

Three-Dimensional C-arm Cone-beam CT: Applications in the Interventional Suite



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C-arm cone-beam computed tomography (CT) with a flat-panel detector represents the next generation of imaging technology available in the interventional radiology suite and is predicted to be the platform for many of the three-dimensional (3D) roadmapping and navigational tools that will emerge in parallel with its integration. The combination of current and unappreciated capabilities may be the foundation on which improvements in both safety and effectiveness of complex vascular and nonvascular interventional procedures become possible. These improvements include multiplanar soft tissue imaging, enhanced pretreatment target lesion roadmapping and guidance, and the ability for immediate multiplanar posttreatment assessment. These key features alone may translate to a reduction in the use of iodinated contrast media, a decrease in the radiation dose to the patient and operator, and an increase in the therapeutic index (increase in the safety-vs-benefit ratio). In routine practice, imaging information obtained with C-arm cone-beam CT provides a subjective level of confidence factor to the operator that has not yet been thoroughly quantified.

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C-ARM cone-beam computed tomography (CT) is an advanced imaging capability that uses state-of-the-art C-arm flat-panel fluoroscopy systems to acquire and display three-dimensional (3D) images. C-arm cone-beam CT provides high- and low-contrast soft tissue ("CT-like") images in multiple viewing planes, which constitutes a substantial improvement over conventional single-planar digital subtraction angiography

(DSA) and fluoroscopy. Although C-arm cone-beam CT has been in development for the past 2 decades, it has only been applied in the interventional radiology clinic in recent years. The clinical emergence of C-arm cone-beam CT has lagged only a little behind that of flat-panel detector fluoroscopy systems, which, as early research has demonstrated, offer higher spatial resolution than conventional image intensifier detector systems (1).

In general, the assessment of whether C-arm cone-beam CT adds value to existing technologies in the interventional radiology suite requires that several questions be answered. Among them, will C-arm cone-beam CT enable the treating physician to plan more effective interventions, and will this result in a reduction in treatment-related complications? On the basis of early experience, it is clear that operators performing complicated interventions requiring information about both vascular and soft tissue anatomy have more confidence in the imaging information provided with C-arm cone-beam CT when it is used as an adjunct to DSA or fluoroscopy. The extent to which operator

confidence is improved, however, is difficult to quantify.

Three C-arm cone-beam CT systems are commercially available in the United States: DynaCT (Siemens Medical Solutions, Forchheim, Germany), XperCT (Phillips Medical Systems, Eindhoven, the Netherlands), and Innova CT (GE Healthcare, Waukesha, Wisconsin). Each of these systems has its own imaging protocol, necessitated by each system's different rotation time, number of projections acquired, image quality, and time required for reconstruction. The two factors that will most affect the successful integration of C-arm cone-beam CT into the interventional radiology practice are time (for set up, image acquisition, and image reconstruction) and image quality.

The use of retrospective case material for this review did not require institutional review board approval at any of the contributing institutions.

EARLY REPORTED CLINICAL EXPERIENCE

Reports of the use of C-arm cone-beam CT are beginning to emerge in the medical literature, with early case re-

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ports of its advantages coming from its use for neurologic interventions. For example, Heran and coworkers (2) used C-arm cone-beam CT to detect intracranial hemorrhages during three neurologic interventions, and Benndorf and coworkers (3,4) used C-arm cone-beam CT to improve the visualization of intracranial and extracranial stents in four patients. In the study by Benndorf et al (4) in which three patients underwent intracranial ($n = 2$) and extracranial ($n = 1$) stent placement, the authors demonstrated that C-arm cone-beam CT depicted both the stent struts and their relationship to the arterial walls and aneurysm lumen. The visualization of these structures with C-arm cone-beam CT was superior to that achieved with conventional DSA and digital radiography.

Reports of the early clinical use of C-arm cone-beam CT for other interventions emerged shortly thereafter. Binkert and coworkers (5) used C-arm cone-beam CT to manage type 2 endoleaks in abdominal aortic aneurysm stent grafts by using a translumbar approach. Hodek-Wuerz and coworkers (6) used C-arm cone-beam CT to assess the distribution of cement after vertebroplasty.

Georgiades and coworkers (7) reported their experience using adjunctive C-arm cone-beam CT during adrenal venous sampling to reduce technical failure in nine consecutive cases. Catheters initially placed for sampling were malpositioned in two cases (22%) on the basis of C-arm cone-beam CT findings and successfully repositioned into the proper location. This resulted in concordance between cortisol results and C-arm cone-beam CT findings.

Hirota and coworkers (8) reported their experience with C-arm cone-beam CT during visceral interventions in 10 cases, including five chemoembolizations, three hepatic port implantations, and two partial splenic embolizations. They concluded that C-arm cone-beam CT provided information that was useful, especially in the chemoembolizations, for confirming the perfusion area of the target region's supplying artery during superselective catheterization; for the partial splenic embolizations, it was helpful in assessing the volume of embolization. Meyer and coworkers (9) recently described five patients who under-

went transarterial chemoembolizations, in whom C-arm cone-beam CT provided such detailed information about patients' vascular anatomy and therapeutic endpoints both during and immediately after the intervention that it ultimately influenced the course of treatment.

Wallace and coworkers (10) have also presented their experience with C-arm cone-beam CT for hepatic arterial interventions, which included infusions, radioembolizations, embolizations, and chemoembolizations. During the study period, C-arm cone-beam CT was used in 86 of 240 interventions (36%) in 135 patients. The mean number of acquisitions per study was 1.9 (range, 1–4). In 35 of the 86 interventions (41%), C-arm cone-beam CT gave additional information without affecting procedure management; it had an effect on patient treatment in 16 cases (19%). Chemoembolization benefited the most from the additional information provided with C-arm cone-beam CT. The authors concluded that C-arm cone-beam CT provided imaging information beyond that provided with DSA during approximately 60% of hepatic arterial interventions and that the additional information had an effect on the technical management in 19% of the procedures.

On the basis of imaging studies using experimental C-arm cone-beam CT units in the abdomen, the contrast resolution of low-contrast structures on C-arm cone-beam CT scans has been reported to be 5–10 Hounsfield units (11,12). Approximately 50 Hounsfield units is a more practical expectation, best demonstrated when an interface exists between the fatty and soft tissue structures or when fluid allows various abdominal organs and structures to be differentiated from each other. When required, iodinated contrast medium can be used to improve the ability of C-arm cone-beam CT to image low-contrast soft tissue structures confined within an organ or surrounded by other tissue of similar densities.

VASCULAR APPLICATIONS

General Considerations

Potential vascular applications of C-arm cone-beam CT include its use for preprocedure anatomic diagnosis and treatment planning, intraproce-

dures device or implant positioning assessment, and postprocedure assessment of procedure endpoints. Most of these applications require the use of iodinated contrast medium to opacify the vascular system and make its corresponding soft tissue structures opaque. However, the acquisition of implant devices (eg, stents, stent-grafts, and stent filters) to evaluate vessel wall apposition and the completeness of device opening after deployment does not necessarily require additional contrast medium. It is important to start contrast medium injection before rotational acquisition to properly fill the vascular structure and, if needed, allow for soft tissue enhancement of the organ and/or region of interest.

The administration of iodinated contrast media requires imaging delays that vary depending on the type of vascular intervention, the proximity of the catheter to the target location, and the degree of image detail required. For example, the acquisition of basic vascular information about an area close to the catheter may require a delay of approximately 2 seconds; examples of this include selective injections into the arteries of the liver, kidney, and spleen. The delay can vary between 2 and 3 seconds in large vessels with high flow rates (aorto-vena cava) or during selective injection of smaller vessels with no need to analyze parenchymal enhancement (Tables 1, 2). This delay can be increased 5–6 seconds during selective injections if visualization of both vascular and soft tissue (parenchyma or lesion) structures is required.

Because C-arm cone-beam CT provides 3D vascular and soft tissue detail, it is instrumental to improve the visualization of the vascular distribution of the selected arterial territories and their corresponding areas of tissue perfusion within an organ or region of interest. Because C-arm cone-beam CT provides this enhanced 3D imaging capability, it provides more subtle vascular and soft tissue information compared with conventional DSA. The additional imaging information enables the operator to adequately identify sites for embolization and potentially avoid complications relating to non-target therapy. These imaging advantages are particularly useful during embolizations of the spine, pelvis,

Table 1
C-arm CT Acquisition Protocols for Hepatic Arterial Interventions at the University of Texas M. D. Anderson Cancer Center

Area of Interest	Catheter Tip Location	Rate of Injection (mL/sec)	Contrast Medium Dilution (%)	Imaging Delay (sec)
Vascular information	CHA, PHA	2	30	2–3
Enhanced parenchymal information	CHA, PHA	2	50	4–6
	Selective RHA, LHA	0.5–1 (to avoid reflux)	50	2–3

Note.—CHA = common hepatic artery, PHA = proper hepatic artery, RHA = right hepatic artery, LHA = left hepatic artery.

Table 2
C-arm CT Acquisition Protocols for Peripheral Arterial Interventions at Centre Hospitalier De L'Université De Montreal

Area of Interest	Contrast Medium Dilution (%)	Imaging Delay (sec)	Flow Rate (mL/sec)	Total Volume (mL)	Contrast Equivalent*
Infrarenal abdominal aorta	30	2–3	8	80–88	24–26
Infraabdominal aorta during endovascular aneurysm repair	30	5–6	8	104–112	31–34
Iliac arteries	30	3	6	66	20
Femoropopliteal arteries	20	3	3	33	7

Note.—Protocols are for an 8-second rotational acquisition time.

* Since the contrast is diluted, the contrast equivalent is the amount of undiluted contrast used.

solid organs (liver, kidney, spleen), and vascular anomalies in addition to interventions in other peripheral vascular territories.

One of the most important advantages to using the detailed anatomic images from C-arm cone-beam CT over the conventional, frontal projection images from DSA is that they enable the user to “page through” C-arm cone-beam CT image sections and reformat them for viewing in various slab thicknesses and projections; this allows vascular structures to be viewed in relation to complex overlapping anatomy. If these improvements are proved to reduce the number of selective catheterizations and the number of DSA acquisitions from various obliquities required to delineate crucial anatomic structures, both patient and operator exposure to contrast medium and radiation—even during complex interventions—could be minimized.

In addition, C-arm cone-beam CT is helpful for planning the treatment of target lesions that are difficult to visualize at DSA but that can be visualized with either conventional CT or magnetic resonance (MR) imaging. Although the resolution of low-contrast structures at C-arm cone-beam CT is not as good as that of conventional multidetector CT, C-arm cone-beam

CT images acquired with use of iodinated contrast media can capture more soft tissue detail than can conventional DSA (Fig 1)—enough to enable the identification of parenchymal lesions or structures of interest. Operators can then confidently identify and correlate the findings from C-arm cone-beam CT images with those from conventional CT or MR imaging in the appropriate plane of viewing.

The ability to page through different planes of C-arm cone-beam CT scans depicting arterial structures can also be useful in the characterization of arterial stenoses, occlusions, and aneurysms. During early clinical experience, C-arm cone-beam CT appears better than DSA for the pre- and post-therapeutic evaluation of stenoses in large and medium-sized arteries, especially when en face arterial lesions limit the extent to which the residual arterial lumen can be adequately imaged. The high level of detail on C-arm cone-beam CT scans also allows the dimensions and shape of patients' lesions to be more precisely measured before stent implantation; after implantation, it allows the adequacy of coverage and lumen restoration to be assessed.

C-arm cone-beam CT can also provide information used in aneurysm interventions, which is especially crucial

when a clear understanding of the aneurysm, the neck, and the adjacent branching structures that may be at risk for occlusion with the insertion of a covered prosthesis is required or if those structures require embolization before device deployment. C-arm cone-beam CT appears to be better than DSA in the evaluation of the adequacy of wall apposition in the case of both stents and stent-grafts. After stent-graft deployment, C-arm cone-beam CT can also be used to confirm aneurysm sac exclusion and immediately identify some types of endoleaks. As with arterial interventions for occlusive disease, C-arm cone-beam CT may be helpful for similar venous recanalization types of interventions.

Hepatic Arterial Interventions

Early clinical experience has demonstrated C-arm cone-beam CT to be a useful adjunct to DSA in hepatic vascular interventions, including arterial infusions, embolizations, chemoembolizations, and radioembolizations. One specific advantage to using C-arm cone-beam CT with conventional DSA is that C-arm cone-beam CT gives users the information they need to create an anatomic survey for treatment planning that delineates a patient's vascular anatomy and accounts for

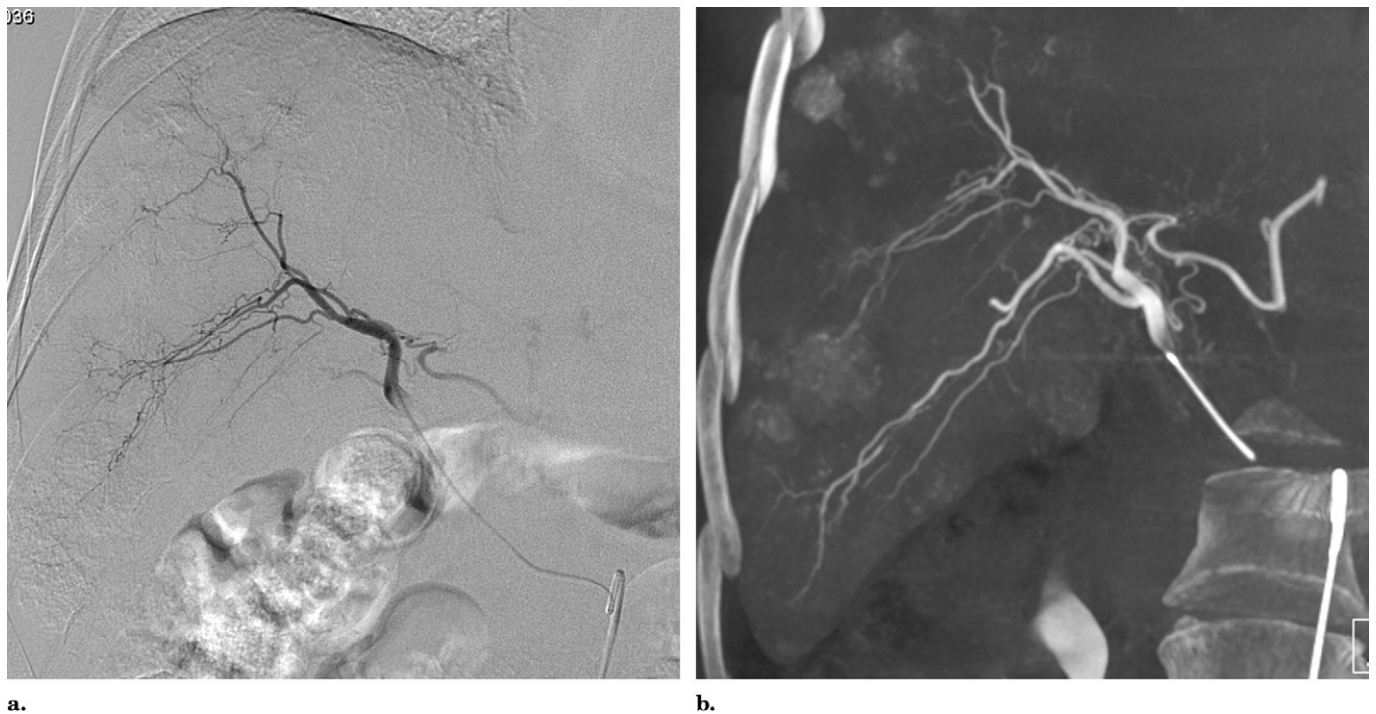


Figure 1. (a) Image from DSA in the anterior-posterior projection and (b) coronal reformatted C-arm CT scan in a patient undergoing hepatic artery chemoembolization. Note the additional soft tissue detail provided with C-arm CT compared with DSA. Specific arteries supplying individual tumors can be discretely identified more readily with the C-arm CT image compared with the DSA image.

vascular structures, the associated parenchyma, and the target lesion. This ability enables more selective catheterizations to be performed, which may improve the safety and efficacy of interventions by depositing therapeutic agents more selectively; that is, the amount of therapeutic agent delivered to the target area is increased and the amount of non-tumor-bearing liver exposed to the agent decreased.

In addition to delineating crucial anatomic structures, an anatomic survey also allows for the confident identification of nontarget extrahepatic arteries and variant anatomic structures supplying the small bowel (supraduodenal and retroduodenal arteries), stomach (right gastric artery, **Fig 2**), diaphragm (anomalous phrenic artery), and skin (falciform artery) during hepatic arterial chemotherapy infusion, radioembolization, or chemoembolization (13). C-arm cone-beam CT may depict vessels not identified at DSA or, more likely, help clarify extrahepatic or variant anatomic vascular structures that are indeterminate at DSA evaluation without or despite selective catheterization and DSA imaging in multiple obliquities.

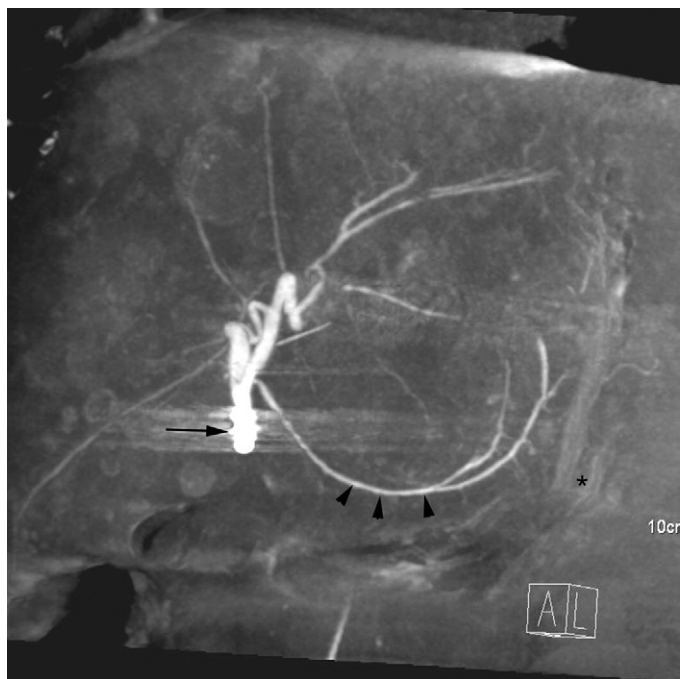


Figure 2. Oblique-coronal maximum intensity projection-reformatted contrast-enhanced C-arm CT scan obtained with 15-mm-thick slabs in a patient being evaluated for hepatic arterial radioembolization. A microcatheter tip is positioned in the proper hepatic artery. The course of the right gastric artery (arrowheads) arises from the base of the left gastric artery and extends to the stomach (* demarks the mucosal pattern of the stomach). Note the presence of metallic artifact from coils (arrow) placed in the gastroduodenal artery after coil embolization.



b.

Figure 3. Images from conventional CT and C-arm CT in a patient undergoing hepatic artery chemoembolization. **(a)** Conventional CT scan (axial projection) demonstrates a large hyper-vascular mass in the posterior aspect of the right lobe of the liver. **(b)** Composite contrast-enhanced C-arm CT scans of the left hepatic artery obtained in the sagittal (x), coronal (y), and axial (z) projections before therapy demonstrate substantial arterial supply of the tumor from a branch of the left hepatic artery. The volume of the lesion that is supplied by the branch of the left hepatic artery was assessed with 15-mm-thick maximum intensity projection reformations. The black arrows denote the enhancing portion of the tumor supplied by the left hepatic artery. The branch vessel from the left hepatic artery was subsequently catheterized and a portion of the iodized oil-based chemoembolic regimen administered. The remaining portion of the regimen was administered into the supplying arteries from the right hepatic artery. **(c)** Composite C-arm CT scans obtained after therapy demonstrate adequate distribution of the chemoembolic agents throughout the tumor, with only a small portion of the "normal" hepatic parenchyma included in the treatment area.

In addition to providing a better vascular roadmap for selective catheterizations, C-arm cone-beam CT can also allow the operator to determine, before therapy, whether the entire target lesion is included within the treatment area. If only a portion of the lesion is supplied by the branch vessel in question, that portion of the tumor can be estimated (**Fig 3**) and the chemoembolic regimen can be proportioned accordingly. Because C-arm cone-beam CT provides soft tissue information, the operator can still selec-

tively treat lesions that are difficult to visualize at DSA but that can be visualized with other conventional imaging modalities (CT or MR imaging) and would potentially not have been feasible to treat with DSA alone (**Fig 4**).

Information acquired with C-arm cone-beam CT can also allow the accurate correlation of vascular anatomy or distribution with the corresponding volume of parenchyma. This is especially useful in patients with extensive bilobar hepatic metastases and those with hormonally active tumors that

are to be treated palliatively by using embolization. Volume assessments based on C-arm cone-beam CT information are likely to be more accurate than those based on conventional DSA information; operators also value the ability of C-arm cone-beam CT to allow the viewing of soft tissue and thin-slab-reformatted images.

The current technique used at the University of Texas M. D. Anderson Cancer Center (source: M.J.W.) varies depending on the imaging information desired. Variable factors include

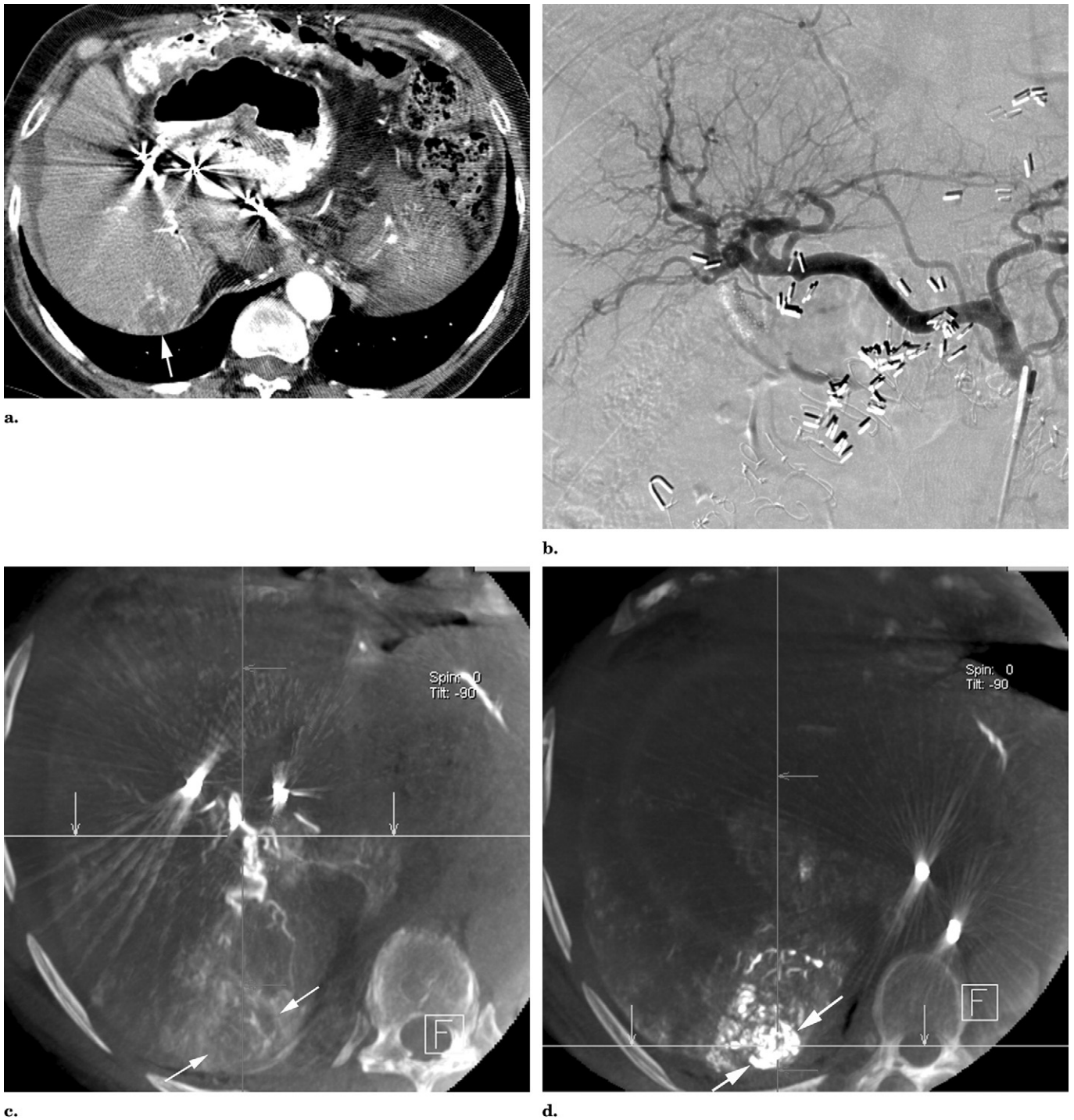


Figure 4. Images from conventional CT (a), DSA (b), and C-arm CT (c) in a patient undergoing hepatic artery chemoembolization. (a) Axial multisection contrast-enhanced conventional CT scan demonstrates a mass in the posterior aspect of the right lobe of the liver (arrow). There is only a mild degree of peripheral tumor enhancement. (b) Image from DSA obtained before chemoembolization shows that the lesion could not be visualized because it was not adequately hypervascular. C-arm CT was used to identify the lesion and the supplying branch hepatic artery to enable superselective catheterization. (c) C-arm CT scan obtained before chemoembolization with a microcatheter superselective in a branch of the right posterior hepatic artery demonstrates the angiographically occult lesion (white arrows) within the arterial territory of the catheterized vessel with enhancing parenchyma surrounding the relative less enhancing tumor. (d) Unenhanced C-arm CT scan obtained after chemoembolization demonstrates adequate ethiodized oil accumulation within the target lesion (white arrows).

imaging delay after contrast medium initiation (seconds), rate of injection (milliliter/second), and dilution of contrast medium (percentage by volume). The imaging delay varies by target area and catheter tip location (**Table 1**). For basic arterial imaging of the hepatic arterial system, a delay of approximately 2–3 seconds is usually sufficient assuming the contrast medium has been injected into the proper or common hepatic artery. The usual rate of injection is 2 mL/sec, and the injection is typically administered via a microcatheter. A longer imaging delay of up to 6 seconds is used when hepatic parenchymal or lesion enhancement is also needed. For subselective arterial examinations, a lower rate of injection (0.5–1 mL/sec) is used to avoid reflux into an adjacent branch artery paired with a shorter imaging delay (2–3 seconds). Diluted iodinated contrast medium (30%–50% by volume) is used for contrast medium-enhanced C-arm cone-beam CT. Higher percentages are used for hepatic arterial applications when parenchymal or tumor enhancement is desired; lower percentages are usually adequate for visualization of arterial anatomy.

Although the soft tissue contrast resolution of contrast-enhanced C-arm cone-beam CT is not equivalent to that of conventional multidetector CT, C-arm cone-beam CT is helpful in its ability to identify parenchymal lesions that DSA cannot adequately depict. With use of C-arm cone-beam CT, operators can confidently identify structures and correlate findings to those on conventional CT (**Fig 4**) or MR images in the appropriate viewing plane. C-arm cone-beam CT also provides better information than DSA and, occasionally, conventional CT about the number and distribution of tumors. When C-arm cone-beam CT does provide more information than conventional CT, it may be because of the hyperacute nature of the arterial contrast medium bolus and its ability to depict even very small lesions. When C-arm cone-beam CT is used in chemoembolization procedures that employ ethiodized oil as part of the therapeutic regimen, it can also help assess whether a therapeutic endpoint has been achieved after the intervention. This is because ethiodized oil acts as both a carrier of the chemotherapeutic

agent and a contrast agent, accumulating preferentially within hypervascular tumors (**Fig 3c**). This preferential accumulation can be imaged with C-arm cone-beam CT and does not require additional iodinated contrast media enhancement. The completeness of therapy can then be assessed by evaluating the distribution of ethiodized oil within the target lesion. If the oil has not accumulated in a portion of the lesion, the operator can search for hepatic or extrahepatic collateral tumor supply.

Portal Vein Embolization

For portal vein embolizations, having a good understanding of the portal venous anatomy is crucial—especially when partial or segmental embolization is required (eg, when performing an extended right hepatic embolization that includes the embolization of segment IV of the liver). C-arm cone-beam CT accurately depicts segment IV branches (**Fig 5**) in various planes and can potentially help the operator avoid nontarget embolization to branches supplying segments II and III. For extended left hepatectomy, C-

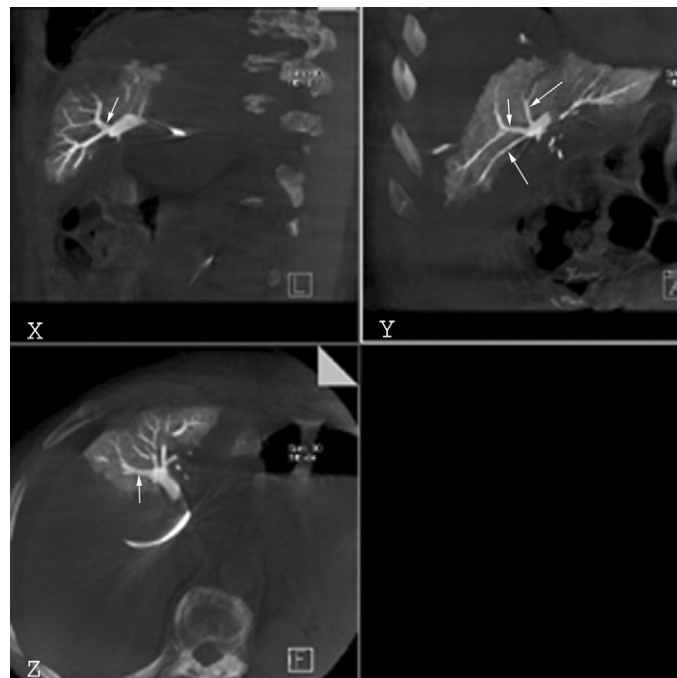


Figure 5. Reformatted contrast-enhanced C-arm CT scans in sagittal (x), coronal (y), and axial (z) projections obtained during portal vein embolization with a catheter positioned in the left portal vein. The segment IV portal venous branches are clearly delineated (arrows) in all three projections and used as a planning tool for subsequent embolization.

arm cone-beam CT is useful for visualizing the right-side hepatic segments clearly enough to determine which are to be preserved and which are to be embolized. C-arm cone-beam CT is also useful for assessing portal venous supply to various liver segments when portal venous variants (which are not uncommon) are present; this reduces the possibility that nontarget segments will be embolized during portal vein embolization.

The current technique used at M. D. Anderson Cancer Center (source: M.J.W.) for visualizing portal venous anatomy during portal vein embolization is to use 30% dilute iodinated contrast medium injected at a rate of 3 mL/sec with an imaging delay of 4 seconds for a main portal vein injection. For left portal vein injections, an imaging delay of 2 seconds is usually sufficient to accomplish adequate portal opacification.

Transjugular Intrahepatic Portosystemic Shunts (TIPS)

One of the most challenging aspects of TIPS placement is completing the puncture from the hepatic to the portal



Figure 6. 3D reconstruction of the portal vein during wedged portography with carbon dioxide. Note that the 3D image is overlaid on the fluoroscopic image to understand the relationship between the desired portal branch and the needle access system.

vein. This step, during which needle passes are made, contrast medium is injected, and radiation from fluoroscopy and/or DSA accumulates, is often the rate-limiting portion of the procedure. Biliary, capsular, and arterial punctures may occur during this phase of the procedure and lead to complications. For example, if contrast medium is injected into the parenchyma during needle pull-back, it can obscure visualization, and both patients and staff in the procedure room can be exposed to large amounts of radiation if access proves difficult. Classically, guidance for the puncture is obtained by using wedged venography with CO₂ or contrast medium. Two or three DSA runs are performed in different obliquities to delineate the portal vein and its branches with respect to the accessed hepatic vein. The puncture is then carried out blindly under live fluoroscopy on the basis of these runs. As mentioned earlier, C-arm cone-beam CT has the potential to provide information to build a 3D roadmap for a portal vein puncture. To accomplish this, a compliant balloon occlusion catheter is positioned in the accessed hepatic vein and a wedge CO₂ injection performed to opacify the portal vein. If the portal vein is not filled, C-arm cone-beam CT is not attempted. The current technique used at Mallinckrodt Institute of Radiology

(source: C.C.) includes the use of two 60-mL syringes containing CO₂ connected with a three-way stopcock to the balloon occlusion catheter by means of high-pressure injector tubing. The injector tubing allows the operator to manually inject the CO₂ from a safe distance behind a leaded shield. C-arm cone-beam CT scans are then obtained with the manual injections done in rapid succession throughout the entire C-arm rotation. Wedged CO₂ C-arm cone-beam CT portography is performed by using an 8-second program without an imaging delay, with the patient's arms alongside the body. The 3D roadmap of the portal vein is then laid over the working fluoroscopy screen (Fig 6) and portal vein puncture performed. Although several maneuvers in this procedure still require refinement, C-arm cone-beam CT has the potential to improve the targeting of the portal vein during TIPS placement.

Misregistration of the 3D model and fluoroscopic overlay is one of the main shortcomings of this technique. It can be caused by respiratory and

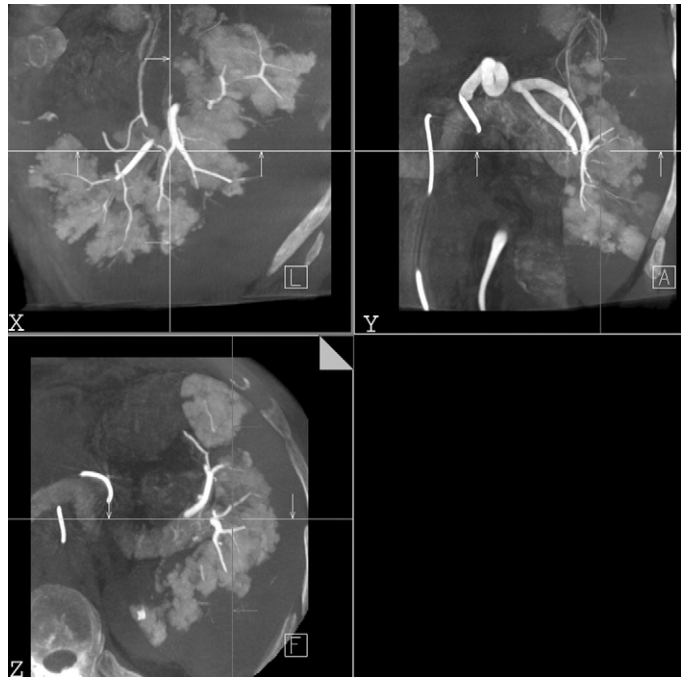


Figure 7. Reformatted contrast-enhanced C-arm CT scans obtained in sagittal (x), coronal (y), and axial (z) projections after partial splenic artery embolization. Paging through the images in the various planes enables the operator to assess the volume or percentage of infarcted spleen as a means of assessing the therapeutic endpoint of the procedure.

organ motion, inferior displacement, and rotation of the liver when the portal access needle is inserted into the hepatic vein. To minimize the time delay between portal opacification and needle positioning, simultaneous placement of a balloon occlusion catheter and the portal vein access needle via a 30-cm-long, 14-F sheath can be achieved. C-arm cone-beam CT is then performed with the needle in place, allowing the physician to see the relationship of the needle to the portal vein and minimize misregistration artifacts.

Partial Splenic Embolization

C-arm cone-beam CT can be used to determine the proportion of embolized parenchyma during partial splenic embolization procedures. The intent of partial splenic embolizations is to treat hypersplenism-related thrombocytopenia and to boost platelet count by embolizing 50%–70% of the organ. The ability of C-arm cone-beam CT to acquire multiplanar soft tissue parenchymal information en-

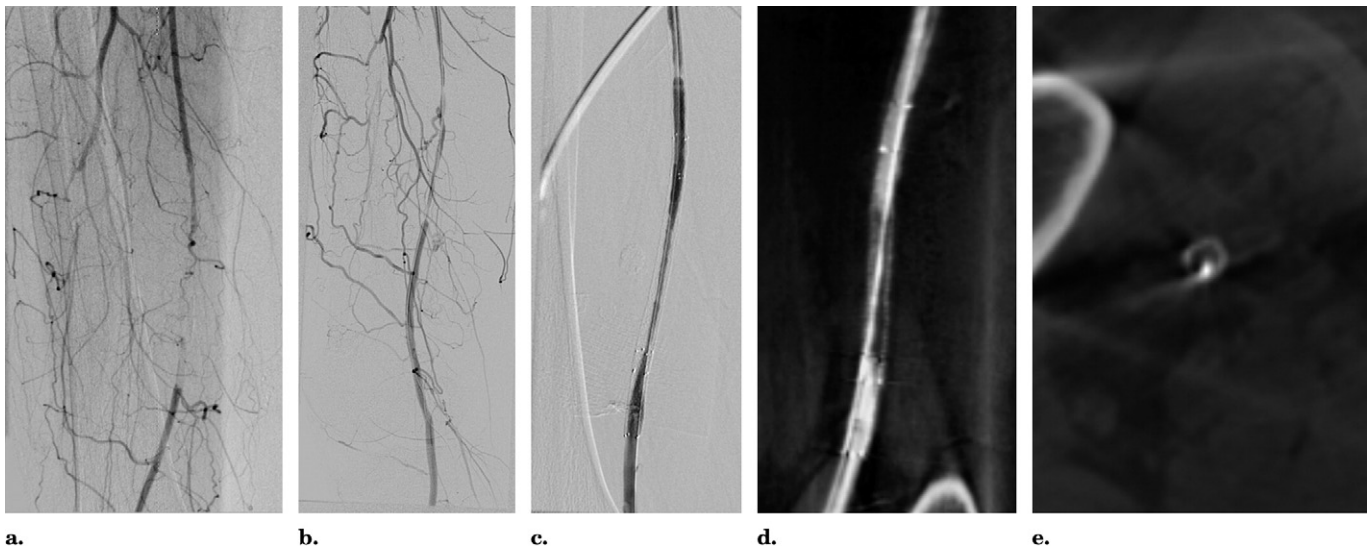


Figure 8. Images in a patient with severe claudication secondary to occlusion of the mid-portion of the superficial femoral artery obtained during peripheral arterial revascularization and stent placement. (a–c) Images from DSA obtained before angioplasty (a), after angioplasty (b), and after stent placement (c). The images demonstrate intraluminal narrowing within the stent that persisted after prolonged balloon inflation (c). (d, e) Coronal (d) and axial (e) C-arm CT scans demonstrate hypoattenuating material (thrombus) within the stent lumen despite appropriate stent deployment and wall apposition. Intraarterial infusion of Abciximab and anticoagulation were then initiated.

ables the operator to better understand the quantity of parenchyma that has been embolized (Fig 7). At M.D. Anderson, the current technique includes acquiring a contrast-enhanced C-arm cone-beam CT scan with a catheter in the proximal to middle splenic artery at an injection rate of 3–4 mL/sec, an imaging delay of 4–6 seconds, and iodinated contrast medium diluted to 30% by volume (source: M.J.W.).

Peripheral Vascular Interventions

The ability to create multiplanar reformations with soft tissue imaging information is useful when performing peripheral revascularization procedures. The injection protocols used at the Centre Hospitalier de l'Université de Montréal for various peripheral revascularization or stent-graft procedures are detailed in Table 2 (source: G.S.). For peripheral stent placement, high-resolution acquisitions (0.25-mm pixel size) in the area of interest are necessary to get a good definition of the vessel lumen, stent struts, and vessel wall. For stent-graft procedures, a larger field of view and lower spatial resolution (0.5-mm pixel size) are preferred. The ability to generate multiplanar reformations orthogonal to the ves-

sel central line is helpful for quantifying eccentric atheromatous lesions. Soft tissue differentiation is helpful for documenting the extension of the plaque within the vessel wall and its composition (soft vs calcified). This information is helpful for defining landing zones, balloon and stent sizing, and choosing the type of stent (self- vs balloon-expandable) to be implanted during these procedures. It is also useful for assessing the presence of thrombus during revascularization procedures (Fig 8). During angioplasty and stent placement procedures, it is particularly useful to document the presence of intimal dissection after angioplasty, the adequate coverage of the lesion by the stent, and stent opening and wall apposition (Fig 9).

C-arm cone-beam CT can also provide useful information during endovascular aneurysm repair. Because femoral clamping induces a slow flow condition in the infrarenal aorta and iliac arteries, it is necessary to increase the time between injection and image acquisition (Table 2). C-arm cone-beam CT may be better than DSA for delineating thrombus extension within the aorta to decide on the type of stent-graft when imaging clarification during device deployment is required. It is also well suited for con-

firmed aneurysm sac exclusion and immediately identifying and characterizing potential endoleaks (Fig 10). Finally, it is also helpful for documenting stent-graft opening—in particular at the level of the aorto-iliac bifurcation (Fig 11). This technology could potentially be useful during the management of ruptured aneurysms. C-arm cone-beam CT as an adjunct to DSA is sufficient to provide adequate imaging for stent planning during the insertion of an occlusion balloon in emergency situations when there is insufficient time for standard preprocedure imaging.

Vascular Anomalies

Slow flow vascular malformations (venous, lymphatic malformation) are usually treated with direct puncture guided by ultrasonography (US) and fluoroscopy. The sclerosing agent is injected after documentation of adequate needle positioning with direct phlebography for venous malformation or cyst opacification for lymphatic malformation. Direct phlebography is performed to delineate the lesion and its venous drainage. At the Centre Hospitalier de l'Université de Montréal, C-arm cone-beam CT is currently used to document needle positioning during sclerotherapy sessions

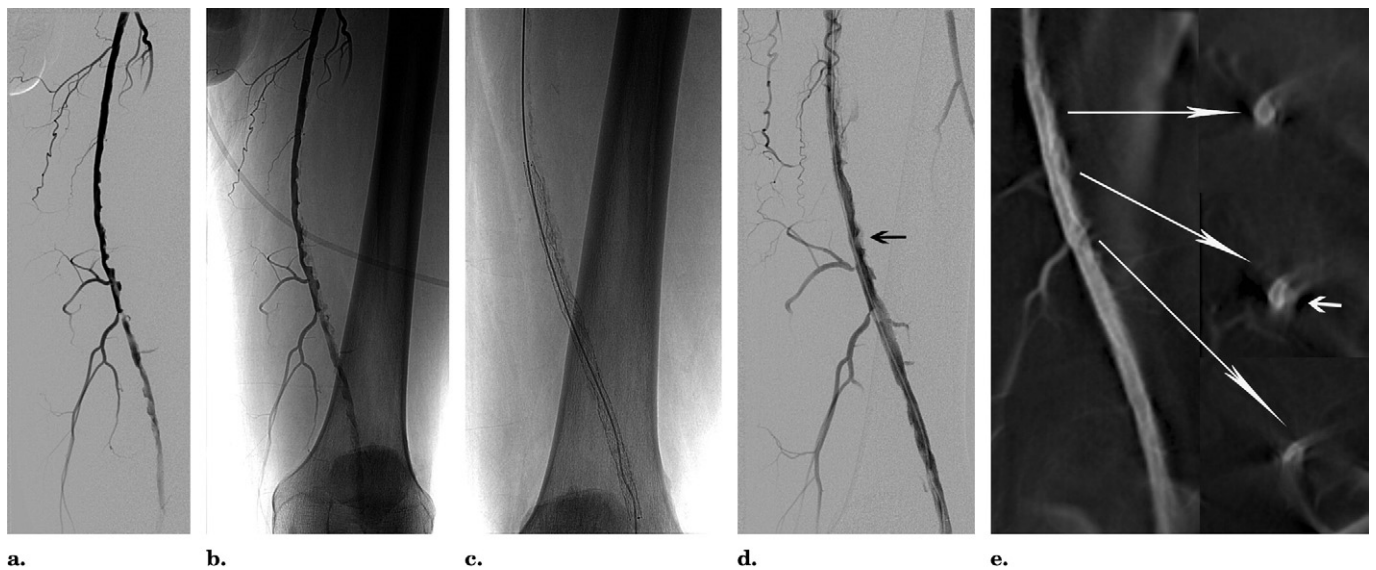


Figure 9. Images in a patient with diabetes who presented with severe claudication. (a–d) Images from DSA and C-arm CT during peripheral vascularization and stent placement. (a, b) DSA images obtained before intervention demonstrate diffuse severe eccentric irregularity, calcification, and stenosis involving the distal superficial femoral and proximal popliteal arteries. (c, d) DSA images obtained after angioplasty and stent deployment demonstrate residual stenosis (arrow in d). (e) Composite longitudinal and corresponding axial contrast-enhanced C-arm CT multiplanar reformations (indicated by long arrows) demonstrated two areas of severe stenosis in which the stent failed to open adequately (middle and lower long arrows). Note the presence of atherosclerotic calcified plaque (short arrow) in the region of the residual stenosis. Prolonged balloon inflation with high-pressure balloon technology was subsequently required for adequate management.

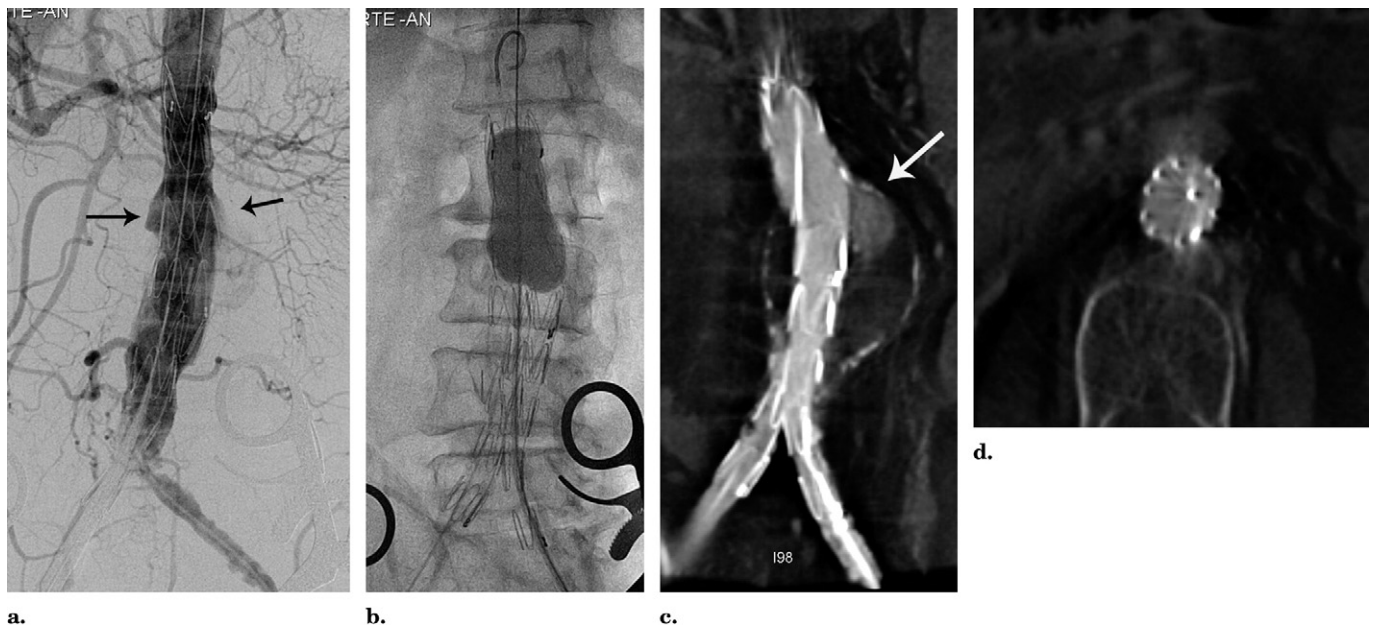


Figure 10. Endovascular repair of an infrarenal aortic abdominal aneurysm. (a) Image from DSA obtained after stent-graft deployment demonstrates a type IA endoleak (arrow). (b–d) After prolonged dilation of the proximal portion of the stent-graft (b), coronal (c) and axial (d) C-arm CT reformations were obtained and demonstrated good apposition of the stent-graft in the region of the proximal neck. Note a faint and homogeneous area of contrast (arrow in c) identified in the nonthrombosed portion of the aortic sac. This was believed to represent a type IV leak (porosity) leak.

for complex venous or lymphatic malformations (source: G.S.). C-arm cone-beam CT is useful when the malforma-

tion cannot be adequately visualized with US (Fig 12). After the injection of the sclerosing agent, C-arm cone-beam

CT (without additional contrast medium infusion) is useful for documenting the distribution of the sclerosing

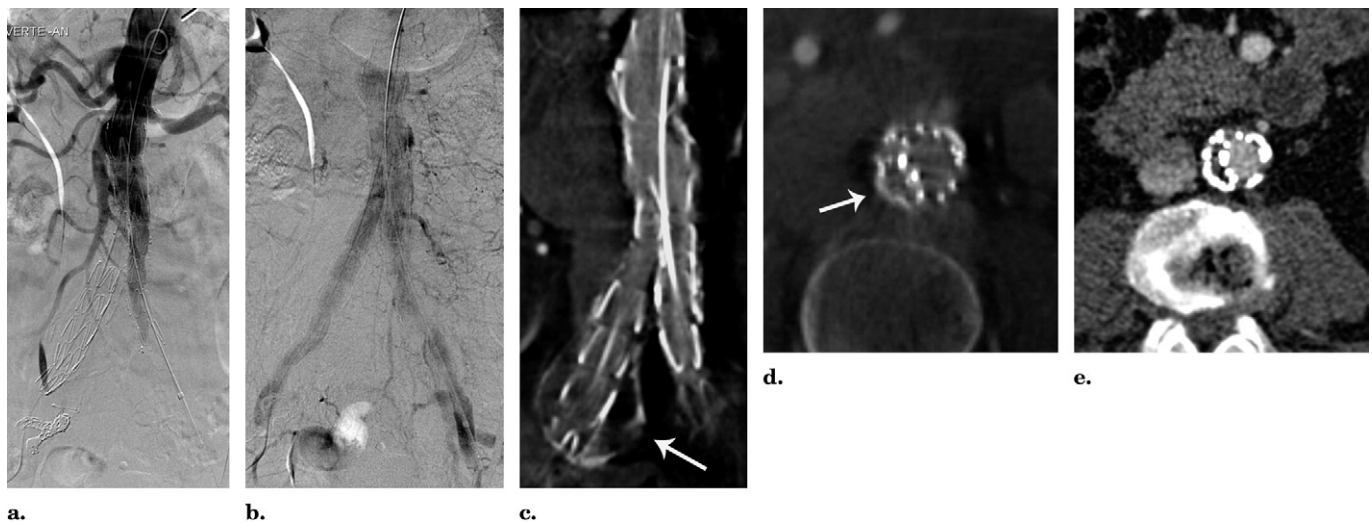


Figure 11. Endovascular repair of a right common iliac aneurysm treated with placement of a bifurcated stent-graft. (a, b) Images from early (a) and late (b) phase DSA demonstrate exclusion of the aneurysm and adequate stent-graft opening. (c) Coronal reformatted C-arm CT scan demonstrates adequate exclusion of the aneurysm (arrow). (d) Axial C-arm CT scan shows compression of the right iliac component of the stent-graft at the level of the aorto-iliac bifurcation (arrow). This latter finding was noticed after the procedure was completed and confirmed on follow-up conventional CT scans (e). The patient developed progressively worsening right lower extremity claudication necessitating repeat intervention.

agent within the malformation. For venous malformation, an injection of sclerosing foam combining 2 mL of sodium tetradecyl sulfate 3%, mixed with 1 mL of ethiodized oil and 3 mL of air. The 3D volume is reconstructed by using 2-mm thick multiplanar reformations in two orthogonal planes with a pixel size close to 0.5 mm. The postinjection C-arm cone-beam CT scans are compared with preprocedure T2-weighted MR images and perfusion acquisitions to evaluate the distribution of the sclerosing agent and the adequacy of therapy (Fig 12). On the basis of this information, inadequately treated regions of the lesion can be treated. C-arm cone-beam CT can also be used in a similar manner when treating cystic lymphangiomas.

For high-flow arteriovenous malformations, multiplanar reformations and soft tissue imaging provide useful information for delineating the extension of the malformation and the territory to be embolized during superselective opacification.

NONVASCULAR INTERVENTIONS

Spine Interventions

Fluoroscopic guidance, used alone to provide a real-time overview of a

large area, usually provides sufficient information to guide appropriate needle placement for the injection of cement in lower thoracic or lumbar spine interventions. However, both C-arm cone-beam and conventional CT can be helpful in difficult spine procedures by revealing, in more detail than fluoroscopy, areas suitable for safe needle placement; C-arm cone-beam CT provides exact needle locations in three dimensions. Unlike C-arm cone-beam CT-capable systems, however, conventional CT does not afford real-time surveillance during cement injection. Immediately after injection, C-arm cone-beam CT can also be used to assess cement distribution, even while the patient is in the interventional radiology suite.

C-arm cone-beam CT is ideal when both “CT-like” imaging and real-time fluoroscopic imaging are required for complex or high-risk interventions such as in cervical and upper thoracic vertebroplasties or kyphoplasties, for sacroplasty (Fig 13), or when there is destruction or posterior displacement of the posterior wall of the vertebral body. Combined imaging is also useful when specific lytic lesions must be accessed or when an alternate route for needle entry is required (Fig 14). In these situations, before C-arm cone-

beam CT made it possible to combine modalities in the interventional radiology suite, patients would either be transferred from the interventional radiology suite to the CT suite or a portable C-arm fluoroscopy unit was brought into the CT suite; neither of these options was ideal.

Another advantage of C-arm cone-beam CT over conventional radiography is its ability to provide information for the assessment of cement distribution in different planes by using multiplanar data reconstruction. C-arm cone-beam CT also makes it easier to identify cement that has inadvertently extended into the spinal canal or other crucial structures, an event that may require emergent surgical intervention. It may be that future studies will show that the use of C-arm cone-beam CT improves the safety of spine interventions.

Enterostomy Interventions

Gastrostomy tube placement is typically performed under fluoroscopic guidance, and, on occasion, it is difficult to adequately define the relationship between the stomach and colon or stomach and liver. C-arm cone-beam CT can get around this problem by capturing adequate information

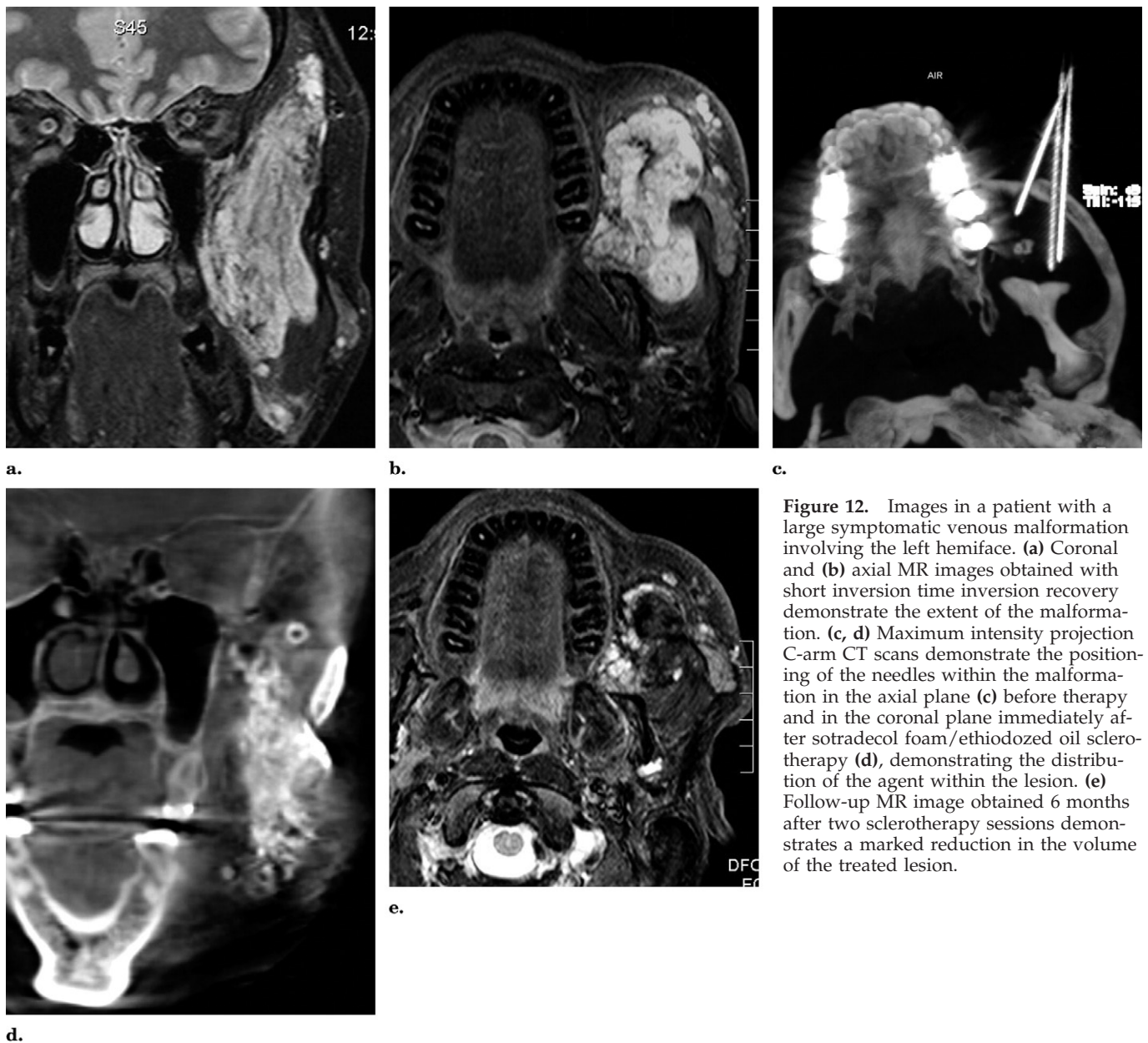


Figure 12. Images in a patient with a large symptomatic venous malformation involving the left hemiface. (a) Coronal and (b) axial MR images obtained with short inversion time inversion recovery demonstrate the extent of the malformation. (c, d) Maximum intensity projection C-arm CT scans demonstrate the positioning of the needles within the malformation in the axial plane (c) before therapy and in the coronal plane immediately after sotradecol foam/ethiodized oil sclerotherapy (d), demonstrating the distribution of the agent within the lesion. (e) Follow-up MR image obtained 6 months after two sclerotherapy sessions demonstrates a marked reduction in the volume of the treated lesion.

about the soft tissue structures anterior to the stomach, which then allows the safest access path for tube insertion to be identified. Although the benefits are difficult to measure, this ability does increase operator confidence and overall safety for the more complex and higher-risk cases. C-arm cone-beam CT can also be used for other gastrointestinal interventions such as direct percutaneous jejunostomy tube placements. In the latter situation, images assist in the selection of an appropriate loop of bowel for access.

Biliary Interventions

The current use of C-arm cone-beam CT for biliary interventions primarily is for acquiring images that show biliary anatomy and tumor abnormalities rather than for needle guidance. This is especially the case when variant biliary anatomy is identified and surgical intervention is considered an option (Fig 15). Compared with conventional cholangiography, C-arm CT is better for gaining an understanding of the vol-

ume of liver being drained when complex hilar obstructions with intrahepatic duct isolation are encountered and the placement of additional drains must be considered.

TECHNICAL ISSUES

The set-up time required for C-arm cone-beam CT image acquisition can range from 5 to 10 minutes, depending on the experience of the team and the frequency of C-arm cone-beam CT use. This time interval, the main im-

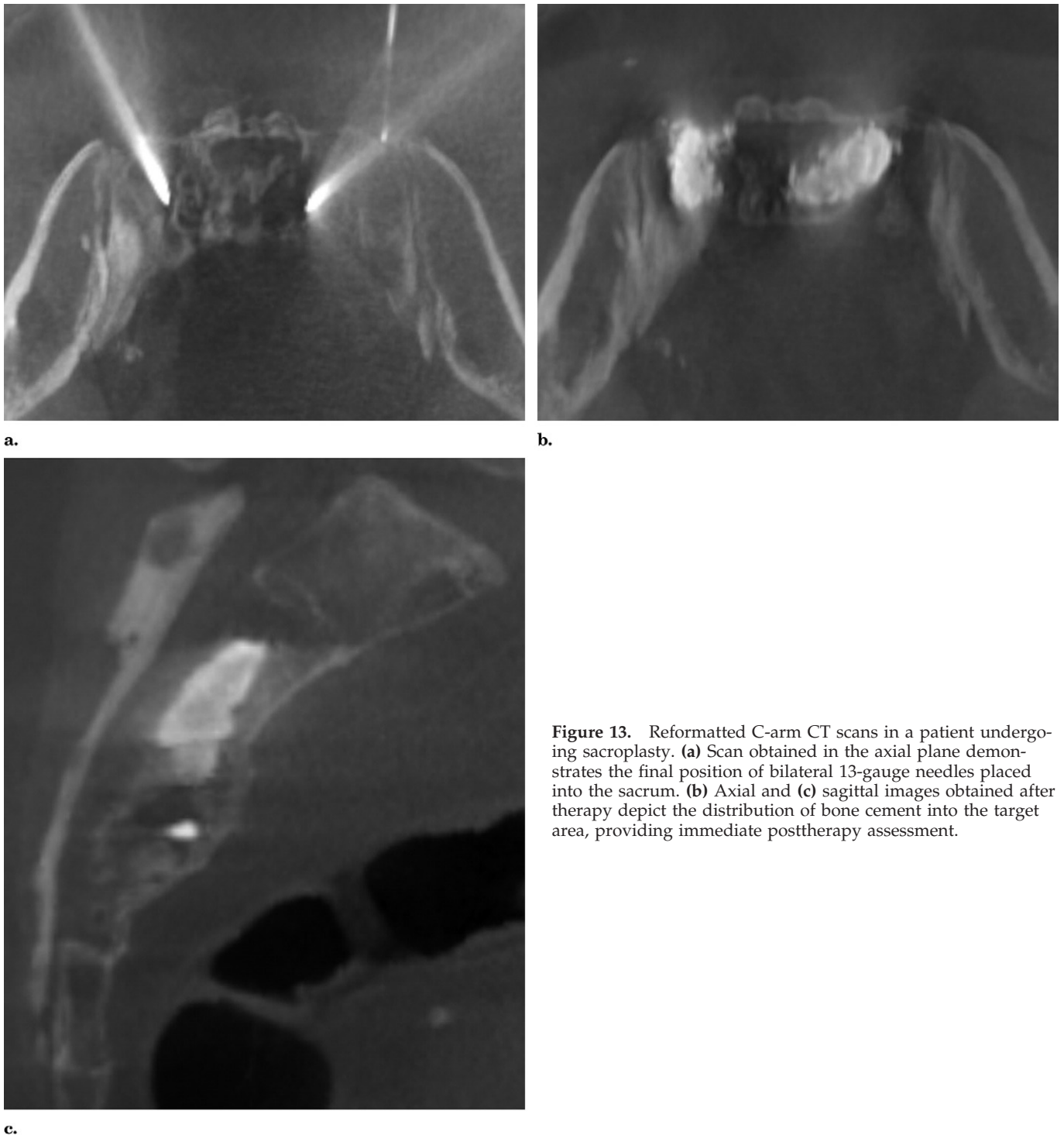


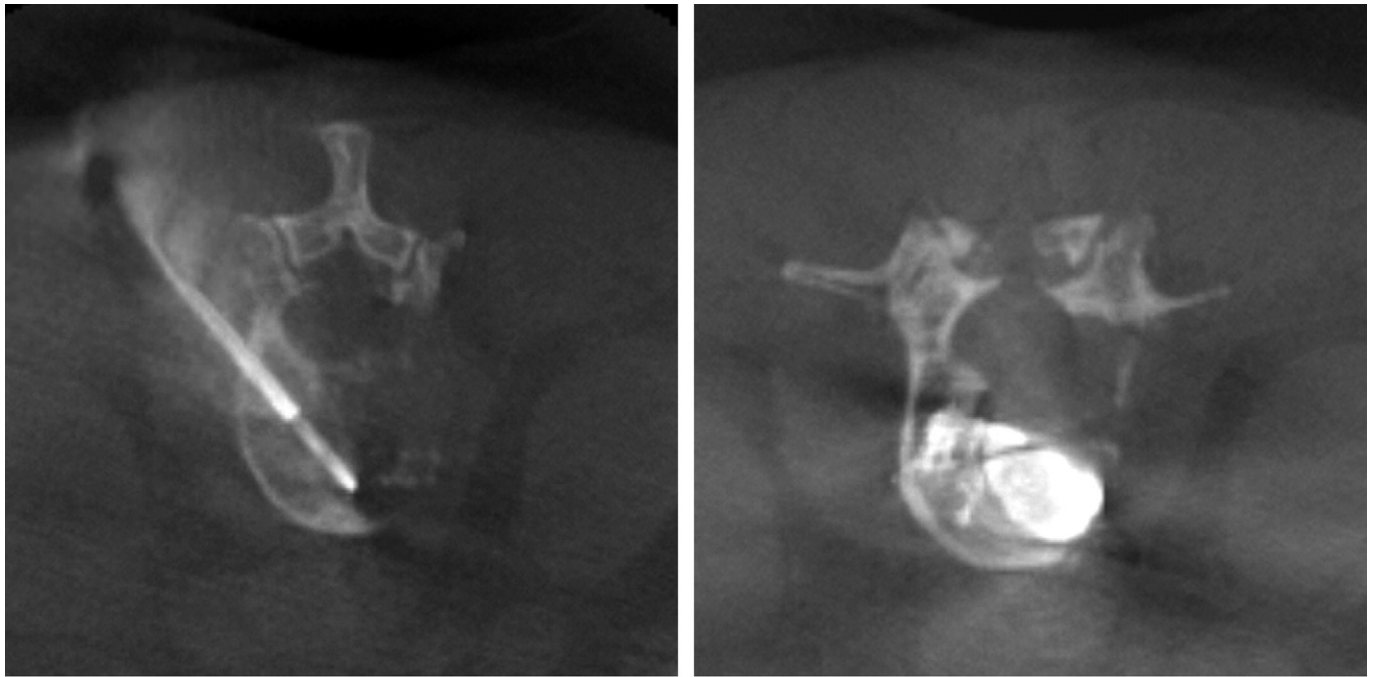
Figure 13. Reformatted C-arm CT scans in a patient undergoing sacroplasty. **(a)** Scan obtained in the axial plane demonstrates the final position of bilateral 13-gauge needles placed into the sacrum. **(b)** Axial and **(c)** sagittal images obtained after therapy depict the distribution of bone cement into the target area, providing immediate posttherapy assessment.

pediment to integrating C-arm cone-beam CT into routine clinical practice, includes the time required to position the patient, examination table, and C-arm so that the area of interest is in the isocenter; the time required to prepare contrast media (eg, contrast medium

dilution), if applicable; and the time required to select the appropriate treatment protocol. Set-up time can be considered a limitation of this technology when multiple (>2) C-arm cone-beam CT acquisitions are obtained during any given intervention. The

time requirements for set-up may overshadow the future reductions in image reconstruction time, limiting the use of this useful technology in routine clinical practice.

Acquisition time, that is, the time it takes the C-arm to rotate around the



a. **b.**
Figure 14. Reformatted axial C-arm CT scans in a patient undergoing targeted vertebroplasty of an osteolytic spine lesion demonstrate (a) the adequacy of the initial needle placement and (b) the adequacy of cement distribution within the target lesion.



a. **b.**
Figure 15. Images from frontal projection cholangiography (a) and reformatted C-arm CT (b) in the sagittal (x) coronal (y), and axial (z) views and volume rendered technique view (lower right) demonstrate variant biliary anatomy. With the conventional fluoroscopic spot view from the cholangiogram it is difficult to tell with certainty the segmental ductal anatomy projecting over the right lobe (arrow). With C-arm CT, the anatomy is more clearly depicted as the posterior trunk of the right hepatic duct anomalously inserting on the left hepatic duct. The information was crucial for planning subsequent surgical resection.

patient, includes the imaging delay after the injection of contrast medium. Rotation time ranges from 8 to 20 seconds, depending on the device used. For examinations that are optimized for soft tissue applications, all three models listed earlier—the DynaCT, XperCT, and Innova CT—offer 10- and 20-second programs; DynaCT also has an 8-second program.

A key advantage of using C-arm cone-beam CT is that the 3D data set is easily manipulated to allow the viewing of two-dimensional oblique sections through any part of the imaged object. Although sophisticated data processing algorithms have been designed to overcome data distortions, reconstruction times are still affected by the large amount of data and the limited speed with which data can be processed. Reconstruction and image generation times range from ~1.5 to 11 minutes, depending on which device and program are used. As C-arm cone-beam CT technology develops further, manufacturers have indicated that image reconstruction will soon require less than 1 minute.

The maximum field of view for current C-arm cone-beam CT systems is limited on the basis of the size of the flat panel detector. Both Siemens and Phillips employ a 30 × 40-cm detector that operates in the landscape position. The dimensions of GE's flat panel are 41 × 41 cm. This limitation is frequently encountered during hepatic vascular interventions because the liver cannot often be imaged in its entirety. Patient and target area positioning is crucial to ensure that vital areas of interest are included in the field of view in both the transverse and cranial-caudal dimensions. This can be monitored by the operator when the

technologist performs a test run by viewing the region of interest in both the anterior-posterior and lateral positions.

In conclusion, C-arm cone-beam CT represents the next generation of imaging technology to be integrated into the interventional radiology suite that is to be the platform for many of the 3D roadmapping and navigational tools as the technology develops. The combination of these current and future capabilities may serve as the foundation upon which improvements to the efficacy and safety of complex fluoroscopic procedures are made. These improvements should ultimately reduce the use of iodinated contrast media and decrease the radiation exposure to the patient and operator. The information provides an added level of confidence for the operator.

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