Imaging of Small High-Density Structures in CT:
A Phantom Study[1]

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Rationale and Objectives. The aim of this work is to study how the limited spatial resolution of a computed tomographic (CT) system affects the imaging of small high-density structures. This knowledge is relevant not only to understand and interpret clinical data, but also to apply and develop quantification methods for calcifications and stented vessels.

Materials and Methods. A dedicated phantom containing small differently sized aluminum cylinders was imaged on a 64-slice multidetector row CT (MDCT) while varying acquisition and reconstruction parameters from a high-resolution protocol. In addition, a bead phantom was imaged to estimate the point spread function (PSF) for the different parameter settings. The accuracy in determining object density and size was established for various imaging protocols and compared with simulations based on the estimated PSF.

Results. Attenuation values and size measurements were accurate for objects larger than two times the size of the system PSF at the full-width-at-half-maximum. For smaller objects, attenuation values were increasingly underestimated and size was increasingly overestimated. The convolution kernel had the most influence on object signal and size. Use of edge-enhancing kernels yielded more accurate size measurements and higher signal for small objects. However, their application was constrained by noise amplification and edge-ringing artifacts, which led to lower signal-to-noise ratio, degrading the visualization of low densities and small high-density objects.

Conclusion. Results presented in this report provide insight into limitations in the quantification of small high-density structures and their effect on the visualization of surrounding tissues with recently developed MDCT systems.

Key Words. 64-Slice multidetector row computed tomography (CT); size measurement accuracy of small high-density objects; phantom experiments; blur; point spread function.

Computed tomographic (CT) imaging of small high-density structures such as calcifications and stents is of high importance in the diagnosis, treatment planning, and follow-up of patients with cardiovascular disease. Calcification detection and quantification and stent restenosis assessment are clinically relevant. Calcifications are markers for arterial pathological states, and total amount of calcium in coronary arteries and carotids is being used as a risk indicator because it is associated with thrombotic syndromes and/or stroke (1,2). Postsurgical angiographic follow-up is used to detect stent restenosis (3). However, because of patient risks and treatment costs, CT angiography is being investigated as a noninvasive alternative to conventional coronary angiography (4).

CT is a sensitive technique to detect calcifications in atherosclerotic arteries (1) and to image stents. However, limitations in both spatial resolution and signal-to-noise ratio (SNR) hamper image quality and especially affect the visualization and quantification of the smallest objects. The main consequence of the limited spatial resolu-

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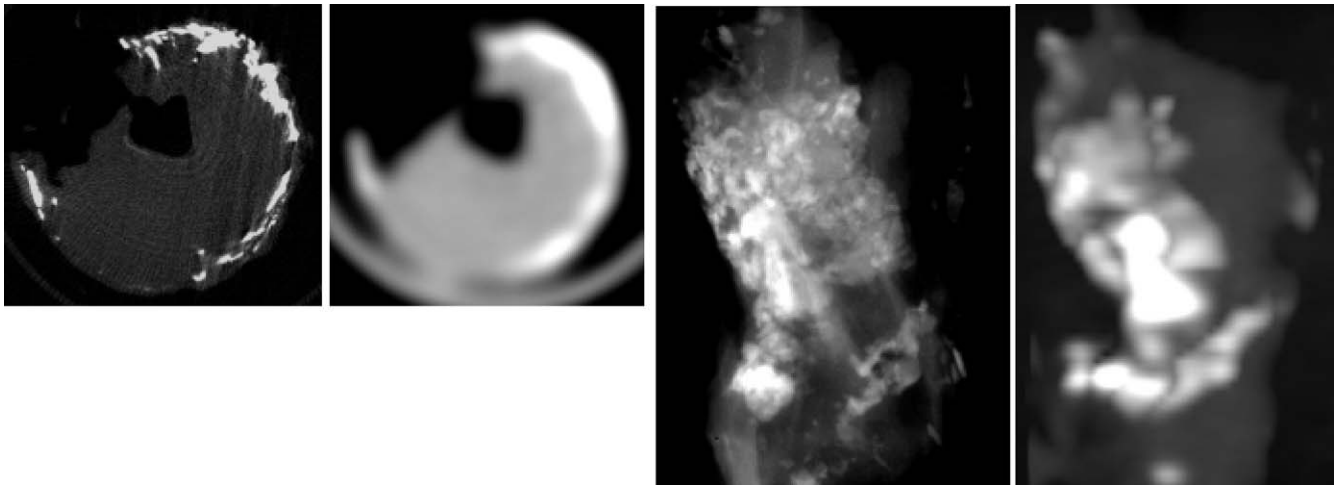

Figure 1. From left to right: cross-sectional μCT image of an in vitro calcified plaque (image size = 12.6 × 11.9 mm, pixel size = 18.2 μm in both the *x* and *y* directions); closest corresponding slice acquired with MDCT (pixel size = 0.098 mm in both the *x* and *y* directions); longitudinal maximum intensity projection of the μCT image of the whole plaque (image size = 12.6 × 19.3 mm, pixel size = 18.2 μm in both the *x* and *z* directions), closest corresponding projection acquired with MDCT (pixel size = 0.098 × 0.10 mm in the *x* and *y* directions, respectively).

tion of the system is the blur of the image, which can be characterized by measuring the point spread function (PSF) (5).

Atherosclerotic plaques consist of calcifications, ie, nodules of crystalline calcium (mainly hydroxyapatite), distributed among lipid cores and fibrous tissue (1,6–8). In a previous work (9), we compared CT volume images of in vitro carotid atherosclerotic plaques with the corresponding Microfocus X-ray CT (μCT; SkyScan-1172; www.skyscan.be) volume images and observed that calcifications generally have heterogeneous densities and amorphous shapes. Maximum diameters and lengths of these nodules typically range from only a few hundred microns to more than half a centimeter, and they frequently are found very close to each other, forming what we refer to as a "cluster of calcifications" (Figure 1). As a result of the convolution of small high-density objects with the system PSF, imaged object edges are blurred, leading to several problems in their quantification and visualization: (1) sizes of small calcifications and stent struts are overestimated, (2) objects in close proximity (such as clusters of calcifications and stent struts) are convolved together, (3) quantification and visualization of calcifications and stents strongly depend on both the selected Houndsfield unit (HU) threshold and display settings (window level and window width), and (4) small calcifications may not be detected (especially when they do not extend along the entire slice thickness) because they are not sufficiently dense to generate the minimal SNR required for detection (9).

The blur of small high-density objects not only leads to inaccuracies in their quantification and visualization, but also limits the interpretation of their surrounding low-density structures. This would, for example, hamper the measurement of lumen stenosis in places with calcified plaques and in stented vessels. These measurements have clinical repercussions because lumen stenosis larger than 70% (10) and in-stent restenosis larger than 50% (11) are considered eligible for surgical intervention. In view of these aspects, limiting the blur of small high-density objects may improve CT angiographic diagnosis. However, there is a trade-off because limitation of blur can compromise image quality due to the increasing noise and artifacts (12,13). Therefore, detailed evaluation of a scanning system in terms of noise, artifacts, and accuracy in imaging of small high-density structures is relevant for such clinical applications as atherosclerotic plaque characterization and vessel stenosis assessment in the presence of calcifications and stents.

A number of studies related to CT imaging of small high-density structures have already been performed, eg, fixed-threshold–based quantification of true and artificial calcifications (14–17), investigation of CT accuracy limits in cortical bone thickness and density determination for osteoporosis diagnosis (18–20), and evaluation of image spatial resolution and SNR as a function of CT acquisi-