

Computed Tomography Angiography as a Non-Invasive Diagnostic Tool for Limb Arteries: A Current Application

Ozkan Alatas¹, Hidayet Kayancicek², Hasan Baki Altinsoy³, Erhan Hafiz⁴, Davut Azboy⁵, Zeki Temizturk⁵, Omer Faruk Dogan^{6*} and Umit Duman⁷

¹Department of Radiology, The Health Sciences University Elazığ Research and Training Hospital, Elazığ, Turkey

²Department of Cardiology, Medical Park University, School of Medicine Elazığ Hospital, Turkey

³Department of Radiology, Duzce University School of Medicine, Duzce, Turkey

⁴Department of Cardiovascular Surgery, Gaziantep University School of Medicine, Gaziantep, Turkey

⁵Department of Cardiovascular Surgery, The Health Sciences University Elazığ Research and Training Hospital, Turkey

⁶Department of Cardiovascular Surgery, Istanbul Medipol University, Turkey

⁷Department of Cardiovascular Surgery, The Health Sciences University Adana Numune Research and Training Hospital, Turkey

***Corresponding author:** Omer Faruk Dogan, Department of Cardiovascular Surgery, Istanbul Medipol University, S. Demirel Bulvari, 1/1, Çukurova, Adana, Turkey. Tel: +90 322 3550101; Fax: +90 322 355 0101; Email: ofdogan@hacettepe.edu.tr

Published Date: February 28, 2017

ABSTRACT

Diagnostic procedures of limb arteries are changing and rapidly advancing field. Diagnostic and imaging modalities shows that vascular illness is more prevalent especially in older patients or in youngs who have additional risk factors such as diabetes, renal failure, etc. [1-19]. The prompt diagnosis and treatment of lower limb vascular illness is a key role to prevent salvage an ischemic limb(s). Advancements in Computed Tomography Angiography (CTA) have made vascular CTA the modality of choice for accurately diagnosing vascular disease and the management of its treatment. Three-D multi-detector CT provides noninvasive, direct imaging of virtually the entire

vascular system is accepted as a safe, effective and accurate method without the inherent risk attributed to invasive angiography. CTA is widely available in nearly all institutions in around the world that do not perform invasive angiography. Vascular CTA and the diseases for which it is meant to diagnose into an easy to follow and inclusive resource. CTA angiography in elective and emergent situations is given valuable informations for cardiovascular surgeons and radiologists as well as for those already in practice. This work makes 'difficult to understand' concepts easy to comprehend with the aid of simple, and quality images. For those already proficient in vascular CTA, this chapter will serve as a resource as it compiles a complete radiation review, imaging protocols, screening recommendations, disease states and imaging tips in all location of the limb arteries.

CT imaging of the arterial system is generally performed in trauma patients, patients with ischemic symptoms, for preoperative planning of complex extremity vascular reconstructions and dialysis access, and for follow-up evaluation of endovascular or surgical procedures [1]. CTA imaging in patients with arterial pathology and its abnormalities has been the domain of digital subtraction angiography (**DSA**) because of it has dynamic nature and superior spatial resolution [20-43]. As we know that, DSA is not a cost effective and time-consuming invasive procedure. DSA provides limited information about anatomic relationships between the arterial system and soft-tissue of the lower extremity. On the other side, DSA has potential complications such as hematoma, pain, pseudoaneurysm, etc. With recent advances in MDCT allowing routine acquisition of sub millimeter isotropic datasets. Combined with standard post processing techniques, CTA has made rapid, accurate noninvasive evaluation of the upper extremity arterial vasculature possible. This chapter focuses on the role of CTA in the evaluation of arterial system of the lower extremity.

METRIX OF CTA

CTA image quality metrics focus on the ability to resolve, differences between tissues, namely spatial resolution, temporal resolution and volume coverage [21,23,29,30,34]. Contrast media administration is briefly discussed because it is an essential part of the CTA acquisition.

Spatial resolution measures the smallest high contrast object depicted by the CT system and depends largely on the detector collimation and reconstruction kernel. Another key parameter is the size of the focal spot [5]. Sub millimeter slices generated from modern hardware has expanded the role of CTA from aortography to smaller vessels. Consider a set of equally spaced lines where the spaces have the same thickness as the lines. The "spatial frequency" is measured in line pairs per centimeter. Larger objects with poorly defined edges have predominantly low spatial frequencies; small objects with sharp edges have higher spatial frequencies [6]. Although inferior to conventional DSA, CTA can assess arteries as small as 1 mm in diameter. Because it is volumetric, CT angiography allows three-dimensional visualization of the vasculature to separate superimposed structures (Figure 1, Figure 2 and Figure 3). As we illustrate in the applications (Figure 4), CTA can image small arteries as well as the distal vascular circulation, up to and including an evaluation of the ascending aorta.



Figure 1

Figure 1: A volumetric three-D computed angiography shows a descending aorta and the peripheral system (the white arrow demonstrates descending aortic, iliac and femoral artery calcific disease.). Patent femoro-popliteal bypass graft is also visualised (red arrow-head).

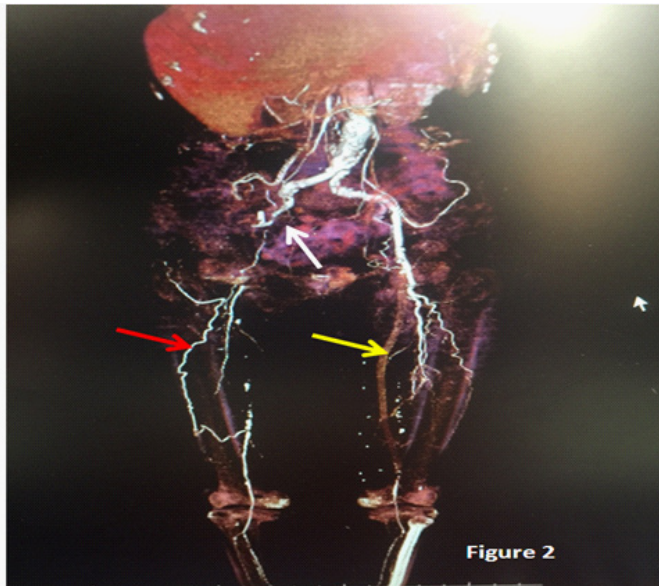


Figure 2

Figure 2: This figure shows using a 3-D aorto-femoro-popliteal computed tomography angiography in a 74 years old male patient. There is a total occlusion of the right and the left femoral artery (white arrows head.). The red arrow demonstrates a collateral circulation which arising from the common femoral artery. The yellow arrow shows a patent femoro-popliteal artery by-pass graft.



Figure 3: shows that there is severe occlusion of the left femoral artery (arrow). The distal femoral artery occlusion is also indicated using another arrowhead.

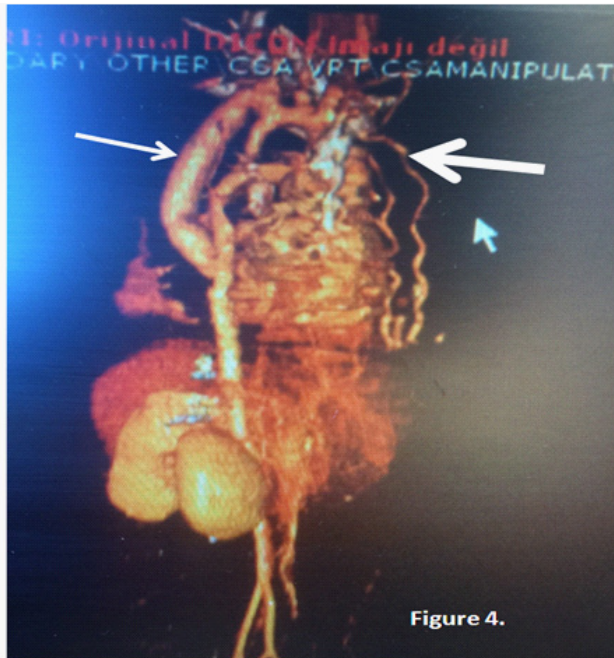


Figure 4: Demonstrates that postoperative view of patent subclavian to thoracic aortic graft after an operation performed for aortic coarctation in a 9 year old boy (the white arrow-head). The collateral artery arising from subclavian artery indicates using a white arrow-head.

The Z-axis coverage per gantry rotation plays an important role in the CTA acquisition. For example, 4X1 mm detector-row CTA requires the following trade-off between acquisition speed and slice thickness [7,8]. With 0.5 second gantry rotation and a 1.25 pitch, 30 cm cephalocaudad coverage typical of aortoiliac or its branches CTA requires a 30 second acquisition. Using a 4X3 mm detector row configuration, scan time is reduced to 10 sec. Wide area detector systems (8-16 cm per rotation) can image axially, i.e. without table motion, and may have advantages for dynamic perfusion imaging [9].

CONTRAST MEDIUM AND ITS APPLICATION

The injection of contrast medium is a key factor to provide quality images of the vascular lumen. CTA should discriminate the true lumen of the vascular wall. The ideal agent for CTA is nonionic, iso- or low osmolar, and has high iodine concentration [44-55]. 370-400 mg of iodine per milliliter may be used in CTA. Artefacts because of cardiac or vena cava system may be seen with high iodine concentrations. Therefore, large volumes reflect sub-optimized imaging protocols. Saline flush injection following contrast has been suggested by the authors to avoid this problem [56-60]. Protocols must be tailored to the vascular bed and typically require rapid contrast administration (3-6 cc per second). Biphasic injection can provide a more homogeneous enhancement profile over time [61-74]. Faster acquisitions enable smaller contrast volumes because peak enhancement is required for shorter acquisition times [75-80].

IMAGE ACQUISITION

Helical CT angiography has been used in a large number of patients. During the procedure, continuous gantry rotation and table motion is required for high quality image reconstruction (Figure 4 and 5). Along with the rotation time, the helical pitch determines the table speed, and therefore the speed at which the volume is scanned [15]. The helical pitch and table speed with the first circulation of contrast medium through the anatomic region is an important factor. The timing of a CTA scan is of critical importance so that the data is acquired during peak enhancement and not before or after the contrast has arrived [16]. To ensure suitable circulation timing, we may use a scanner's automatic bolus tracking software (Figure 6). After the test bolus approach, a small amount of contrast medium is injected, and low radiation dose scans are acquired to time the contrast arrival. After then, a CTA scan is acquired with the full dose of contrast material with a scan delay as determined by the test bolus (Figure 7). The second, more common, approach is automatic tracking of the main bolus arrival with subsequent automatic initiation of the acquisition. When contrast opacification reaches a preset threshold, the scanner automatically moves to the start position and begins the CTA helical acquisition.

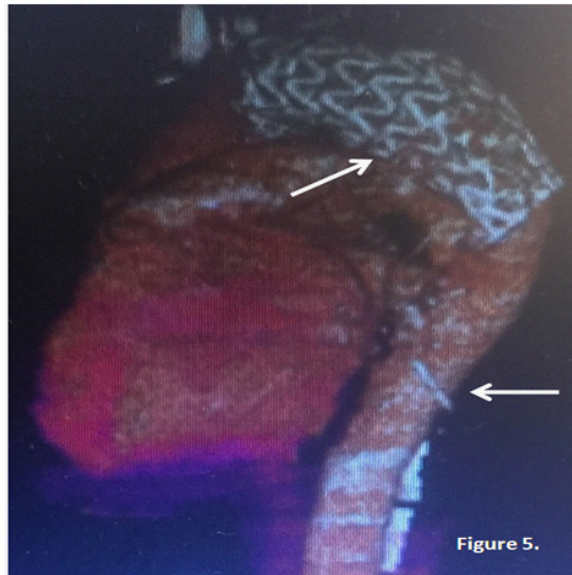


Figure 5: shows that a post-intervention ascending aortic stent graft in a 54 year old female patient who has dissection of descending aorta (The first and the second white-arrowhead shows the stent graft and normal descending aorta, respectively).

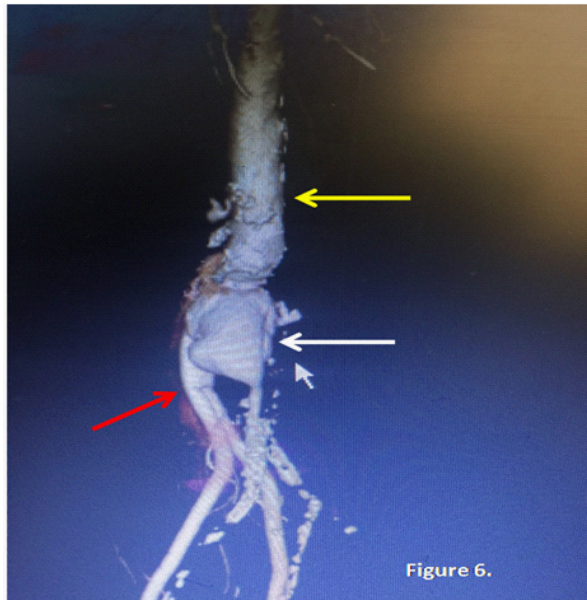


Figure 6: demonstrates the aortic pseudoaneurysm which developed after aorto-bifemoral by-pass grafting surgery in a 68 year old male patient. Endovascular stent graft replacement has been performed successfully in this patient after diagnosis of pseudoaneurysm formation. Upper yellow arrow shows atherosclerotic abdominal aorta. The white arrow-head exhibits pseudoaneurysm formation (7 mm Diameter). The red arrow-head demonstrates aorto-bifemoral graft.



Figure 7: shows that bilateral distal femoral arteries and the anterior peroneal and posterior tibial artery in a young patient with popliteal artery entrapment syndrome. In this picture, we see that there is an artifact between the arterial system and soft tissue area.

Helical CT can be used to freeze motion, either from the aortic root in CT aortography. Retrospective gating is not required for evaluation of the descending aorta and should not be used since retrospective gating inherently has a higher radiation dose than helical imaging without gating. The data is then post-processed to correlate with the ECG and assign cardiac phase to each segment of the reconstructed data. Image quality is degraded by blurring secondary to rapid heart rates and misregistration artifacts secondary to heart rate variability and arrhythmia [81-97]. For single source x-ray systems, beta-blockers should be used to decrease the heart rate, dependent on patients tolerance. Motion compensation algorithms allow for more consistent image quality [98] (Figure 5 and Figure 8).

Multi-energy CTA with bone subtraction software is an important device. The long-term aim of multi-energy imaging is additional anatomical information based on the energy dependence of tissue attenuation differences [99-101]. Tissue components can be determined via post-processing of images collected at two energies [64,65] or via direct analysis within the multidetector CT data simultaneously acquired at separate energies [66]. Dual source CTA has been suggested, with each tube operating at a different kV and acquiring data 90 degrees apart. Each tube can operate different currents to equalize the noise between the different energies [79,86,88,102-106].

Both slow kV switching and dual source use image based decomposition. In order to use raw data based decomposition, each projection must be acquired at both energies simultaneously. Fast kV switching allows the energy to be changed for each adjacent projection which approximates

simultaneous acquisition and has the potential for plaque characterization [29]. A spectrally sensitive detector uses distinct detector materials to separate different energy levels from each layer [62,73,81,86,87,95].

CLINICAL COMPUTED TOMOGRAPHY ANGIOGRAPHY

Compute Tomography Aortography

CTA has replaced catheter angiography as the gold-standard for imaging the aorta [107-110]. The entire aorta, from aortic root to distal end, may be imaged in seconds, and the z-axis field of view can be extended to iliac systems in a single breath hold. Imaging is rapid, accurate, and widely available. CT completely characterizes the aorta for either catheter-based or surgical intervention (Figure 5); size, shape, and severity of calcification of aneurysms morphology of the true and false lumen in dissection (Figure 6), extent of the stenoses (Figure 7), and the anatomic relationship between the artery and juxta positioned tissue (Figure 8). CT is the best method to detect post-surgery complications [restenosis (Figure 9); thrombosis, or endoleak after aneurysm repair]. CTA may provide useful insights into the thickness and composition of vessel walls by differentiating lumen and vascular wall. Image post-processing includes three-dimensional volume rendering and maximum intensity projections. The latter can be very accurate for larger vessels such as the aorta with adequate intraluminal contrast concentration. Smaller vessels such as femoral or distal arteries are best analysed with multiplanar reformations.

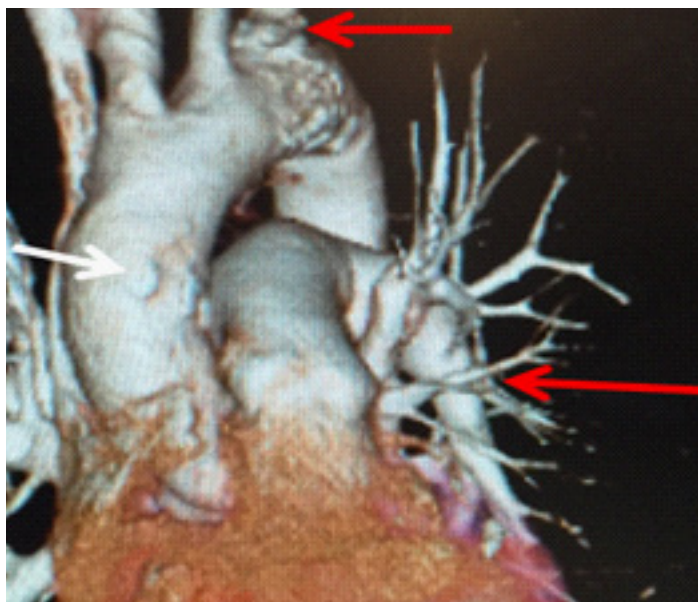


Figure 8: shows that there are arterial calcific disease and plaque formation on the ascending aorta (short white arrow), and left common carotid artery (short red arrow). There is a normal main pulmonary artery and segmental pulmonary branches (long red arrow-head). The yellow-arrow head shows a normal descending artery.

CT Pulmonary Angiography

CTA for pulmonary arterial system has replaced catheter angiography as the gold-standard for imaging the pulmonary arteries like a traditional arteriography. Traditional arteriography is indicated only the patient who has contraindication to CTA. A multi-detector row of the entire thorax during breath hold is routinely used per gantry rotation less than one-half second. Pulmonary artery CTA has high sensitivity and specificity in detecting pulmonary embolism [111,112].

Renal and Mesenteric CTA

Renal arteries may be affected by atherosclerosis with associated stenosis, or aneurysms, or stenosis. Because the renal artery has a small diameter (approximately 4-5 mm), and it has a smaller accessory arteries, 15% of vessels cannot be visualised by row CTA. Submillimeter isotropic resolution from more modern hardware improves spatial resolution; these scanners also have shorter acquisition times to better visualize normal and atherosclerotic renal arteries. CTA may be used for other diagnoses such as fibromuscular dysplasia. Three-dimensional volume rendering projection is playing an important role for planning of therapy in patients with renal artery stenosis. Mesenteric arteries have also smaller diameter. Distal branches diameter is 1 mm or less. CTA may be used for mesenteric ischemia. At multiple phases of contrast enhancement to evaluate arteries, veins, and the bowel wall. A dynamic protocol can also be used to pinpoint the location of a gastrointestinal bleed. CT can also be used as an imaging modality of choice for clinically suspected median arcuate ligament syndrome.

PERIPHERAL CTA

CTA is being increasingly used for detect peripheral artery disease using a three-dimensional high quality images [113,114]. Patients with peripheral artery disease (Figure 10), acute arterial embolus, post-traumatic diagnosis, and complications after surgery may be evaluated. Because the diameter of distal peripheral arterial system is small, according to previous suggestions, adequate enhancement requires an understanding of the scanner speed and kinetics of the iodinated contrast medium. In patients with severe peripheral arterial disease, the speed of the contrast bolus can be 30 millimeters per second. 64,128 (or more) slices per gantry rotation may be used in these patients [35,40,56]. Maximum intensity projections and three-dimensional volume rendering provides a good overview of the vessel anatomy, graft patency after surgery, and the development of collateral vessels.

CONCLUSION

Recent development in technology has moved three-dimensional computed tomography angiography to the front line for many vascular diseases, and postsurgical control dramatically changing clinical evaluation pathways. In our opinion, multi detector CT technology is critical for optimizing protocols for patients' diagnosis and postsurgical graft or stent-graft control.

References

1. Blankstein R, Shah A, Pale R, Abbata S, Bezerra H, et al. Radiation dose and image quality of prospective triggering with dual-source cardiac computed tomography. *Am J Cardiol*. 2009; 103: 1168-1173.
2. Blobel J, Baartman H, Rogalla P, Mews J, Lembcke A. Spatial and temporal resolution with 16-slice computed tomography for cardiac imaging. *Rofo*. 2003; 175: 1264-1271.
3. Herzog C, Arning-Erb M, Zangos S, Eichler K, Hammerstingl R, et al. Multi-detector row CT coronary angiography: influence of reconstruction technique and heart rate on image quality. *Radiology*. 2006; 238: 75-86.
4. Leschka S, Wildermuth S, Boehm T, Desbiolles L, Husmann L, et al. Noninvasive coronary angiography with 64-section CT: effect of average heart rate and heart rate variability on image quality. *Radiology*. 2006; 241: 378-385.
5. Wintersperger BJ, Nikolaou K, Von Ziegler F, Johnson T, Rist C, et al. Image quality, motion artifacts, and reconstruction timing of 64-slice coronary computed tomography angiography with 0.33-second rotation speed. *Invest Radiol*. 2006; 41: 436-442.
6. Hein I, Taguchi K, Silver MD, Kazama M, Mori I. Feldkamp-based cone-beam reconstruction for gantry-tilted helical multislice CT. *Med Phys*. 2003; 30: 3233-3242.
7. Dewey M, Laule M, Schnapauß D, Rogalla P, et al. Multisegment and halfscan reconstruction of 16-slice computed tomography for detection of coronary artery stenoses. *Invest Radiol*. 2004; 39: 223-229.
8. Klingebiel R, Siebert E, Diekmann S, Wiener E, Masuhr F, et al. 4-D Imaging in cerebrovascular disorders by using 320-slice CT: feasibility and preliminary clinical experience. *Acad Radiol*. 2009; 16: 123-129.
9. Fleischmann D, Rubin GD, Bankier AA, Hittmair K. Improved uniformity of aortic enhancement with customized contrast medium injection protocols at CT angiography. *Radiology*. 2000; 214: 363-371.
10. Halpern EJ. Triple-rule-out CT angiography for evaluation of acute chest pain and possible acute coronary syndrome. *Radiology*. 2009; 252: 332-345.
11. Kalender WA, Seissler W, Klotz E, Vock P. Spiral volumetric CT with single-breath-hold technique, continuous transport, and continuous scanner rotation. *Radiology*. 1990; 176: 181-183.
12. Nieman K, Rensing BJ, Van Geuns RJ, Vos J, Pattynama PM, et al. Non-invasive coronary angiography with multislice spiral computed tomography: impact of heart rate. *Heart*. 2002; 88: 470-474.
13. Mather R, Boedeker K, Nicholson T. Automatic Cardiac Phase Selection for Motion-free Coronary Imaging. Second Annual Meeting of the SCCT. 2007.
14. Budoff MJ, Achenbach S, Blumenthal RS, Carr JJ, Goldin JG, et al. Assessment of coronary artery disease by cardiac computed tomography: a scientific statement from the American Heart Association Committee on Cardiovascular Imaging and Intervention, Council on Cardiovascular Radiology and Intervention, and Committee on Cardiac Imaging, Council on Clinical Cardiology. *Circulation*. 2006; 114: 1761-1791.
15. Fazel R, Krumholz HM, Wang Y, Ross JS, Chen J, et al. Exposure to low-dose ionizing radiation from medical imaging procedures. *N Engl J Med*. 2009; 361: 849-857.
16. Arnoldi E, Johnson TR, Rist C, Wintersperger BJ, Sommer WH, et al. Adequate image quality with reduced radiation dose in prospectively triggered coronary CTA compared with retrospective techniques. *Eur Radiol*. 2009; 19: 2147-2155.
17. Shuman WP, Branch KR, May JM, Mitsumori LM, Lockhart DW, et al. Prospective versus retrospective ECG gating for 64-detector CT of the coronary arteries: comparison of image quality and patient radiation dose. *Radiology*. 2008; 248: 431-437.
18. Martini C, Palumbo A, Maffei E, Rossi A, Rengo M, et al. Dose reduction in spiral CT coronary angiography with dual-source equipment. Part I. A phantom study applying different prospective tube current modulation algorithms. *Radiol Med*. 2009; 114: 1037-1052.
19. Hirai N, Horiguchi J, Fujioka C, Kiguchi M, Yamamoto H, et al. Prospective versus retrospective ECG-gated 64-detector coronary CT angiography: assessment of image quality, stenosis, and radiation dose. *Radiology*. 2008; 248: 424-430.
20. Earls JP, Berman EL, Urban BA, Curry CA, Lane JL, et al. Prospectively gated transverse coronary CT angiography versus retrospectively gated helical technique: improved image quality and reduced radiation dose. *Radiology*. 2008; 246: 742-753.
21. Steigner ML, Otero HJ, Cai T, Mitsouras D, Nallamshetty L, et al. Narrowing the phase window width in prospectively ECG-gated single heart beat 320-detector row coronary CT angiography. *Int J Cardiovasc Imaging*. 2009; 25: 85-90.
22. Fleischmann D, Rubin GD. Quantification of intravenously administered contrast medium transit through the peripheral arteries: implications for CT angiography. *Radiology*. 2005; 236: 1076-1082.
23. Ligon BL. Biography: history of developments in imaging techniques: Egas Moniz and angiography. *Semin Pediatr Infect Dis*. 2003; 14: 173-181.

24. Mueller RL, Sanborn TA. The history of interventional cardiology: cardiac catheterization, angioplasty, and related interventions. *Am Heart J* 1995; 129: 146-172.
25. Waugh JR, Sacharias N. Arteriographic complications in the DSA era. *Radiology*. 1992; 182: 243-246.
26. Krnic A, Vucic N, Sucic Z. Duplex scanning compared with intra-arterial angiography in diagnosing peripheral arterial disease: three analytical approaches. *Vasa* 2006; 35: 86-91.
27. Wardlaw JM, Chappell FM, Best JJ, Wartolowska K, Berry E. Noninvasive imaging compared with intra-arterial angiography in the diagnosis of symptomatic carotid stenosis: a meta-analysis. *Lancet*. 2006; 367: 1503-1512.
28. Heijnenbroek-Kal MH, Kock MC, Hunink MG. Lower extremity arterial disease: multidetector CT angiography meta-analysis. *Radiology*. 2007; 245: 433-439.
29. Schoenhagen P, Halliburton SS, Stillman AE, Kuzniak SA, Nissen SE, et al. Noninvasive imaging of coronary arteries: current and future role of multi-detector row CT. *Radiology*. 2004; 232: 7-17.
30. Rybicki FJ, Nallamshetty L, Yucel EK, Holtzman SR, Baum RA, et al. ACR appropriateness criteria on recurrent symptoms following lower-extremity angioplasty. *J Am Coll Radiol*. 2008; 5: 1176-1180.
31. Leiner T, De Haan MW, Nelemans PJ, Van Engelshoven JM, Vasbinder GB. Contemporary imaging techniques for the diagnosis of renal artery stenosis. *Eur Radiol*. 2005; 15: 2219-2229.
32. Arora S, Chien JD, Cheng SC, Chun KA, Wintermark M. Optimal carotid artery coverage for carotid plaque CT-imaging in predicting ischemic stroke. *J Neuroradiol*. 2009.
33. Rozie S, De Weert TT, De Monye C, Homburg PJ, Tanghe HL, et al. Atherosclerotic plaque volume and composition in symptomatic carotid arteries assessed with multidetector CT angiography; relationship with severity of stenosis and cardiovascular risk factors. *Eur Radiol*. 2009; 19: 2294-2301.
34. Buckley O, Rybicki FJ, Gerson DS, Huether C, Prior RF, et al. Imaging features of intramural hematoma of the aorta. *Int J Cardiovasc Imaging*. 2010; 26: 65-76.
35. Hsieh J. *Computed tomography: principles, design, artifacts, and recent advances*. SPIE Optical Engineering Press; Bellingham, WA. 2003.
36. Flohr TG, McCollough CH, Bruder H, Petersilka M, Gruber K, et al. First performance evaluation of a dual-source CT (DSCT) system. *Eur Radiol*. 2006; 16: 256-268.
37. McCollough CH, Schmidt B, Yu L, Primak A, Ulzheimer S, et al. Measurement of temporal resolution in dual source CT. *Med Phys*. 2008; 35: 764-768.
38. Araoz PA, Kirsch J, Primak AN, Braun NN, Saba O, et al. Optimal image reconstruction phase at low and high heart rates in dual-source CT coronary angiography. *Int J Cardiovasc Imaging*. 2009.
39. Xu L, Yang L, Zhang Z, Li Y, Fan Z, et al. Low-dose adaptive sequential scan for dual-source CT coronary angiography in patients with high heart rate: comparison with retrospective ECG gating. *Eur J Radiol*. 2010; 76: 183-187.
40. Dewey M, Zimmermann E, Laule M, Rutsch W, Hamm B. Three-vessel coronary artery disease examined with 320-slice computed tomography coronary angiography. *Eur Heart J*. 2008; 29: 1669.
41. Alvarez RE, Macovski A. Energy-selective reconstructions in X-ray computerized tomography. *Phys Med Biol*. 1976; 21: 733-744.
42. Avrin DE, Macovski A, Zatz LE. Clinical application of Compton and photo-electric reconstruction in computed tomography: preliminary results. *Invest Radiol*. 1978; 13: 217-222.
43. Maass C, Baer M, Kachelriess M. Image-based dual energy CT using optimized pre-correction functions: a practical new approach of material decomposition in image domain. *Med Phys*. 2009; 36: 3818-3829.
44. Schmidt TG. Optimal "image-based" weighting for energy-resolved CT. *Med Phys*. 2009; 36: 3018-3027.
45. Zou Y, Silver M. Analysis of Fast kV-switching in Dual Energy CT using a Pre-reconstruction Decomposition Technique. *Progress in biomedical optics and imaging*. 2008; 9: 30.
46. Johnson TR, Krauss B, Sedlmair M, Grasruck M, Bruder H, et al. Material differentiation by dual energy CT: initial experience. *Eur Radiol*. 2007; 17: 1510-1517.
47. Yahyavi-Firouz-Abadi N, Wynn BL, Rybicki FJ, Steigner ML, Hussain AZ, et al. Jr Steroid-responsive large vessel vasculitis: application of whole-brain 320-detector row dynamic volume CT angiography and perfusion. *AJNR Am J Neuroradiol*. 2009; 30: 1409-1411.
48. Uotani K, Watanabe Y, Higashi M, Nakazawa T, Kono AK, et al. Dual-energy CT head bone and hard plaque removal for quantification of calcified carotid stenosis: utility and comparison with digital subtraction angiography. *Eur Radiol*. 2009; 19: 2060-2065.

49. Barreto M, Schoenhagen P, Nair A, Amatangelo S, Milite M, et al. Potential of dual-energy computed tomography to characterize atherosclerotic plaque: ex vivo assessment of human coronary arteries in comparison to histology. *J Cardiovasc Comput Tomogr*. 2008; 2: 234-242.
50. Mendonca P, Bhotika R, Thomsen B, Licato P, Joshi M. Multi-material decomposition of dual-energy CT. *SPIE Medical Imaging*. 2009; 7622: 67.
51. Roess E, Ziegler A, Proksa R. On the influence of noise correlations in measurement data on basis image noise in dual-energylike x-ray imaging. *Med Phys*. 2007; 34: 959-966.
52. Heismann B, Wirth S. SNR performance comparison of dual-layer detector and dual-kVp spectral CT. *Nuclear Science Symposium Conference Record, 2007. NSS '07. IEEE*. 2007; 5: 3820-3822.
53. Schlomka JP, Roessl E, Dorscheid R, Dill S, Martens G, et al. Experimental feasibility of multi-energy photon-counting K-edge imaging in pre-clinical computed tomography. *Phys Med Biol*. 2008; 53: 4031-4047.
54. Henrich G, Mai N, Backmund H. Preprocessing in computed tomography picture analysis: a "bone-deleting" algorithm. *J Comput Assist Tomogr*. 1979; 3: 379-384.
55. Li Q, Lv F, Li Y, Li K, Luo T, et al. Subtraction CT angiography for evaluation of intracranial aneurysms: comparison with conventional CT angiography. *Eur Radiol*. 2009; 19: 2261-2267.
56. Morhard D, Fink C, Graser A, Reiser MF, Becker C, et al. Cervical and cranial computed tomographic angiography with automated bone removal: dual energy computed tomography versus standard computed tomography. *Invest Radiol*. 2009; 44: 293-297.
57. Deng K, Liu C, Ma R, Sun C, Wang XM, et al. Clinical evaluation of dual-energy bone removal in CT angiography of the head and neck: comparison with conventional bone-subtraction CT angiography. *Clin Radiol*. 2009; 64: 534-541.
58. Meyer BC, Werncke T, Hopfenmuller W, Raatschen HJ, Wolf KJ, Albrecht T. Dual energy CT of peripheral arteries: effect of automatic bone and plaque removal on image quality and grading of stenoses. *Eur J Radiol*. 2008; 68: 414-422.
59. Boll DT, Merkle EM, Paulson EK, Mirza RA, Fleiter TR. Calcified vascular plaque specimens: assessment with cardiac dual-energy multidetector CT in anthropomorphically moving heart phantom. *Radiology*. 2008; 249: 119-126.
60. Otero HJ, Steigner ML, Rybicki FJ. The "post-64" era of coronary CT angiography: understanding new technology from physical principles. *Radiol Clin North Am*. 2009; 47: 79-90.
61. Dewey M, Zimmermann E, Deissenrieder F, Laule M, Dubel HP, et al. Noninvasive coronary angiography by 320-row computed tomography with lower radiation exposure and maintained diagnostic accuracy: comparison of results with cardiac catheterization in a head-to-head pilot investigation. *Circulation*. 2009; 120: 867-875.
62. Hoe J, Toh KH. First experience with 320-row multidetector CT coronary angiography scanning with prospective electrocardiogram gating to reduce radiation dose. *J Cardiovasc Comput Tomogr*. 2009; 3: 257-261.
63. Geleijns J, Salvadó Artells M, De Bruin PW, Matter R, Muramatsu Y, et al. Computed tomography dose assessment for a 160 mm wide, 320 detector row, cone beam CT scanner. *Phys Med Biol*. 2009; 54: 3141-3159.
64. Rybicki FJ, Otero HJ, Steigner ML, Vorobiof G, Nallamshetty L, Mitsouras D, Ersoy H, Mather RT, Judy PF, Cai T, Coyner K, Schultz K, Whitmore AG, Di Carli MF. Initial evaluation of coronary images from 320-detector row computed tomography. *Int J Cardiovasc Imaging*. 2008; 24: 535-546.
65. Siebert E, Böhner G, Dewey M, Masuhr F, Hoffmann KT, et al. 320-slice CT neuroimaging: initial clinical experience and image quality evaluation. *Br J Radiol*. 2009; 82: 561-570.
66. Kandel S, Kloeters C, Meyer H, Hein P, Hilbig A, et al. Whole-organ perfusion of the pancreas using dynamic volume CT in patients with primary pancreas carcinoma: acquisition technique, post-processing and initial results. *Eur Radiol*. 2009; 19: 2641-2646.
67. Hein PA, Romano VC, Lembcke A, May J, Rogalla P. Initial experience with a chest pain protocol using 320-slice volume MDCT. *Eur Radiol*. 2009; 19: 1148-1155.
68. Achenbach S, Marwan M, Schepis T, Pflederer T, Bruder H, et al. High-pitch spiral acquisition: a new scan mode for coronary CT angiography. *J Cardiovasc Comput Tomogr*. 2009; 3: 117-121.
69. Joseph PM, Spital RD. The effects of scatter in x-ray computed tomography. *Med Phys*. 1982; 9: 464-472.
70. Haykin SS, Justice JH. Array signal processing. Prentice-Hall; Englewood Cliffs, N.J. 1985.
71. Endo M, Mori S, Tsunoo T, Miyazaki H. Magnitude and effects of x-ray scatter in a 256-slice CT scanner. *Med Phys*. 2006; 33: 3359-3368.
72. Feldkamp L, Davis L, Kress J. Practical cone-beam algorithm. *J. Opt. Soc. Am. A*. 1984; 1: 612-619.
73. Wang G, Lin TH, Cheng P, Shinzaki DM. A general cone-beam reconstruction algorithm. *IEEE Trans Med Imaging*. 1993; 12: 486-496.

74. Tzedakis A, Damilakis J, Perisinakis K, Stratakis J, Gourtsoyannis N. The effect of z overscanning on patient effective dose from multidetector helical computed tomography examinations. *Med Phys.* 2005; 32: 1621-1629.
75. Van der Molen AJ, Geleijns J. Overranging in multisection CT: quantification and relative contribution to dose--comparison of four 16-section CT scanners. *Radiology.* 2007; 242: 208-216.
76. Deak PD, Langner O, Lell M, Kalender WA. Effects of adaptive section collimation on patient radiation dose in multisection spiral CT. *Radiology.* 2009; 252: 140-147.
77. Yoshida S, Akiba H, Tamakawa M, Yama N, Hareyama M, et al. Thoracic involvement of type A aortic dissection and intramural hematoma: diagnostic accuracy--comparison of emergency helical CT and surgical findings. *Radiology.* 2003; 228: 430-435.
78. Hayter RG, Rhea JT, Small A, Tafazoli FS, Novelline RA. Suspected aortic dissection and other aortic disorders: multi-detector row CT in 373 cases in the emergency setting. *Radiology.* 2006; 238: 841-852.
79. Winer-Muram HT, Rydberg J, Johnson MS, Tarver RD, Williams MD, et al. Suspected acute pulmonary embolism: evaluation with multi-detector row CT versus digital subtraction pulmonary arteriography. *Radiology.* 2004; 233: 806-815.
80. Stein PD, Fowler SE, Goodman LR, Gottschalk A, Hales CA, et al. Multidetector computed tomography for acute pulmonary embolism. *N Engl J Med.* 2006; 354: 2317-2327.
81. Kershenovich A, Rappaport ZH, Maimon S. Brain computed tomography angiographic scans as the sole diagnostic examination for excluding aneurysms in patients with perimesencephalic subarachnoid hemorrhage. *Neurosurgery.* 2006; 59: 798-801.
82. Silvennoinen HM, Ikonen S, Soinne L, Railo M, Valanne L. CT angiographic analysis of carotid artery stenosis: comparison of manual assessment, semiautomatic vessel analysis, and digital subtraction angiography. *AJNR Am J Neuroradiol.* 2007; 28: 97-103.
83. Sakamoto S, Kiura Y, Shibukawa M, Ohba S, Arita K, Kurisu K. Subtracted 3D CT angiography for evaluation of internal carotid artery aneurysms: comparison with conventional digital subtraction angiography. *AJNR Am J Neuroradiol.* 2006; 27:1332-1337.
84. Katzberg RW, Haller C. Contrast-induced nephrotoxicity: clinical landscape. *Kidney Int Suppl.* 2006;3-7.
85. Solomon R, Dumouchel W. Contrast media and nephropathy: findings from systematic analysis and Food and Drug Administration reports of adverse effects. *Invest Radiol.* 2006; 41: 651-660.
86. Agatston AS, Janowitz WR, Hildner FJ, Zusmer NR, Viamonte M, et al. Quantification of coronary artery calcium using ultrafast computed tomography. *J Am Coll Cardiol.* 1990; 15: 827-832.
87. Liang Z, Karl W, Do S, Hoffmann U, Brady T, et al. Calcium De-blooming in Coronary CT Image.. *Bioinformatics and Bioengineering, 2007. BIBE 2007. Proceedings of the 7th IEEE International.* 2007: 257-262.
88. Prat-Gonzalez S, Sanz J, Garcia MJ. Cardiac CT: indications and limitations. *J Nucl Med Technol.* 2008; 36: 18-24.
89. Dey D, Lee CJ, Ohba M, Gutstein A, Slomka PJ, Cheng V, Suzuki Y, Suzuki S, Wolak A, Le Meunier L, Thomson LE, Cohen I, Friedman JD, Germano G, Berman DS. Image quality and artifacts in coronary CT angiography with dual-source CT: initial clinical experience. *J Cardiovasc Comput Tomogr.* 2008; 2: 105-114.
90. Zhang S, Levin DC, Halpern EJ, Fischman D, Savage M, et al. Accuracy of MDCT in assessing the degree of stenosis caused by calcified coronary artery plaques. *AJR Am J Roentgenol.* 2008; 191: 1676-1683.
91. Kong LY, Jin ZY, Zhang SY, Zhang ZH, Wang YN, Song L, Zhang XN, Zhang YQ. Assessment of coronary stents by 64-slice computed tomography: in-stent lumen visibility and patency. *Chin Med Sci J.* 2009; 24: 156-160.
92. Lettau M, Sauer A, Heiland S, Rohde S, Bendszus M, et al. Carotid Artery Stents: In Vitro Comparison of Different Stent Designs and Sizes Using CT Angiography and Contrast-Enhanced MR Angiography at 1.5T and 3T. *AJNR Am J Neuroradiol.* 2009.
93. Motoyama S, Sarai M, Harigaya H, Anno H, Inoue K, et al. Computed tomographic angiography characteristics of atherosclerotic plaques subsequently resulting in acute coronary syndrome. *J Am Coll Cardiol.* 2009; 54: 49-57.
94. Cyrus T, Gropler RJ, Woodard PK. Coronary CT angiography (CCTA) and advances in CT plaque imaging. *J Nucl Cardiol.* 2009; 16: 466-473.
95. Rybicki F, Melchionna S, Mitsouras D, Coskun A, Whitmore A, et al. Prediction of coronary artery plaque progression and potential rupture from 320-detector row prospectively ECG-gated single heart beat CT angiography: Lattice Boltzmann evaluation of endothelial shear stress. *Int J Cardiovasc Imaging.* 2009; 25: 289-299.
96. Ramkumar PG, Mitsouras D, Feldman CL, Stone PH, Rybicki FJ. New advances in cardiac computed tomography. *Curr Opin Cardiol.* 2009; 24: 596-603.
97. Kordish I, Philipp S, Boese D, Sack S, Erbel R. [Dissection of the right coronary artery as a complication after the IVUS procedure]. 2007; 32: 573-577.

98. Valgimigli M, Agostoni P, Serruys PW. Acute coronary syndromes: an emphasis shift from treatment to prevention; and the enduring challenge of vulnerable plaque detection in the cardiac catheterization laboratory. *J Cardiovasc Med (Hagerstown)*. 2007; 8: 221-229.
99. Tobis J, Azarbal B, Slavin L. Assessment of intermediate severity coronary lesions in the catheterization laboratory. *J Am Coll Cardiol*. 2007; 49: 839-848.
100. Patil UD, Ragavan A, Nadaraj, Murthy K, Shankar R, et al. Helical CT angiography in evaluation of live kidney donors. *Nephrol Dial Transplant*. 2001; 16: 1900-1904.
101. Saad WE, Saad N. Computer tomography for venous thromboembolic disease. *Radiol Clin North Am*. 2007; 45: 423-445.
102. Johns HE, Cunningham JR. The physics of radiology. Charles C. Thomas; Springfield, Ill, USA.: 1983.
103. Bushberg JT. The essential physics of medical imaging. 2nd ed. Lippincott Williams & Wilkins; Philadelphia. 2002.
104. Seeram E. Computed tomography : physical principles, clinical applications & quality control. Saunders; Philadelphia. 1994.
105. McNitt-Gray MF. AAPM/RSNA Physics Tutorial for Residents: Topics in CT. Radiation dose in CT. *Radiographics*. 2002; 22: 1541-1553.
106. Kalender WA, Deak P, Kellermeier M, Van Straten M, et al. Application- and patient size-dependent optimization of x-ray spectra for CT. *Med Phys*. 2009; 36: 993-1007.
107. Downes P, Jarvis R, Radu E, Kawrakow I, Spezi E. Monte Carlo simulation and patient dosimetry for a kilovoltage cone-beam CT unit. *Med Phys*. 2009; 36: 4156-4167.
108. Horiguchi J, Fujioka C, Kiguchi M, Yamamoto H, Kitagawa T, et al. Prospective ECG-triggered axial CT at 140-kV tube voltage improves coronary in-stent restenosis visibility at a lower radiation dose compared with conventional retrospective ECG-gated helical CT. *Eur Radiol*. 2009; 19: 2363-2372.
109. Huda W. Dose and image quality in CT. *Pediatr Radiol*. 2002; 32: 709-713.
110. Mahesh M. MDCT Physics: The Basics-Technology, Image Quality and Radiation Dose. 1st ed Lippincott Williams & Wilkins. 2009.
111. Shiraishi J, Tsuda K, Inoue Y, Onoyama Y. Measurement of CT section thickness by using the partial volume effect. *Radiology*. 1992; 184: 870-872.
112. Lu MT, Ersoy H, Whitmore AG, Lipton MJ, Rybicki FJ. Reformatted Four-Chamber and Short-Axis Views of the Heart Using Thin Section.
113. Mc Collough CH, Zink FE. Performance evaluation of a multi-slice CT system. *Med Phys*. 1999; 26: 2223-2230.
114. Sirineni GK, Kalra MK, Pottala K, Waldrop S, Syed M, et al. Effect of contrast concentration, tube potential and reconstruction kernels on MDCT evaluation of coronary stents: an in vitro study. *Int J Cardiovasc Imaging*. 2007; 23: 253-263.