Introduction

Greater scan coverage and faster scanning with multidetector-row computed tomography (MDCT) has provided a unique opportunity for noninvasive and accurate imaging of vascular diseases of lower extremities [1]. This chapter describes scanning parameters, contrast medium administration features, image postprocessing techniques, and clinical applications of MDCT angiography (MDCTA).

Scanning Parameters

For an average-size patient, we use 120 kV and 300 mA for peripheral MDCTA. A lower tube current and/or tube potential can be used for smaller patients, greater current and potential can be used for obese patients. Alternatively, automatic exposure control techniques can also be used to adapt tube current to patient size. Using the greater trochanter as a bony landmark, a small to medium imaging field of view, is used for section reconstruction. For reconstruction of CT angiography (CTA) images, we use a soft or medium reconstruction kernel.

For peripheral CTA, the patient is placed supine and feet first on the CT table, with careful alignment of the patient’s knees and feet positioned close to the gantry isocenter [2, 3]. The anatomic scan length for a typical lower-extremity CTA study is 110–130 cm and extends from the renal artery origins at T12 vertebra to the patient’s feet. Compared with the 4- and 8-row MDCT scanners, 16- and 64-row MDCT scanners allow acquisition of thinner sections at faster speed. With these latter scanners, it is also possible to acquire submillimeter, isotropic images of the entire peripheral arterial tree. These “thinner” image data sets can improve visualization of small vessels (Fig. 1). This maximum spatial resolution may translate into improved visualization and treatment planning of patients with advanced peripheral arterial occlusive disease. For most routine CTA of the entire peripheral arterial tree, we reconstruct images at 1.25- to 1.5-mm section thickness for 8- and 16-row scanners, and 1-mm section thickness with 64-row MDCT scanners while maintaining constant image quality with use of automatic exposure control techniques.

Contrast Medium

Oral contrast is not administered to patients undergoing peripheral CTA. Although the same principles for contrast medium injection for CTA (relationship of injection flow rate and injection duration with arterial enhancement) apply to peripheral CTA, the latter is more complex due to the need for acquiring optimum enhancement of the entire lower extremity arterial tree in a single CT acquisition.

For peripheral CTA studies, we inject 1–1.5 g of iodine per second for an average person (75 kg) and make patient-weight-based adjustment to the contrast volume and injection flow rate for heavier (>90 kg) or smaller (<60 kg) subjects. In peripheral CTA studies, attenuation values are usually lowest in the abdominal aorta and peak at the level of the infrageniculate popliteal artery [4]. This can be explained on the basis of continuous arterial enhancement with a continuous and prolonged intravenous injection of contrast media (e.g., 35 s) [5]. Thus, biphasic injections may result in more uniform enhancement over time, particularly for longer scan and injection times (>25–30 s) [6].

In addition to volume and injection for contrast media, an optimum scan delay for peripheral CTA is also critical. Contrast medium transit time (tCMT), the time interval between the beginning of an intravenous contrast medium injection and arrival of the bolus in the aorta, varies considerably between pa-
tients with coexisting cardiovascular diseases and may range from 12–40 s. Therefore, individualization of scanning delay (or determination of the individual’s tCMT) is recommended in peripheral CTA with the help of either a small test-bolus injection or automated bolus triggering techniques. These techniques help the choice of scanning delays that may equal to the tCMT or exceed tCMT by being chosen at a predefined interval (e.g., “tCMT+5 s” implies that the scan starts 5 s after contrast medium has arrived in the aorta).

Contrast medium injection protocols in peripheral CTA are also complicated since arterial stenosis, occlusions, or aneurysms anywhere between the infrarenal abdominal aorta and the pedal arteries can substantially delay downstream arterial enhancement [7, 8] (Fig. 2). In fact, patients with peripheral arterial occlusive disease, transit times of intravenous (IV) contrast medium from the aorta to the popliteal arteries can range from 4 s (at transit speed of 177 mm/s) to 24 s (at a transit speed of 29 mm/s) [9]. This is particularly important with the use of faster acquisition speeds, as the scanner table may move faster than the intravascular contrast medium, and the scanner may thus outrun the bolus. It is important to note that this phenomenon of “outrunning” has only been reported at a table speed of 37 mm/s in one study on peripheral CTA [10], but it has not been reported at table speeds of 19-30 mm/s in other studies [10-14]. Thus, we categorize injection strategies for peripheral CTA into those for “slow” acquisitions (at a table speed of ≈ 30 mm/s).

For slow acquisitions, table speed usually translates into a scan time of approximately 40 s for the entire peripheral arterial tree. As data acquisition follows the bolus from the aorta to the feet, injection duration can be about 5 s shorter than the scan time (e.g., 40-s acquisition = 35-s injection duration). At a constant injection rate of 4 ml/s, this translates to 140 ml of contrast medium. If the beginning of data acquisition is timed closely to contrast arrival time in the aorta (using a test bolus or bolus triggering), biphasic injections achieve more favorable enhancement profiles with improved aortic enhancement.

In patients with peripheral arterial occlusive disease, fast acquisition protocols (>30 mm/s table speed) may be faster than contrast medium transit times through the peripheral arterial tree. In order to prevent CT acquisition from outrunning the bolus, the bolus should be given a “head start” by combining fixed injection duration of 35 s to fill the arterial tree and a delay of the start of CT acquisition relative to tCMT. The faster the acquisition, the longer “diagnostic delay” should be. We employ such a strategy with both a 16-row scanner with a 16×1.25-mm protocol, beam pitch 1.375:1, and 0.6-s gantry rotation period (table speed 45 mm/s) and a 64-row scanner with a 64×0.6-mm, beam pitch 1.0:1, and 0.5-s gantry rotation period, and table speed 45 mm/s. Our diagnostic delay is typically 15–20 s in these cases.

As there is a possibility of even more delayed arterial opacification than accounted for with the
Fig. 2a, b. a Multidetector-row computed tomography angiogram (MDCTA) obtained with 32×1.0-mm-thick sections and a table speed of 80 mm/s immediately after arrival of contrast medium into the abdominal aorta. Arteriomegaly is present throughout but most notably in the iliofemoral arteries. Arterial opacification ceases in the popliteal artery, resulting in a nondiagnostic examination of the popliteal, crural, and pedal arteries. b A curved planar reformation through the proximal right popliteal artery demonstrates the presence of a popliteal artery aneurysm. The slow-flow characteristic of patients with large arteries results in a CT angiogram where the CT table is moving faster than the blood flow and the scanner thus overruns contrast medium bolus.
slow acquisition protocol [9], a second CTA acquisition (covering the popliteal and infrapopliteal vasculature) must be preprogrammed into the scanning protocol and can be initiated by CT technologists if they do not see any contrast medium opacification in the distal vessels. Opacification of deep and superficial veins cannot be completely avoided in some patients with rapid arteriovenous transit times [4, 15] and is more likely to occur with longer scan times and in patients with active inflammation, e.g., from infected or nonhealing ulcers (Fig. 3). However, stronger arterial enhancement with correct injection timing [4], along with adequate anatomic knowledge and postprocessing tools, can help to avoid diagnostic problems from venous enhancement.

**Visualization Techniques**

Despite the availability of state-of-the-art two-(2-D) and three- (3-D) dimensional image postprocessing techniques, transverse CT images are indispensable for assessment of nonvascular abdominal and/or pelvic abnormalities. These source images can also be used to analyze findings on 2-D or 3-D images that suggest artifactual lesions. For some vascular lesions, transverse images may provide an initial impression or may provide all the required information, for example, in patients with or without only minimal disease, trauma, or suspected acute occlusions. However, for most patients with peripheral vascular disease, review of large number of transverse images is time consuming and less accurate [11] than alternative 2-D and 3-D visualizations.

Three dimensional overview techniques with at least one 2-D technique are generally used for atherosclerotic peripheral vascular diseases. Our protocol for peripheral MDCTA comprises curved planar reformations (CPRs), thin-slab maximum intensity projections (MIPs) through the renal and visceral arteries, and interactive exploration of volume renderings (VRs) of the abdomen, pelvis, and each leg. These 2-D and 3-D techniques enable faster and easier interpretation of huge data sets of axial images. MIP and VR techniques facilitate assessment of vascular structures by providing “angiographic maps” of the arterial tree. Being closest to the angiographic map, MIP images are suitable for illustrating abnormalities to the requesting physicians and can serve as a vascular map for patient management in the catheter angiography suite or operating rooms (Fig. 4). However, need for time-consuming bone removal from image data, inadvertent removal of vascular structures adjacent

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**Fig. 3a,b.** Two volume-rendered (VR) views of the feet in a patient with right-foot cellulitis. Extensive venous opacification (narrow arrows) complicates analysis of the right foot while arteries only are opacified in the left foot, allowing clear visualization of a dorsalis pedis arterial occlusion (wide arrow)
Fig. 4. Frontal maximum projection intensity (MIP) of computed tomography angiography (CTA) comprising the entirety of the aorta, iliac arteries, and runoff performed to assess for a source of distal embolization. This full-volume MIP requires preliminary removal of the bones to allow visualization of the arterial anatomy. There is an occlusion of the proximal right popliteal artery with robust collateralization reconstituting the posterior tibial artery.
to bony structures, and lack of depth information are some of the limitations of the MIP technique. On the other hand, VR techniques maintain 3-D depth information, and bone removal is not essential (Fig. 5). VR is an ideal technique for rapid and interactive viewing and exploration of peripheral CTA data sets. The main limitation of both MIP and VR is that vessel calcifications and stents may completely obscure the vascular flow channel. This precludes its exclusive use in up to 60% of patients with peripheral arterial occlusive disease [16].

In the presence of calcified plaque, diffuse vessel-wall calcification, or endoluminal stents, cross-sectional views such as transverse source images, sagittal, coronal, or oblique multiplanar reformations in conjunction with VR are important for assessing luminal contrast flow. Alternatively, longitudinal cross-sections along a predefined vascular centerline (CPR) can be created with either manual or (semi) automated tracing of the vessel centerlines for the most comprehensive cross-sectional display of luminal pathology [17, 18] (Figs. 6 and 7). At least
**Fig. 6a-c.** a Volume rendering (VR), b maximum intensity projection (MIP), and c curved planar reformation (CPR) through a mid superficial femoral artery lesion. All images demonstrate a >75% stenosis distal to a large calcified plaque. The lumen adjacent to the calcification is partially obscured on VR and MIP. The CPR (c) establishes that there is only minimal luminal narrowing as a result of this calcified plaque.

**Fig. 7a-c.** a Volume rendering (VR), b maximum intensity projection (MIP), and c curved planar reformation (CPR) through a stented segment of the superficial femoral artery. The lumen of the stent is obscured on both VR and the MIP. The CPR (c) demonstrates the lumen of the stent with irregular neointimal hyperplasia. (Images courtesy of Justus Roos, MD and Dominik Fleishmann MD, Department of Radiology, Stanford University School of Medicine, Stanford, CA, USA)
two orthogonal CPRs per vessel segment (e.g., sagittal and coronal views) are required for complete evaluation of eccentric disease. One problem of (single) CPRs in the context of visualizing the peripheral arterial tree is their limited spatial perception. Unless clear annotations are present, the anatomic context of a vascular lesion may be ambiguous. In this context, multipath CPRs provide simultaneous longitudinal cross-sectional views through the major blood vessels without obscuring vascular calcifications and stents while maintaining spatial perception [18] (Fig. 8).

Despite remarkable improvements in 3-D image postprocessing, no algorithms allow fully automated detection of vessel centerlines, automated segmentation of bony structures, and detection (and subtraction) of vessel-wall calcification for peripheral CTA studies. Although it is reasonable to expect further improvements in computer-assisted segmentation and visualization in the not too dis-
tant future, it appears unlikely that expert user interaction (radiologist or 3-D technologist) can be completely avoided for creating clinically relevant and representative peripheral CTA images.

**Clinical Applications**

Several noninvasive imaging techniques, such as ultrasound, CTA, and magnetic resonance angiography (MRA) are available for evaluating clinical conditions involving the lower-extremity vascular structures. Peripheral CTA with state-of-the-art MDCT scanners has the advantages of high spatial resolution, relative freedom from operator dependence, and widespread (and increasing) availability. As a result, peripheral CTA is increasingly used in many imaging centers for a wide range of clinical indications. However, only sparse original data on its accuracy in patients with peripheral arterial occlusive disease, particularly for 16- or 64-row MDCTA, are available when compared with conventional angiography [4, 10–13]. Published studies suggest that peripheral CTA has a high diagnostic accuracy relative to conventional angiography [10–13]. Reported sensitivities and specificities range from 88% to 100%. In general, sensitivity and specificity are greater for arterial occlusions than for detection of stenoses. Accuracies and interobserver agreement are also higher for femoropopliteal and iliac vessels when compared with infrapopliteal arteries. Pedal arteries have not been specifically analyzed in the literature. At least in patients with intermittent claudication, peripheral CTA has the potential to be cost effective [19].

**Intermittent Claudication**

Surgical or endovascular revascularization is performed when medical management of patients with claudication fails to improve the symptoms. Factors that influence choice of treatment include lesion morphology (degree of stenosis/occlusion and lesion length) [20], location, and, most importantly, status of runoff vessels, specifically the calf arteries, which can predict long-term patency rates after intervention [21]. Peripheral CTA provides complete delineation of both the femoropopliteal segment and inflow and outflow arteries, including lesion number, length, stenosis diameter and morphology, adjacent normal arterial caliber, degree of calcification, and status of distal runoff vessels. These findings help in planning the procedure with respect to route of access, balloon selection, and expected long-term patency after femoropopliteal intervention. Compared with catheter angiography, peripheral CTA provides better estimates of the effects of eccentric stenoses on luminal diameter reduction [22]. In addition, collateral vessels can be evaluated with MIP and VR images, and arterial segments distal to long-segment occlusions are well visualized (Fig. 9). It is also expected that peripheral CTA is more cost effective than digital subtraction angiog-
raphy (DSA) for preprocedure evaluation of patients with claudication [23, 24].

**Chronic Limb-Threatening Ischemia**

In patients with chronic limb-threatening ischemia, the principal goal of treatment is prevention of tissue loss and need for amputation, assessment, and promotion of blood flow through the calf arteries. An accurate roadmap to lesions amenable to percutaneous transluminal angioplasty or other endovascular techniques and delineation of patent, acceptable target vessels for distal bypass are the challenges of vessel analysis in this advanced disease group (Fig. 10). In this respect, “isotropic” image data sets (<1 mm) and optimum contrast-medium delivery, especially with the
state-of-the-art 64-row MDCT scanners, may provide improved visualization of small crural and pedal vessels in patients with chronic limb-threatening ischemia.

**Acute Ischemia**

For evaluation of acute lower-extremity ischemia, catheter angiography appears to be the most appropriate evaluation technique if urgent percutaneous (thrombolysis, etc.) or surgical intervention is planned [25]. However, in some situations, peripheral CTA may guide the choice of percutaneous or surgical intervention and help in preprocedural planning. For example, CTA can determine the extent and location of thrombosis and whether thrombus or emboli involves all trifurcation vessels, a previously patent bypass graft, or resides within a popliteal aneurysm, and whether thrombolytic therapy may be most efficacious [26] (Fig. 8). In addition, demonstration of thrombus in locations not accessible to embolectomy may direct treatment to catheter-based techniques. In the subacute ischemic population for whom surgical intervention may be best, peripheral CTA can provide a comprehensive map of the affected vascular territories for surgery planning. CTA may provide rapid and adequate evaluation for patients who refuse catheter angiography and/or thrombolysis. It is important to remember that in these settings, an additional CTA acquisition in a delayed phase immediately after the initial arterial phase is often helpful to differentiate patent but slowly flowing vessels from thrombus.

**Aneurysms**

Peripheral CTA is a noninvasive and cost-effective alternative to DSA for detection and characterization of lower-extremity aneurysms. It provides detailed information about aneurysm size, presence, and amount of thrombus, presence of distal embolic disease, associated significant proximal and distal steno-occlusive disease, and coexistent abdominal or iliac aneurysms. Three-dimensional volumetric analysis provides accurate measurement of aneurysm volume as well as luminal dimension.

**Follow-Up and Surveillance After Percutaneous or Surgical Revascularization**

Ultrasound is the first choice for routine bypass graft surveillance or serial follow-up evaluation after intervention (e.g., in research protocols) [27, 28]. However, peripheral CTA is an important problem-solving tool for the workup of patients with nondiagnostic (limited access due to skin lesions, wounds, draping, or obesity) or equivocal ultrasound studies. In these settings, CTA provides rapid, noninvasive, and accurate evaluation of peripheral arterial bypass grafts and stents and detects related complications, including stenosis, aneurysmal changes, and arteriovenous fistulae [29] (Fig. 7). CTA can also demonstrate the results of percutaneous interventions and reveal residual disease and both vascular and extravascular complications. Peripheral CTA has replaced catheter DSA completely at our institution in these settings and is used to decide upon further management.

**Vascular Trauma**

CTA provides rapid and accurate demonstration of traumatic arterial injuries, relationship of arterial segments to adjacent fractures, bone fragments, and soft tissue injuries, hematoma, associated vascular compression, or pseudoaneurysm. CTA can be performed in combination with CT of other organ systems (abdomen, chest, etc.) for complete delineation of the distribution and severity of injuries in each individual organ system [30]. Transverse source images are usually sufficient for interpretation, although MPRs may improve rapidity of analysis. VR images can improve depiction of the anatomic relationship between arteries and adjacent bony/soft tissue injuries and foreign bodies (Fig. 11).

**Vascular Mapping**

Peripheral CTA data sets can be used to generate vascular maps for subsequent surgical intervention. Prior to MDCTA, catheter angiography was used to generate these vascular maps. Peripheral CTA in the trauma setting is useful if subsequent surgical reconstruction is planned. Likewise, preoperative knowledge of vascular anatomy is also important for plastic surgery reconstruction for various diseases. Fibular free-flap procurement requires preoperative assessment of the limb to prevent ischemic complications and flap failure and to exclude variant peroneal artery anatomy and occlusive disease, which could alter the surgical procedure [31]. CTA allows high-resolution 3-D evaluation of arteries, veins, and soft tissues [32–34] with less risk and at lower cost than catheter angiography [34]. Vascular mapping with CTA is also useful for character evaluation and vascular supply of musculoskeletal tumors [30] and evaluation of suitability of the thoracodorsal and internal mammary arteries prior to trans-
verse rectus abdominis muscle flap reconstruction.

Miscellaneous Applications

Peripheral CTA can provide important information about many other vascular conditions affecting the lower extremity, such as vascular malformations, arterial compression by adjacent masses, vasculitides, inflammatory/infective processes of soft tissue and bone affecting adjacent vessels, adventitial cystic disease, and popliteal entrapment syndrome [30, 35]. Image acquisition at rest and with provocative maneuvers (e.g., active plantarflexion against resistance) in patients with popliteal entrapment syndrome allows anatomic delineation of the medial head of the gastrocnemius as well as the dynamic degree of arterial obstruction.

Pitfalls

It is important to review peripheral CTA studies in the context of a patient’s symptoms, disease stage, and available therapeutic options. This can help overcome the learning curve and avoiding interpretation pitfalls associated with visual perception and interpretation of vascular abnormalities in a new and different format (such as VR or CPR images).

Commonly, pitfalls related to interpretation of peripheral CTA studies can occur with use of narrow viewing-window settings in the presence of arterial wall calcifications or stents. Blooming artifacts related to these high-attenuation structures leads to overestimation of a vascular stenosis or suggest spurious total occlusion, even at relatively wide window settings. Thus, we use a much higher window width of at least 1,500 HU for evaluating luminal patency at the site of a calcified lesion or a stent. Some vendors (Siemens Medical Solutions) recommend use of special higher spatial resolution reconstruction kernels in the presence of stents. Despite these measures, peripheral CTA studies may not resolve luminal diameter in presence of extensive atherosclerotic or media calcification within small crural or pedal arteries, such as those found in diabetic patients and in patients with end-stage renal disease.

Pitfalls related to image interpretation can also result from misinterpretation of editing artifacts (inadvertent removal of vascular structures in MIP images) and pseudostenosis and/or occlusions due to inaccurate centerline definition (in CPR images). These pitfalls underscore the importance of reviewing source images, additional views, or complimentary imaging modalities.

Conclusion

In conclusion, state-of-the-art MDCT scanners with 16 and 64 detector rows enable acquisition of high spatial resolution peripheral CTA, which helps in noninvasive imaging and treatment planning of peripheral arterial disease.

References

of bolus geometry for CT angiography using the discrete Fourier transform. J Comput Assist Tomogr 23(3):474–784