremental prognostic value of the SSS method has been shown.78 The progression of stenosis may potentially be followed over time on a semiquantitative level using the SSS.

Segmental Plaque Score

The amount of plaque present and severity of stenosis are not necessarily correlated. An approach to account for both severity of stenosis and degree of plaque is the segmental plaque score. For this score, the amount of plaque (both calcified or noncalcified) in each segment is graded visually into the categories none or trace=0, mild=1, moderate=2, and severe=3.79 As with the prior scores, a total score is derived as the sum of the individual segment scores.

The segment scores described above may be readily applied but all rely on angiographic naming conventions of coronary artery segments. In a segment-free approach, Lehman et al81 first identified the centerline of each coronary artery. The number of cross-sections along the centerline showing any plaque was then counted. In the same manner calcified and noncalcified plaque was assessed.
**IVUS-like Methodology Applied to CCTA**

Using IVUS, plaque volumes are calculated as the difference between the external elastic membrane area and the lumen area for successive cross-sections of a coronary artery. Change in plaque volume has been successfully used to monitor plaque progression in IVUS studies. The spatial resolution of CCTA is insufficient to depict the external elastic membrane as a separate structure, but the outer border of the vessel wall is often defined by epicardial fat. In addition, the inner border of the arterial wall is defined by iodine contrast material in the vascular lumen (Figure 5). The difference between outer vessel volume and lumen volume constitutes the CCTA defined total plaque/media volume. From these volumes, further parameters...

**Figure 3.** Examples for high-quality computed tomography angiography imaging at relatively low doses (A: 1 mSv, 90 kV; B: 0.5 mSv, 80 kV). These are high-pitch prospectively ECG-triggered acquisition reconstructed with model-based iterative reconstruction.

**Figure 4.** Semiquantitative plaque scores by coronary computed tomography angiography. Three coronary segments are shown to demonstrate the scoring system. For the segment involvement score (SIS) each coronary segment is assigned the number 1 for having any plaque or 0 for having no plaque. For the segmental plaque score (SPS) a number is assigned to each segment based on a semiquantitative plaque burden assessment (0, none or trivial; 1, mild; 2, moderate; and 3, severe). For the segment stenosis score the maximum stenosis in each segment is graded into 3 levels (0: <30%, 1: 30%–49%, 2: 50%–69%, and 3: ≥70%). For each of these methods the sum of all segments constitutes the respective score. For the method proposed by Lehman et al (cross-section method) vessel cross-sections spaced at 1 mm intervals along the vessel centerline are evaluated for the presence of plaque. The number of affected cross-sections represents the measurement of the total plaque burden. This can be repeated for calcified plaque and noncalcified plaque.
such as percent atheroma volume or normalized atheroma volume can be derived.\textsuperscript{81}

Defining the lumen and outer vessel boundaries is time consuming and observer dependent when performed manually. Multiple software packages offer automatic and semiautomatic modes. Overall studies using manual measurements or automatic methods showed similar results\textsuperscript{67} (Table 2). Automatic segmentation can be technically difficult because of variations in lumen attenuation, overlap in CT numbers of iodine and calcified plaque, and inherently low tissue contrast of CT. For segmentation the centerline of the vessel is defined first to generate a curved multiplanar reconstruction. An edge finding algorithm traces the lumen border taking into account the current lumen attenuation and an optional manual correction of the contours is offered. In the next step the outer contours are generated. Traditionally, fixed HU cutoffs have been used to differentiate plaque subtypes but lumen attenuation can affect plaque attenuation. This can be addressed using adaptive thresholds that account for partial volume averaging because of lumen attenuation values.\textsuperscript{62} Accurate, reproducible, and fully automatic measurements would be ideal for plaque progression studies but in our experience user interaction is often necessary for optimal contours. A study directly comparing different plaque measurement methods with IVUS showed the best results for semiautomatic expert-guided measurements.\textsuperscript{61}

Semiautomated quantification of plaque volume was of incremental predictive value in a study of patients with stable angina pectoris.\textsuperscript{82} In patients with ACS plaque volume predicted recurrent ACS in univariate analysis.\textsuperscript{83}

Characterization of Plaque by CCTA
Calcified and noncalcified plaque have different pathophysiology and prognostic implications and thus their separate components of plaque have been emphasized in CCTA analysis. Noncalcified plaque was seen more frequently in acute chest pain when compared with stable angina patients.\textsuperscript{84} The amount of noncalcified plaque was an independent predictor of adverse events in a population with stable angina.\textsuperscript{82}

Using CCTA, calcified versus noncalcified plaque can be quantified based on CT density cutoff values. Using this approach, Kwan et al\textsuperscript{54} showed that the percentage of calcified plaque was greater in diabetic patients with high calcium scores and larger CCTA total plaque volumes (Figure 6). An ex vivo comparison to histology showed the ability of CCTA to differentiate noncalcified, mixed, and calcified plaques.\textsuperscript{85} Further subclassification of noncalcified plaque into fibrous or fatty components using CT attenuation\textsuperscript{85,86} values is less
reliable. A key difficulty is that voxel sizes of CCTA are relatively large when compared with the pathology being measured with resulting uncertainty in plaque density measurements. As indicated above, CCTA also has relatively low soft tissue contrast resolution, so that attenuation differences between varying plaque components are small.

There are several solutions for further improvement in plaque characterization. Improved spatial resolution of the technique will reduce partial volume effects and improve classification of atheroma density. Dual-energy CT can reduce blooming effects that occur close to calcium and iodine and in theory lead to more valid density measurements of plaques\(^87,88\) (Figure 7). Boll et al\(^89\) showed that dual-energy CT resulted in higher accuracy for calcified plaque measurements. Another possible application is better separation of iodine and calcium and thereby improving plaque segmentation.\(^90\) Dual-energy CT technology is rapidly improving because of better energy separation combined with improved spatial and temporal resolution of the latest generation of CT devices\(^91\) (Figure 8). Future developments have the potential to provide high-speed multi-energy acquisitions using low radiation doses.\(^92\) Applications of dual energy in CCTA have recently been reviewed.\(^92\)

Apart from tissue classification, CCTA can also visualize morphological plaque features that have been shown to provide additional diagnostic and prognostic information (reviewed in 93). Spotty calcification, small (<3 mm) calcification surrounded by noncalcified plaque, has been associated with accelerated plaque progression using IVUS data\(^94\) and was seen more frequently in culprit lesions when compared with stable lesions.\(^84\) The napkin sign (a ring of high attenuation around a coronary plaque), positive remodeling, low Hounsfield unit plaque, and spotty calcium were associated with ACS independently of stenosis in an analysis of the ROMICAT II trial.\(^95\)

**Clinical Trials for CCTA Plaque Regression**

To date, most studies assessing plaque regression by CCTA have evaluated patients with ACS or have been retrospective clinical reviews (Table 1, lower part). Zeb et al\(^33\) retrospectively studied patients who underwent 2 CCTA examinations for clinical indications and used semiautomatic quantification software to compare plaque volumes. In 60 patients treated with statins, the noncalcified plaque volume was reduced after \(\approx 1\) year, whereas calcified plaque volume was unchanged. For ACS patients, Lehman et al\(^35\) recruited 69 patients from the prospective ROMICAT trial. A second CT was performed after 2 years and a semiquantitative score was used for quantification. The study showed an increase in plaque burden.
of 13% driven by an increase of noncalcified plaque with no significant increase of calcified plaque. Papadopoulou et al32 prospectively recruited patients with ACS in the PROSPECT trial to undergo a second CT after 3 years. A semiautomatic quantification software was used and results showed an increase in plaque volume of 5.8% accompanied by compensatory positive remodeling.

Recently, Lo et al34 reported the results of a prospective randomized double-blinded lipid therapy trial in HIV patients. This study underscores the remarkable changes in plaque size that can be observed using CCTA (change +12% in placebo group versus −4.7% in atorvastatin group for lesion total plaque volume for 1 year). Notably, the noncalcified plaque regressed by 19.4% in the atorvastatin group. In addition, the high risk plaque features low attenuation and positive remodeling were reduced.

Taken together, these initial studies are comparable in showing change in noncalcified plaque volume rather than calcified plaque.

Limitations and Challenges of CCTA
There are several issues that have to be clarified for future CCTA plaque follow-up imaging trials. A key issue is high reproducibility (test–retest) which needs to be firmly established. A study conducted in 30 patients on different CT scanners showed reasonable interscan reproducibility (repeatability coefficient 109 mm² for plaque volume measurement and below 10% for plaque composition) using a semiautomatic quantitative software.98

Excellent reproducibility of CCTA images is necessary to reduce sample size in clinical trials and to allow serial assessment of CCTA studies. Image quality is of high importance. For example, in a randomized trial with CT evaluation as a secondary end point in a subgroup 28 of 88 patients had to be excluded because of insufficient image quality in one of the examinations.99 The reproducibility study by Schuhbaeck et al98 noted suboptimal image quality as the most important reason for diverging measurements. Finally, image analysis methods need further optimization. Analytic methods for plaque assessment with CCTA are not standardized. For example, guidelines developed for IVUS discourage measurement of individual plaque volumes because the beginning and end of a plaque is poorly defined99 and instead advocate using anatomic landmarks. Similar approaches have not been adapted to CCTA image analysis. Future image analysis tools enabling a side by side visualization could facilitate image comparison and improve the assessment of plaque progression (Figure 9).

Summary
The current use of coronary CT angiography has focused on depiction of coronary stenosis. Rapid advances in image reconstruction have allowed substantially lower radiation doses for CCTA. Multisenergy technology and improved detector technology have also resulted in improved image quality. Recent research efforts have demonstrated the potential of CCTA for quantification of calcified and noncalcified plaque. Research to date for CCTA plaque quantification has mostly focused on high-risk populations or has been retrospective; additional prospective studies of low to moderate risk subjects are needed to determine the reliability of the CCTA method and to clarify the role of CCTA to detect plaque progression or regression.

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Noninvasive Imaging of Plaque Progression


Noninvasive Imaging of Atherosclerotic Plaque Progression: Status of Coronary Computed Tomography Angiography
Veit Sandfort, Joao A.C. Lima and David A. Bluemke

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