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LEARNING OBJECTIVES

Upon completion of this activity,
participants should be able to:

1. Explain the effect of collimation and pitch on z-axis resolution on protocols for imaging the vascular system with CTA.
2. Design an appropriate workflow for multichannel CT data processing, display, and archiving.
3. Optimize scan parameters, timing, and contrast injection parameters for CTA.
4. Determine considerations for multichannel CTA protocol design.

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Optimizing Protocols for CT Angiography

By Lawrence N. Tanenbaum, M.D.

Since the advent of the slip-ring scanner, CT has been an important modality for imaging the vascular tree. Before multichannel detectors were available, however, CT angiographic (CTA) applications were limited in anatomical coverage. Four-channel systems provided the necessary boost in scanning speed to allow whole-body coverage in a single acquisition. The latest generation (16 to 64-slice) multichannel CT imagers enhance volumetric assessment of vascular anatomy and pathology with ultrathin, isotropic, microvoxel data acquisitions that allow seamless high-resolution evaluation in any plane. This enhanced volumetric scan capability has led to an expansion of the clinical role of CTA as well as a significant boost in image quality. This article will discuss the basic principles of multichannel CT and demonstrate the impact of the latest generation of microvoxel volumetric scan techniques. Optimal regimes for contrast administration will be delineated. Methods for data display and interrogation will be suggested, and the expanded clinical role of CTA will be explored.

MULTICHANNEL SPIRAL CT

Slip-ring CT systems allow continuous scanner gantry motion, which, coupled with synchronous table feed,

provide the basis for helical, or spiral, CT scanning. As opposed to "step and shoot" techniques in which the table moves in increments corresponding to the acquired slice thickness, which was the only option prior to slip-ring systems, with helical techniques one can "stretch the spiral" to cover a distance greater than the collimation during each 360° scanner revolution. This "stretch" is generally described in terms of "pitch," which is defined (for a single-channel system) as the distance the table moves per 360° gantry rotation divided by the scan collimation.

At any given collimation, as pitch increases, the anatomical coverage increases per unit of time. Practical limits on pitch, relating to the richness of the data supplied to the reconstruction algorithm, do exist. As pitch increases, the effective slice profile (thickness) increases. This is less of a limitation than it may seem, since the use of higher pitch values may allow a thinner collimation acquisition, thus providing a thinner slice

profile than a thicker slice with a less aggressive pitch. For example, a 1-mm acquisition at a pitch of 3 yields a scan at a higher z-axis resolution than a 3-mm acquisition at a pitch of 1. The most important practical limit on pitch selection is the incidence of



Figure 1. CTA of aortic occlusion

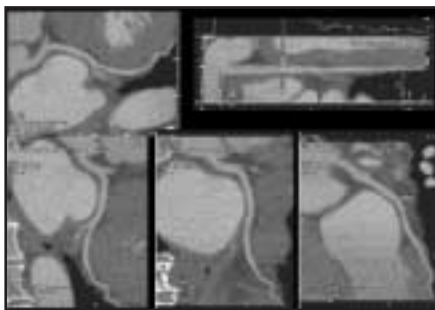


Figure 2. Multiple curved constructions demonstrate the left main coronary artery, proximal LAD, circumflex coronary artery, and obtuse marginal branch.

undersampling “helical” artifacts, as the data stream gets lean with extended pitch. It is generally accepted that a pitch of 2 (or two times the number of imaging channels on a multichannel system) is the practical limit, although on slower single-channel systems this limit could be exceeded in challenging clinical circumstances such as trauma.

The fundamental advantage of multichannel CT systems is the simultaneous acquisition of multiple spiral data streams that contribute to each slice created. This inherently information-rich scan technique permits a proportional increase in the “stretch” of each helical data stream and a proportional increase in table movement/anatomical coverage per unit of time while still protecting slice profile. The definition of pitch for multichannel CT systems (which reflects the relative effective slice profile) is distance the table travels per 360° gantry revolution divided by the dimension of the exposed detector (defined as collimation times the number of imaging channels). As an example, a 64-channel system collimated to 0.625 mm (at 0.5 second per gantry revolution) could cover 1400 mm in 10 seconds. While maintaining a pitch of 1.75, the scanner could cover anatomy almost 76 times faster than a single-channel system operating at a pitch of 1.5. The huge boost in speed facilitates a thinner collimation choice, which more than compensates for a slight increase in slice thickness.

ISOTROPIC DATA ACQUISITION

Multichannel capabilities have led to fundamental changes in the way CT data are acquired, processed, displayed, and interrogated. Typical scan techniques on a 16 to 64-channel imager employ slice thicknesses between 0.5 and 0.75 mm, depending on detector design and body part evaluated. These thin-slice volume acquisitions provide imaging voxels that are effectively isotropic (equal in size in all dimensions). The large, isotropic data sets can be

reformatted and viewed in orthogonal and oblique planes while maintaining image integrity. It is fair to state that the reformatted images that result are superior to and higher in inherent spatial resolution than what was once the gold standard (a typically thicker slice) in the direct acquisition plane. As a result, not only is interpretation of CT data no longer limited to the plane in which it was scanned, but interrogation has largely transitioned to a multiplanar/volumetric mode with interactive review on a workstation or PACS interface with reformat (MPR) and 3D/volume-rendering capability. This is particularly relevant in assessment of the vascular tree, where evaluation in the AP (coronal) and lateral (sagittal) planes is the convention.

The thinner slices used on today’s scanners bring additional imaging benefits. As the slice thickness used for acquisition decreases, the inherent contrast resolution of the volumetric data increases. This is readily evident in low contrast resolution exams such as the posterior fossa of the head and the lumbar spine. Perhaps more important in a discussion of CTA, as acquired slice thickness decreases, partial volume artifacts such as those due to metal instrumentation hardware, like aneurysm clips and vascular stents, diminish.

DATA MANAGEMENT/WORKFLOW

Microvoxel scan techniques force us to reconsider methods of data recording, networking, and archiving. Scan acquisitions produce raw data—zeros and ones—which, depending on system limits, exist as long as space exists on the system’s hard drives. The oldest case is typically erased as the most recent case is scanned. As long as they remain available, raw data can be reconstructed into slices at novel resolution (thickness and field of view), table location, and algorithm. After the raw data have been erased, the slices that have been created can be reformatted in multiple planes and combined to create a thicker slice, but splitting to thinner slices, changing FOV, or altering the reconstruction algorithm are no longer possible. While raw data can be stored for later manipulation, this is rarely done in routine practice.

Prior to the widespread proliferation of multichannel CT, the informal standard of care had been to store all reconstructed slices in the patient’s record in the long-term archive. This posed little challenge for routine imaging purposes as the number of slices used for interrogation has increased only 20% to 50% with recent generations of scanners (e.g., 80 to 100 slices for a typical body study). Where this strains practicality is in applications where multiplanar interrogation is critical, as today’s microvoxel data sets may

contain up to 2500 slices. These ultrathin slices, perhaps best termed “reconstructed source data” may never be viewed directly, but might supply the fuel for a 3D/volume rendering (VR) or MPR interrogation at a thicker slice and wider interval.

A limited number of axial, coronal, and sagittal reformatted and 3D/VR images are typically recorded and made available in the patient record. Ideally, much of this should be accomplished on the scanner itself and generated automatically as part of the scan protocol. Shifting to a new standard where only diagnostic images are stored long-term would reduce PACS network congestion and archiving costs. If workstation review is integral to interpretation, the data sets typically must still traverse the network but can do so on a dedicated subnet. Remote multiuser interaction with data that remain on the scanner (or workstation) is becoming more practical as client-server workstation architectures are more prevalent.

- *Scan protocols for multichannel CTA.* Since the primary plane of diagnostic interrogation



Figure 3. Volume rendering of carotid atherosclerotic disease.

is typically along the long axis of patient anatomy (coronal or sagittal) as opposed to the cross-section (axial), when designing protocols for CTA the highest z-axis (longitudinal) acquisition resolution (0.5 to 0.75 mm) is best. Maximizing in-plane spatial resolution by using the smallest appropriate reconstruction FOV has a positive effect on image quality as well. Moderate to high pitch values are generally chosen to facilitate z-axis anatomical coverage at the expense of some broadening of slice profile. The fourfold boost in data density of 64-channel systems (over 16) can be leveraged to produce an increase in anatomical coverage at less severe pitch, generating thinner slice profiles.

Recent advances in tube capacity and generator power have had a positive impact on x-ray technique flexibility. The lower kV techniques increasingly utilized produce images with superior contrast resolution. Tube current modulation

schemes improve image noise consistency and allow radiation dose reduction.

• *Optimizing contrast agent administration for multichannel CTA.* For CTA applications, the primary goal of contrast administration is to obtain the highest degree of vascular opacification by maximizing iodine flux. One method employed to optimize iodine delivery is high injection rates. Rates of 3 to 5 mL/sec are routinely employed for CT angiography. In a busy outpatient setting, injection rates are limited by a number of practical concerns. These include extravasation risk, as well as the time it takes to obtain suitable intravenous access and the impact this has on throughput. Another method of increasing iodine flux is to employ the highest concentration contrast agent available (370 to 400 mg/mL).

Patient tolerance of contrast injection is also a key factor when using high injection rates. Local effects of contrast, such as a feeling of warmth or a burning sensation—as well as the potential for systemic effects such as nausea and vomiting—must be considered, since an interrupted exam is a lost exam. Nonionic media are essential for applications that require high injection rates, a choice that has been made progressively easier by the reduced cost differential between ionic and nonionic contrast agents.

A saline flush, possible with the later generation power injectors, offers two important benefits. One is that contrast is forced from tubing and extremity veins into the central circulation, where it contributes to image formation, potentially allowing a reduction in total dose administered to the patient. In addition, for some applications (carotid, pulmonary), venous contrast is more effectively cleared from the scanning region, which assists in avoiding partial-volume (beam-hardening) artifact.

Since CTA represents the capture of the first intravascular pass of an injected contrast agent, timing of scan initiation is critical for quality and consistency. Fortunately, because of the superb contrast resolution of CT, as long as scanning does not occur too early (before it arrives), there is a broad window of opportunity in which to adequately image the contrast bolus. This has led some to advocate standard, empiric (scan) delays before scan triggering. This approach is not ideal because a finite number of patients, due to physiologic variation, will fall out of the ideal acquisition window and studies will be sub-optimal or nondiagnostic. Higher overall doses of contrast agent are generally advocated to make the acquisition window more forgiving.

Another, entirely reliable, approach is to administer a timing minibolus while imaging the

target vessel. While this is an acceptable technique, it involves administering a dose of iodinated contrast that doesn't contribute directly to the final diagnostic study. The time and fuss of the additional acquisition and subsequent analysis can be deleterious to throughput as well. In our institutions, for most CTA applications we employ enhancement-triggered scan techniques. This involves repetitive, static-table, low-radiation-dose scanning until the bolus reaches the area intended for the diagnostic study. The location chosen for surveillance is typically flow proximal to the area of

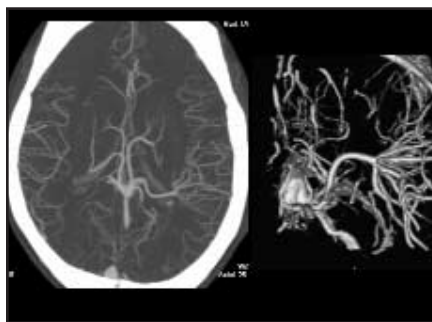


Figure 4. CTA of left frontoparietal developmental venous anomaly.

diagnostic interest. When the contrast reaches a qualitative threshold at the target (is visibly present), the scan is manually initiated, effectively employing the entire contrast dose for the diagnostic CTA.

SCANNING AORTIC DISEASE

CTA has achieved gold-standard status for the evaluation of aortoiliac disease. Typical indications include atherosclerotic occlusive disease of the aorta and the branch vasculature. CTA is routinely employed in cases of suspected renovascular hypertension and mesenteric ischemia. Because of its precise, multidimensional measurement capability CTA has become the study of choice for the evaluation of aneurysmal disease of the aorta and its branches. The modality is best for assessing the key parameters of candidate selection for endovascular graft placement and thus is now an essential element in procedure planning. CTA is also the current study of choice in the ongoing surveillance of stented patients for complications such as endoleak and stent migration. CTA is also well suited for the evaluation of dissection and rupture of the thoracoabdominal aorta, as it offers rapid access to critical information in often urgent circumstances.^{1,2}

RUNOFF VASCULATURE

CTA is rapidly approaching gold-standard status for the evaluation of vascular disease of the extremities, particularly occlusive disease of the

runoff vessels. The superior contrast resolution of CTA and broader diagnostic acquisition window can provide visualization superior to conventional angiography for small distal vessels, particularly in the infrapopliteal region.³ Advanced postprocessing techniques are critical to visualization and demonstration of distal anatomy, as overlying and adjacent bone can obscure anatomy. Fortunately, modern workstations have the ability to segment and remove bone from the 3D vascular model in an automated (or semiautomated) and efficient fashion, allowing diagnostic visualization as far caudal as the feet. Meticulous operator vigilance is required to assure that small-vessel information is not erroneously removed during the segmentation process.

Heavy calcification can be problematic in small vessels and may interfere with adequate interrogation, particularly below the knee. Selected populations prone to distal vessel calcification (e.g., people with diabetes) may be better studied with techniques such as MR angiography.

Studies of the thoracoabdominal aorta generally extend from the aortic level of interest (upper abdominal or arch apex) through the femoral artery bifurcations. Studies of the aorta that continue through the runoff vessels extend inferiorly to the feet. On 16-channel systems, the thinnest collimation is employed at the highest pitch (1.75). Reconstructed source partitions are typically minimum thickness with slight overlap (0.625/0.6 mm), although thicker partitions can be used (e.g., 1.25 mm) to accommodate less capable 3D workstations. Scanning is well accomplished on all generations of multichannel scanners with only 100 cc of an ionic high-osmolar contrast agent (such as 370 or similar) triggered to contrast arrival at the left ventricle of the heart. The speed of the latest generation 64-channel systems may allow some reduction in the total dose administered and improved slice profiles through the selection of more modest pitch values.

PULMONARY STUDIES

CTA is becoming increasingly important in the evaluation of patients with suspected pulmonary embolic disease, serving both as a problem-solving tool in cases with equivocal or noncontributory nuclear medicine studies and as a first-line test in some institutions. CTA has a high negative predictive value, is less likely to be equivocal in patients with underlying parenchymal lung disease, and is likely sufficiently sensitive to distal emboli to determine a need for thrombolytic therapy.^{4,5}

Studies of the pulmonary arteries are obtained by scanning from the lung's base through its apex.

On 16-channel systems, the parameters are the same as for aortic disease studies, as described above. Since enhancement triggering is problematic for the extremely short-lived phase of the first pulmonary artery pass, scan timing is set via a test bolus at the level of the pulmonary artery outflow tract. Improvements in the speed of enhancement triggering may make this technique more applicable in the future. The speed of the latest generation 64-channel systems may allow the total dose administered to be reduced and slice profiles to be improved through the selection of more modest pitch values.

CARDIAC SCANS

Coronary artery CTA has rapidly achieved a clinical role in the evaluation of patients with suspected atherosclerotic disease of the heart. The extraordinarily high negative predictive value of CTA has led to reimbursement in the triage of those with equivocal or discordant stress test results. CTA has also been used in the minimally invasive evaluation of patients for bypass and stent patency and those with aberrant coronaries and suspected myocardial bridges. The superior contrast resolution of CT allows direct identification of clinically compelling coronary artery soft plaque that is occult to calcium scoring studies and unimpressive with conventional coronary angiographic techniques, providing valuable information on high-risk patients.^{6,7}

Studies of the coronary arteries are obtained by scanning from the aortic root through the cardiac apex. On systems that are 16 channel and higher, the thinnest collimation is employed. Pitch is determined by heart rate. B-blockade is routinely administered to keep heart rate slow and steady for retrospective gating and to extend the window of scanning during diastole.⁸ Reconstructed source partitions are

typically minimum thickness without overlap (0.625) Scanning is well accomplished on 16-plus-channel scanners with only 80 cc of a 370 (or similarly high-concentration) agent. Since enhancement triggering is somewhat problematic, scan timing is set via a test bolus at the level of the aortic root. Improvements in the speed of enhancement triggering may make this technique more applicable in the future. Sixty-four-channel CT systems can scan the heart four times faster than the previous-generation 16-channel machines. This reduces scan time to as little as five seconds, improving scan consistency through a reduced exposure to beat-to-beat variability. The improved coverage should also allow routine assessment of internal mammary bypass grafts from origin through target, challenging on earlier systems because of the longer breath-holds required. The speed of the latest generation 64-channel systems may allow some reduction in the total dose administered.

NEUROVASCULAR STUDIES

In many practices, CTA has a secondary and problem-solving role in the evaluation of patients with suspected neurovascular disease, as MRI and MRA dominate the workup. Carotid CTA is important in the patients with MR incompatibilities as well as those with discordant vascular imaging (CTA, ultrasound). CTA is increasingly used in the routine study of intracranial aneurysmal disease, offering 3D information useful in preoperative assessment, as well as in screening high-risk and symptomatic patients. CTA is increasingly a first-line test in the evaluation of patients with acute stroke, assisting in determination of the nature and location of vascular occlusion.⁹ Perfusion imaging is often used in association with CTA to assess the functional significance of structural disease seen

with CTA and in decision-making about thrombolytic therapy in acute stroke (CVA).¹⁰

Studies of the neurovascular tree generally extend from the aortic arch through the intracranial circulation. On systems 16 channels and higher, the thinnest collimation is routinely employed. The carotid portion of the examination is typically acquired at high pitch (1.75) to avoid venous contribution to the image. The resolution of the intracranial portion is augmented by the selection of lower pitch (5) to reduce slice profile broadening. Venous contribution is less problematic on brain studies. Reconstructed source partitions are typically minimum thickness with slight overlap (0.625/0.6 mm), although thicker partitions (e.g., 1.25 mm) can be used for the carotids if the 3D workstation is less capable. On all generations of multichannel scanners, scanning is well accomplished with only 75 cc of a 370 (or similarly high-concentration) agent triggered to contrast arrival at the left ventricle of the heart. Dual-capability power injectors assist in the depiction of the aortic arch by washing high-density contrast out of the central venous structures with a saline flush. As multichannel scanners get faster, total dose may be reduced and slice profiles may improve if more modest pitch values are chosen.

SUMMARY

Continuing developments in multichannel CT technology have had an enormous impact on the style and quality of CTA in clinical practice and are leading to an increasingly important role in the evaluation of disorders of the vascular tree. Improvements in speed and resolution affect contrast usage, thus encouraging optimization of agent concentration and dose. ■

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