CT-Guided Biopsy

2

Kamran Ahrar

Early experience with computed tomography (CT)-guided biopsy was based on the use of conventional multisectional CT, consisting of individual scans obtained during separate breath holds. In these early days, respiratory misregistration presented a major obstacle in identifying the biopsy needle tip. Development of spiral CT scanners, which use a continuously rotating detector system and move the patient continuously through the scanner, has helped avoid some of the respiratory misregistration problems by imaging the entire area of interest in a single breath hold [1]. Modern multidetector CT scanners allow for rapid imaging during biopsy procedures during "quiet respiration" (i.e., diaphragmatic respiration). This chapter outlines the equipment, advantages, disadvantages, applications, and techniques used in CT-guided and CT fluoroscopy (CTF)-guided biopsies.

Equipment

CT

CT-guided biopsies can be performed using any diagnostic CT equipment. However, certain features are more desirable for CT-guided interventions. Multidetector CT scanners with wide detector arrays are ideal for imaging large anatomical sections where the intervention is taking place. This imaging of a large anatomical area helps the interventional radiologist recognize needle deviation in cranial and caudal directions and adjust the puncture direction if organ shift occurs during the intervention. Also, rapid three-dimensional (3D) reconstruction and viewing of the needle in nonaxial planes are possible with multidetector CT scanners.

The gantry on a typical diagnostic CT scanner is 70 cm in diameter, but CT scanners with large-bore gantries (up to 85 cm) are commercially available and are more suitable for CT-guided interventions. A wider CT gantry allows better access to the patient during needle or device placement and imaging. The procedure room should contain at least one monitor so that the radiologist can review the most recent images while inserting the biopsy needle or device; however, a dual monitor system is ideal because it allows reference or planning images to be projected and maintained on one monitor while the other monitor shows the most recent or real-time CT images.

The CT scanner should have a foot pedal control that allows the radiologist to start and stop sequential scans or CT fluoroscopy from the procedure room. The foot control feature is necessary to perform CT fluoroscopy, but even for sequential imaging during a biopsy, a foot pedal enables the radiologist to be more independent of the technologist in the control room. Similarly, table-side controls for moving the table in and out of the gantry make CT-guided biopsies more efficient by allowing the radiologist to control the table. Most manufacturers offer software packages dedicated to CT-guided biopsies. This software makes it possible for the technologist to quickly set up a small section of anatomy to be imaged during a biopsy procedure.

CT Fluoroscopy

CTF can provide continuous imaging with real-time reconstruction and display of images that allows the radiologist to monitor percutaneous biopsy procedures in near-real-time mode. CTF was initially introduced into clinical practice in 1996 [2]. The first prototype was constructed using a third-generation CT scanner (Xpress/SX; Toshiba, Tokyo, Japan) equipped with a slip ring and an 896-channel solid-state

K. Ahrar, MD, FSIR
Department of Interventional Radiology,
Department of Thoracic and Cardiovascular Surgery,
The University of Texas MD Anderson Cancer Center,
1515 Holcombe Boulevard, Unit 1471,
Houston, TX 77030, USA
e-mail: kahrar@mdanderson.org

K. Ahrar, S. Gupta (eds.), *Percutaneous Image-Guided Biopsy*,
DOI 10.1007/978-1-4614-8217-8_2, © Springer Science+Business Media New York 2014

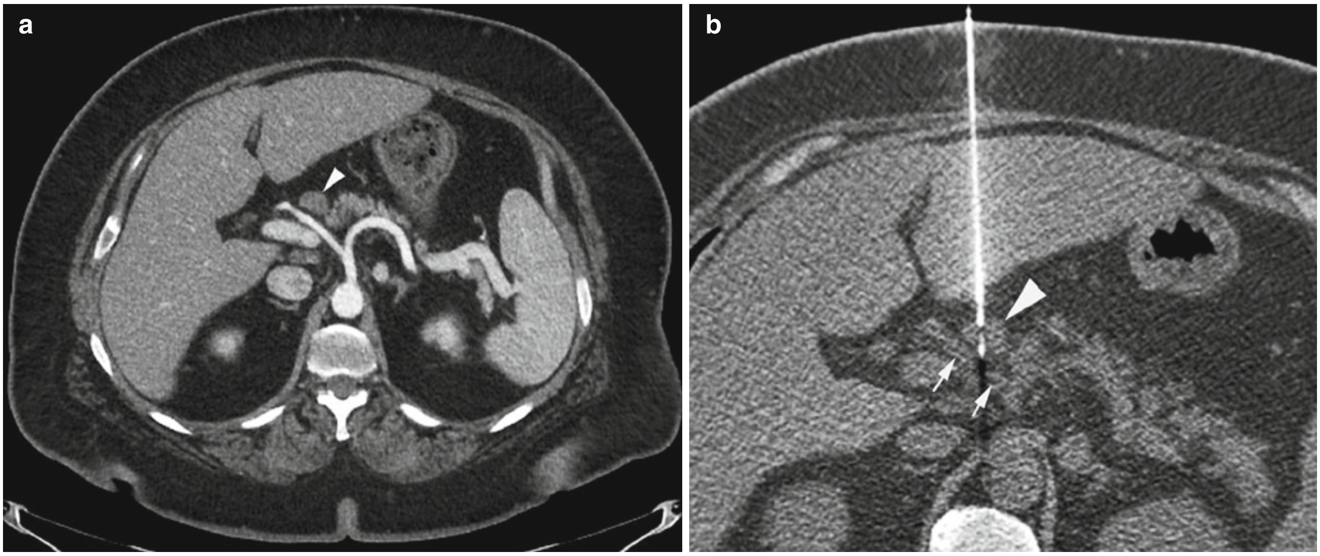

Fig. 2.1 A morbidly obese, 55-year-old woman with endometrial cancer was found to have periportal lymphadenopathy. Diagnostic contrast-enhanced CT image of the abdomen (**a**) shows a 1.5 cm lymph node (*arrowhead*) immediately anterior to the common hepatic artery. Axial CT fluoroscopy image of the abdomen (**b**) shows a transhepatic approach to the lymph node (*arrowhead*). The core biopsy needle is centered within the lesion, anterior to common hepatic artery (*arrows*)

detector array that was modified by adding a high-speed array processor (real-time reconstruction unit) to increase the image reconstruction speed. The CTF prototype unit had a display rate of six images per second with a delay time of 0.17 s [2]. Initially, CTF was performed only in "still mode" without any motion of the patient table or gantry; however, further development of CTF made it possible to perform CTF while sliding the patient table or tilting the gantry.

Currently, all available commercial CTF systems use continuous rotation, fan-beam geometry CT scanners. The high-speed array processor allows image display rates of up to 8 frames per second with an average inter-image spacing of 0.17 s. CTF images are displayed in a "near-real-time" mode on a monitor inside the procedure room to provide immediate feedback to the radiologist.

Demand for CT-guided interventions has increased over the years, and manufacturers have modified CT scanners to include additional hardware and software packages specifically designed to accommodate the needs of interventional radiologists. The wider gantry openings of up to 85 cm provide the radiologist with better patient access during interventional procedures, and ultrafast imaging and near-real-time 3D image reconstruction to help needle path planning and needle artifact prevention have improved the accuracy of interventions. Modern interventional CT units have been designed to obtain optimal imaging while reducing the dose of ionizing radiation to the patient and radiologist. CT scanners with table-side controls have been developed to allow radiologists to control imaging and display during CT-guided interventions.

Advantages

CT provides high-spatial and high-contrast resolution that allows accurate needle-tip localization (Fig. 2.1). CT allows for excellent delineation of intervening vital structures, permitting a safe biopsy path (Fig. 2.2). It also allows for early detection of complications (Fig. 2.3). CT-guided biopsies are associated with a shorter learning curve for the radiologists than are ultrasound-guided biopsies. CT guidance allows the interventional radiologist to target the viable portion of a mass and to avoid areas of necrosis or cystic degeneration [3].

Disadvantages

Density differences between normal tissues and tumors may not be sufficiently large to allow tumor pathology to be distinguished from normal tissue on noncontrast CT images (Fig. 2.4). While contrast-enhanced CT can be performed to help guide the biopsy procedure (Fig. 2.5) [4], contrast enhancement is often transient and may not last for the entire procedure.

Another disadvantage of CT guidance is that CT imaging is limited to an axial plane. As such, the biopsy planning route is often severely restricted. A multidetector CT with automated reconstruction of images in arbitrary planes alleviates some of these limitations (Fig. 2.6).

Another major disadvantage of conventional CT for image-guided biopsies is the lack of real-time imaging.

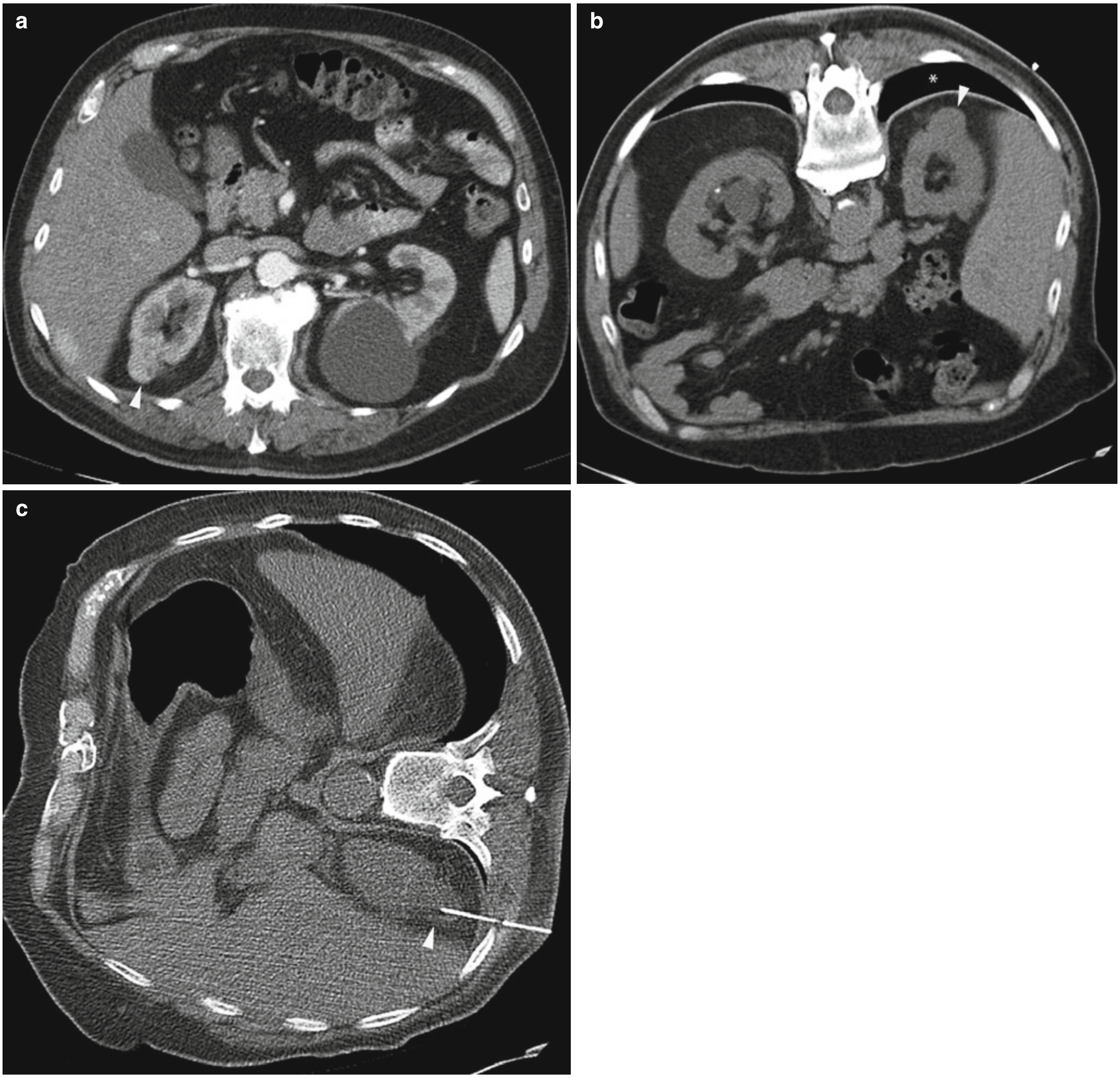

Fig. 2.2 A 78-year-old man was referred for biopsy of a right kidney mass for consideration of percutaneous thermal ablation. Axial CT image of the abdomen (**a**) shows a solid enhancing mass (*arrowhead*) in the upper pole of the right kidney. Axial image of the abdomen in prone position (**b**) shows intervening lung (*asterisk*). When patient was positioned in right lateral decubitus (**c**), the lung volume decreased and a safe window appeared for biopsy of the renal mass (*arrowhead*). A pathologic assessment revealed renal cell carcinoma, clear cell type, nuclear grade 3

Although CTF provides near-real-time imaging, the radiation dose to the patient and operator may prohibit its routine, unrestricted utilization [5–8]. Several studies have documented higher radiation exposure to patients and radiologists from both direct skin exposure and scattered radiation during CTF-guided procedures than during conventional, sequential CT-guided procedures [2, 5–10].

Applications

Although CT can be used to biopsy masses in virtually any part of the body, CT-guided biopsy is most often used for sampling small abdominal (Fig. 2.1), retroperitoneal (Fig. 2.7), thoracic (Fig. 2.8), and musculoskeletal (Fig. 2.9) lesions that are not well visualized on

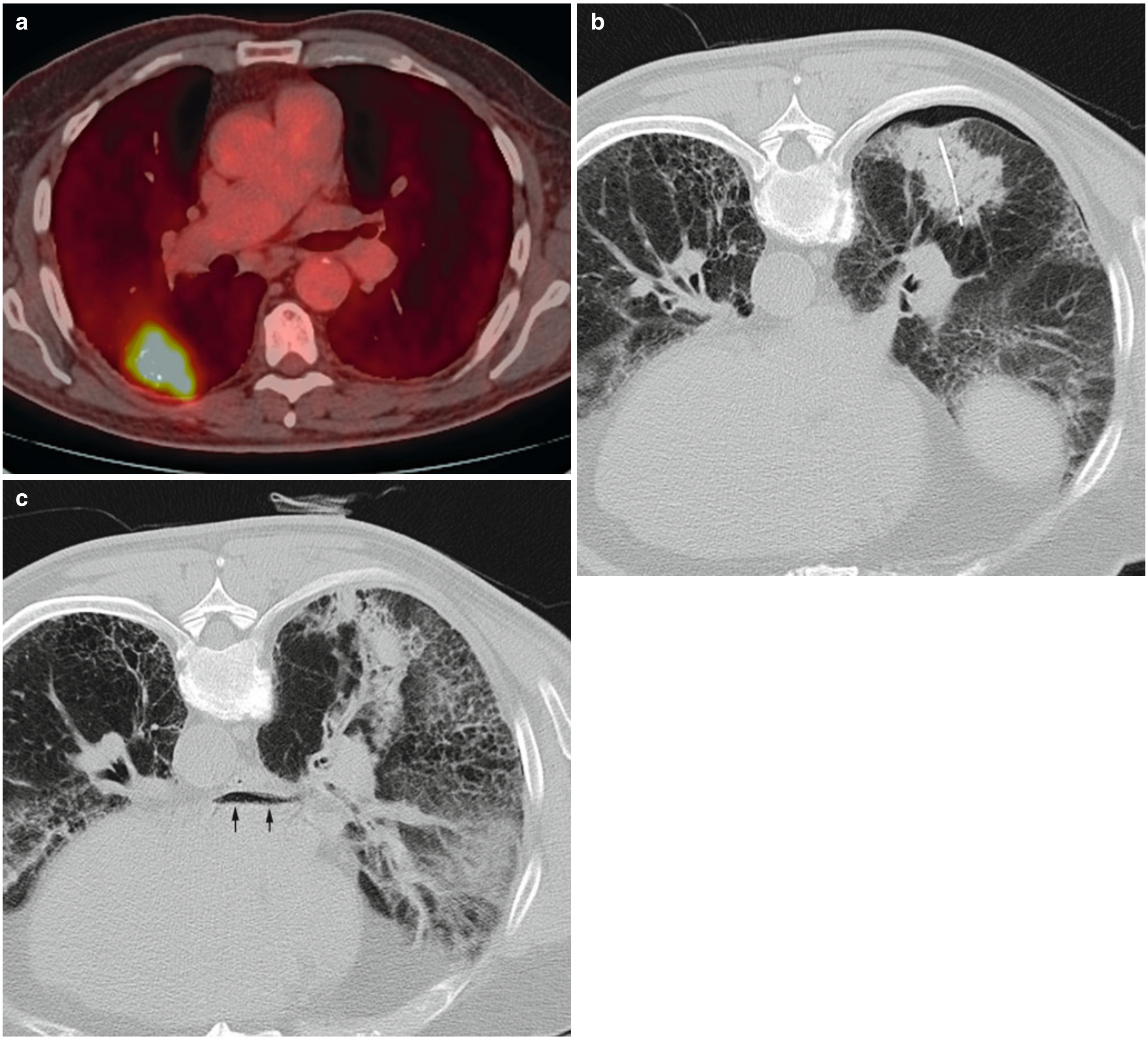

Fig. 2.3 A 75-year-old man with severe emphysema was found to have a mass in the right lower lobe. Axial PET/CT image of the mass (**a**) shows high metabolic activity. CT image of the patient in prone position shows the needle tip within the mass (**b**) and small pneumothorax. After aspiration of the pneumothorax, axial CT image of the chest (**c**) shows air within the left atrium (*arrows*). Systemic air embolism is best treated with hyperbaric oxygen

ultrasonography or fluoroscopy [3]. CTF-guided biopsy has been most commonly used for sampling pulmonary nodules. CTF, with its near-real-time imaging capabilities, allows the interventional radiologist to time the needle puncture with the patient's breathing, which helps in targeting a moving nodule and avoiding ribs during thoracic biopsies. Most studies on the use of CTF-guided biopsy of pulmonary lesions have shown high rates of technical success [11–16]. CTF-guided transthoracic biopsy procedures are associated with shorter procedural times and fewer needle punctures than are conventional CT-guided biopsies [8, 9, 11–17].

In addition, the needle tip and the biopsy target can be visualized during sampling to ensure that the needle tip is indeed within the target. CTF also facilitates placement of the biopsy needle at the edge of a lesion that has a predominantly necrotic center. With CTF, complications are recognized immediately, allowing for rapid institution of appropriate therapy.

Although CTF is not routinely used for abdominal and pelvic biopsies, CTF guidance can be useful in certain circumstances [18, 19]. CTF can be used to guide biopsy of liver lesions that show transient enhancement after intravenous injection of contrast medium, masses with difficult or narrow

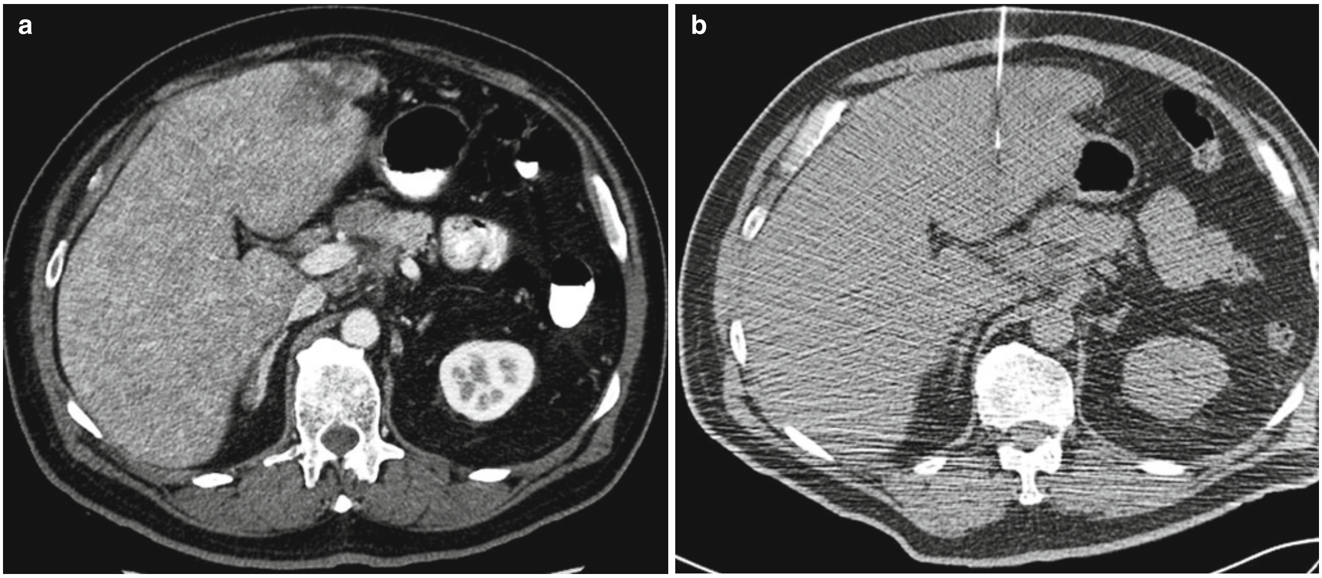

Fig. 2.4 A 65-year-old man with history of Merkel cell carcinoma was referred for liver biopsy. Diagnostic axial CT image of the abdomen after administration of contrast (**a**) shows a lesion in segment II of the liver. A noncontrast axial CT image of the abdomen (**b**) at the time of biopsy did not clearly show the tumor. The lesion was targeted by anatomic landmarks. Immediate assessment of the FNA samples by cytopathologist confirmed metastatic Merkel cell carcinoma. Also note that the diagnostic CT scan (**a**) was performed with the patients arms elevated above his head. Whereas his arms were left on his side during CT-guided biopsy (**b**). The artifact from the arms can hinder visualization of subtle lesions

access routes, and masses close to the diaphragm or critical vascular structures [20, 21]. CTF can assist in needle placement in omental or mesenteric lesions that move with respiration or that may be intermittently surrounded by bowel loops.

Techniques

Setup

For CT-guided biopsies, a sterile field is set up on a movable procedure cart in the CT room. The interventional radiologist reviews existing images, and then the patient is placed in a position that facilitates needle insertion in a safe and efficient manner from the skin surface to the target. Patients can be placed in supine, prone, lateral, or lateral oblique positions as needed, but it is crucial to select a stable and comfortable position for the patient. The patient should remain in the same position after the initial planning images are obtained. Streak artifacts caused by the patient's arms can be reduced by positioning the arms outside the imaging field (Fig. 2.4). Space within the gantry can be maximized by placing the table at the lowest position possible.

A radiopaque marker or grid is placed over the intended area of puncture. Radiopaque grids are commercially available; however, grids can be created on site using various types of catheters that are cut to a length of 10–20 cm, placed parallel at 1- to 2-cm intervals, and taped at the ends. The simplest radiopaque marker consists of a single piece of angiographic or drainage catheter placed on the patient in longitudinal fashion. Alternatively, one can use the laser lights that are built in the gantry together with the grid which can be displayed on the patient's image to determine the needle puncture site.

For most interventions, a spiral scan of the area of interest is performed, including the marker or grid. In most cases, intravenous administration of contrast medium is unnecessary, but occasionally noncontrast images do not allow differentiation of the target from adjacent vascular structures. Tumors within solid organs may be isodense with their surrounding tissue on noncontrast images, in which case the contrast medium may be given intravenously to delineate the vascular structures or to differentiate the lesion from normal parenchyma (Fig. 2.5) [4].

The interventional radiologist identifies the target and then determines a path for placement of the biopsy needle or device. The needle path depends on the organ of interest and the intervening anatomy. In general, the path should be kept short, but it should also avoid certain anatomic structures such as bone, vessels, bowel, or other organs to render the procedure as safe as possible. Once the needle insertion site is determined, the patient is placed into the gantry. The positioning laser light and the radiopaque marker together provide adequate information to localize the exact site for needle insertion. A small ruler and a skin marker are often necessary to mark the puncture site accurately on the

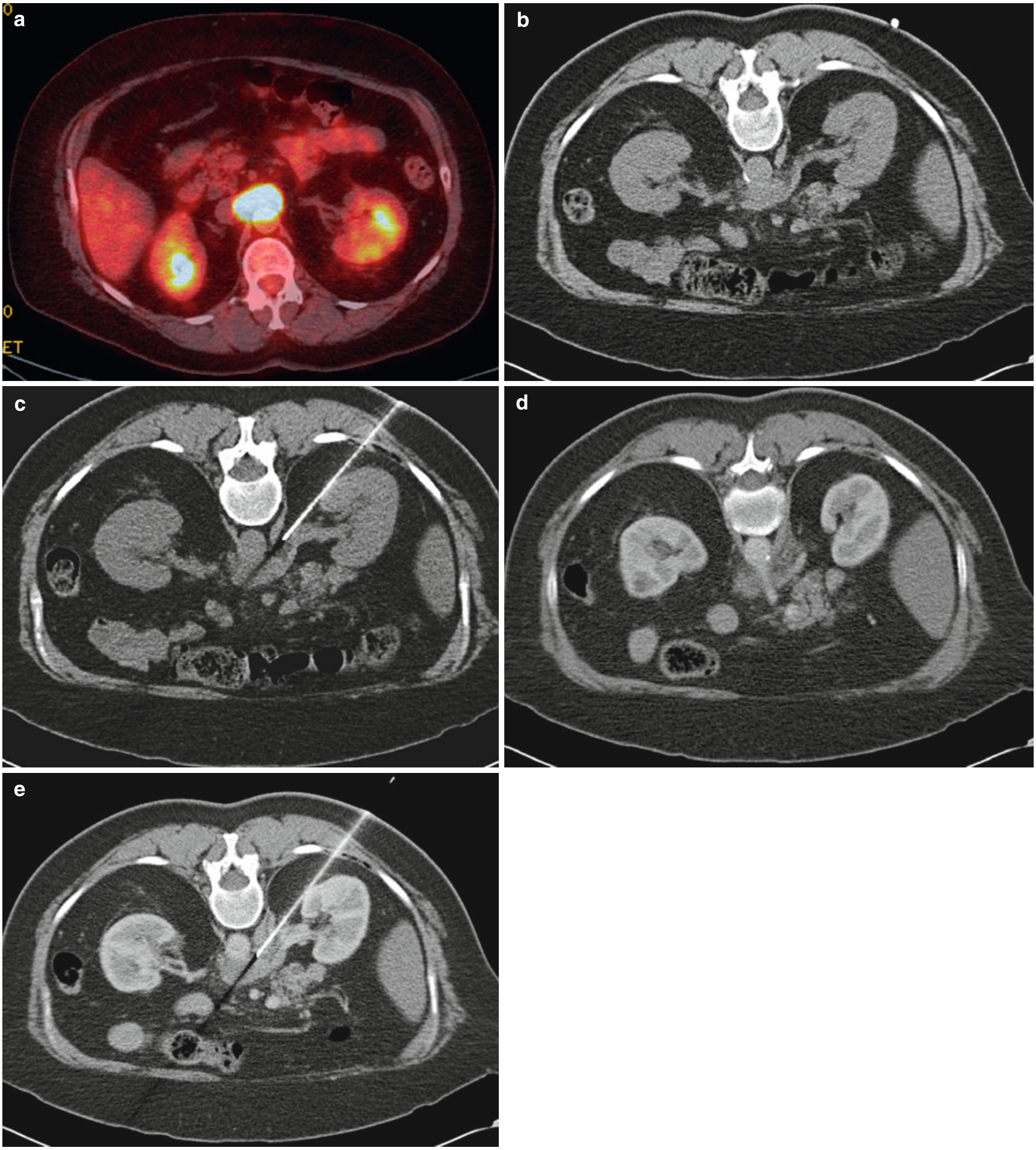

Fig. 2.5 A 62-year-old woman with lymphoma underwent restating PET/CT examination. Axial fused PET/CT image of the abdomen (**a**) shows a metabolically active soft tissue mass encasing the celiac axis. Noncontrast axial CT image of the abdomen in prone position (**b**) shows the soft tissue mass abutting the anterior wall of aorta. A guide needle was advanced to the edge of the lesion (**c**). Immediately before insertion of the core biopsy needle, contrast-enhanced CT images were obtained demonstrating the celiac artery (**d**). The guide needle is identified approximately 10 mm inferior to the celiac artery (**e**). Contrast-enhanced axial CT image of the lesion (**e**) confirms the absence of any major vessels in the path of the needle

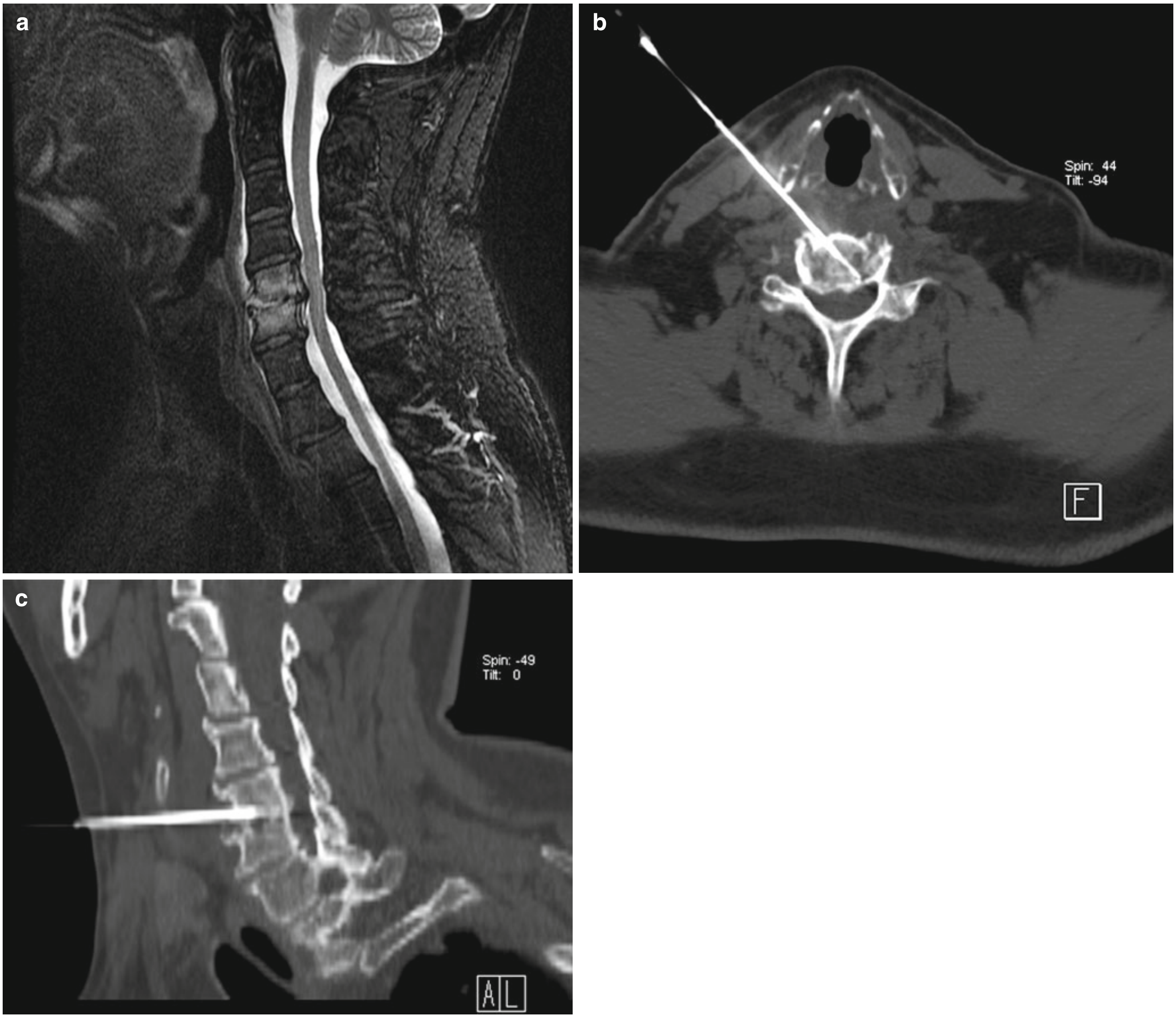

Fig. 2.6 A 53-year-old man with leukemia was referred for biopsy of cervical spine. Sagittal T2 MRI of the cervical spine (**a**) shows high signal intensity in C5 and C6 vertebral bodies with involvement of the disc space. Axial-oblique (**b**) and sagittal-oblique (**c**) multiplanar reformatted images show the position of the needle within the area of interest

skin. The skin is then prepared in a sterile manner, and a keyhole drape is placed over the puncture site. A sterile cover may be applied to the table-side control panel so that the radiologist can operate the CT scanner during the procedure.

Biopsy Technique

Most biopsies are performed under moderate sedation or local anesthesia. The skin entry site is infiltrated with local anesthetic agent (e.g., lidocaine 1 %), and sufficient local anesthetic agent should be injected at the interface of the pleura, peritoneum, or periosteum. A small stab incision is made to help the needle pass through the skin and subcutaneous tissues. CT guidance provides intermittent imaging, and thus the needle is inserted incrementally (1 to a few centimeters at a time) during CT-guided biopsy, and images are obtained after each manipulation to confirm proper advancement of the needle along the desired path.

CTF guidance provides continuous near-real-time imaging that allows monitoring of the needle insertion during CTF-guided biopsy. To avoid excessive radiation to the operator's hand, needle-holding devices may be used [22]. Even with the use of needle-holding devices, radiation exposure to the operator and patient may not warrant real-time continuous-mode CTF. Alternatively, intermittent CTF can be performed after incremental advancement of the needle [23].

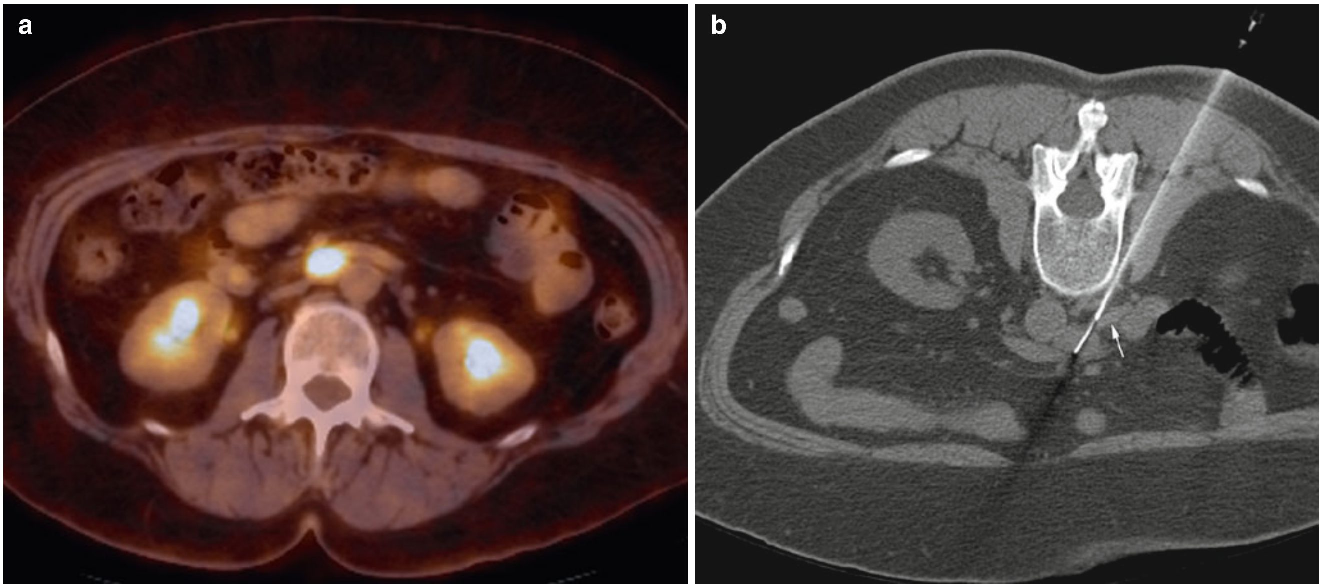

Fig. 2.7 A 56-year-old woman with history of ovarian cancer underwent PET/CT for restaging. Axial PET/CT image of the abdomen (**a**) shows a mass with high metabolic activity in aortocaval space. Axial CT image of the abdomen in prone position (**b**) shows the needle entering the mass from a posterior approach. The *white arrow* shows the inferior vena cava

The operator must be cognizant of two angles when performing CT- or CTF-guided biopsy. Most CT-guided biopsies are performed in a true axial plane. This approach provides the easiest imaging protocol to confirm needle placement. Therefore, the operator has to keep the needle in one axial plane perpendicular to the Z axis. Cranial or caudal angulation of the needle can be detected on sequential CT images, and the path of the needle can be adjusted accordingly. One can take advantage of the laser light of the scanner for alignment of the needle in an axial plane. When the laser light shines on the skin entry site and the hub of the needle, it confirms the positioning of the needle in the imaging plane. The simplest CT-guided biopsy plan is one in which the needle is inserted perpendicular to the skin. However, this approach is not always feasible, depending on the intervening organs or structures that may have to be avoided. Therefore, the second angle that the operator should observe is the steepness of the approach with respect to the skin's surface. Placement of the needle can be guided with the naked eye; however, this is more easily accomplished if the patient is taken out of the gantry and the puncture site is placed directly in front of the operator to avoid issues related to parallax.

Ancillary Techniques

Triangulation Method

The ideal skin entry site may be cranial or caudal to the axial plane containing the target lesion. In these cases, the interventional radiologist can calculate the needle angle using the Pythagorean theorem [24]. This triangulation method is a simple and useful technique that allows the target to be reached without traversing structures directly overlying the target. This technique has been successfully used to reach adrenal lesions without traversing the pleural space. The path of the needle must be followed on sequential axial CT images, and at least one image should be obtained beyond the needle tip to confirm the tip's location (Fig. 2.10).

Angled-Gantry Technique

As discussed above, when the needle path is not in an axial plane, conventional CT images will not show the entire needle in one axial image. Deviation from an axial plane may be necessary to avoid puncturing certain structures, or deviation may develop during the course of biopsy because of patient movement, organ shift, or inaccurate placement of the needle [25, 26]. Sequential axial images have to be reviewed to determine the path of the needle and the location of the needle tip, and localization of the needle tip on sequential axial images requires at least one image to be obtained beyond the needle tip to confirm the tip's position. Alternatively, the interventional radiologist can tilt the gantry cranially or caudally, depending on the angle of the needle path, to view the entire needle in an axial plane (Fig. 2.8). The laser light will shine through the hub of the needle and the skin insertion site when the needle is lined up with the gantry, and the entire needle should be visible in one image. The degree to which the gantry can be tilted depends on two factors: the size of the gantry and the size of the patient. The combination of a large gantry and a small patient allows a greater gantry tilt to

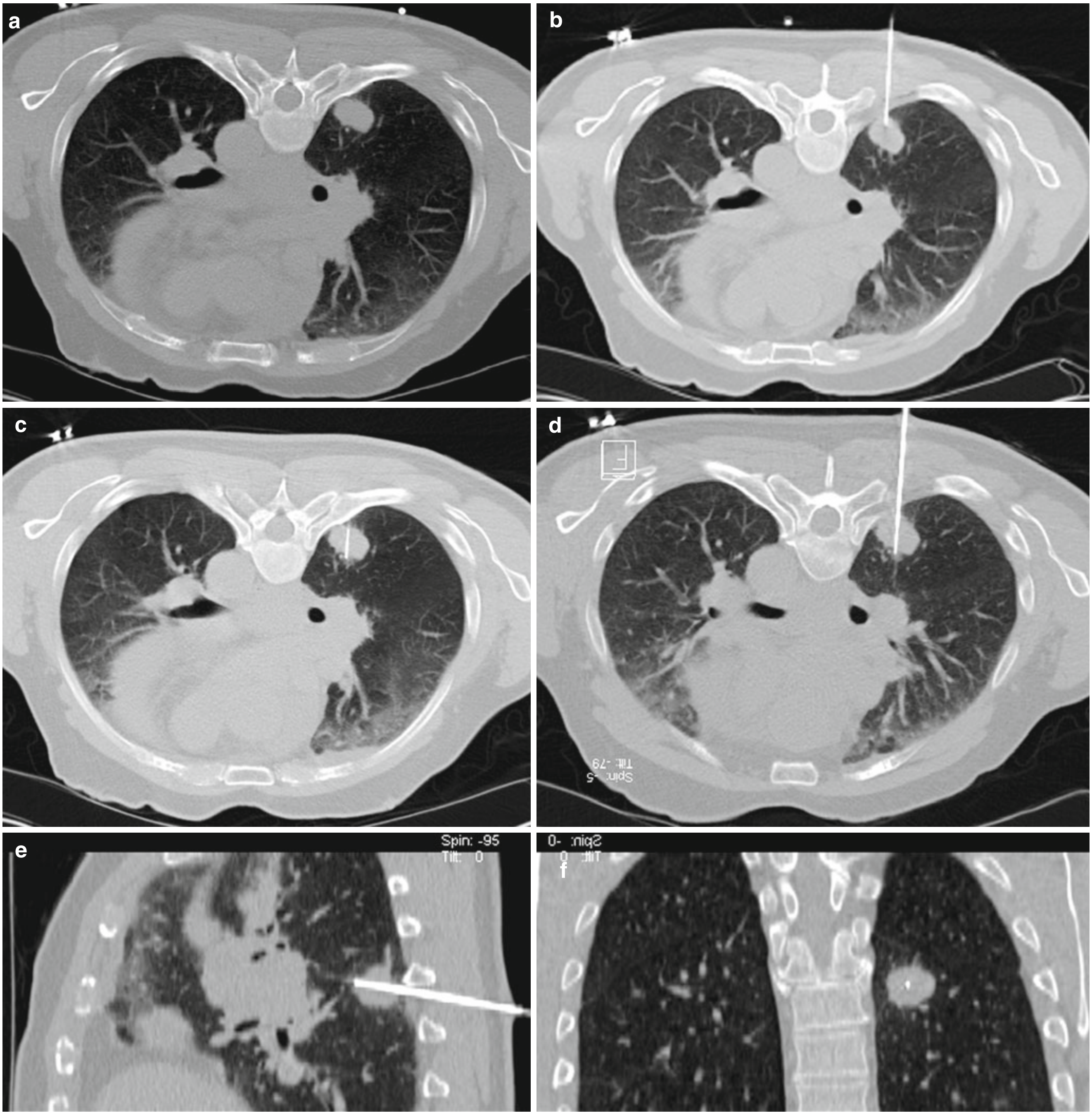

Fig. 2.8 A 57-year-old man with newly diagnosed right lung mass was referred for biopsy. Axial CT image of the chest in prone position (**a**) shows the right lung mass. Overlying rib and costovertebral joint limit access to the lesion in a true axial plane. The gantry was tilted 10° caudo-cranial. Axial-oblique CT fluoroscopy image of the chest (**b**) demonstrates entire length of the needle extending to the posterior border of the tumor. True axial CT image of the chest (**c**) shows only the tip of the needle within the lesion. Multiplanar reformatted images demonstrate entire length of the needle in axial-oblique (**d**) and sagittal-oblique (**e**) planes. A coronal reconstructed image of the patient in prone position (**f**) shows the tip of the needle within the center of the mass

be created. This angled-gantry approach may help overlying ribs to be avoided when performing biopsy of small pleural-based intrathoracic lesions. Another common scenario is avoidance of the lung base while targeting upper pole renal tumors or adrenal tumors [25].

"Salinoma" Creation and Organ Displacement

"Salinoma" refers to an iatrogenic fluid collection that is intentionally created to allow safe passage of a biopsy needle without traversing vital structures (Fig. 2.11). Injection of saline or CO_2 can help displace bowel or bladder to create a

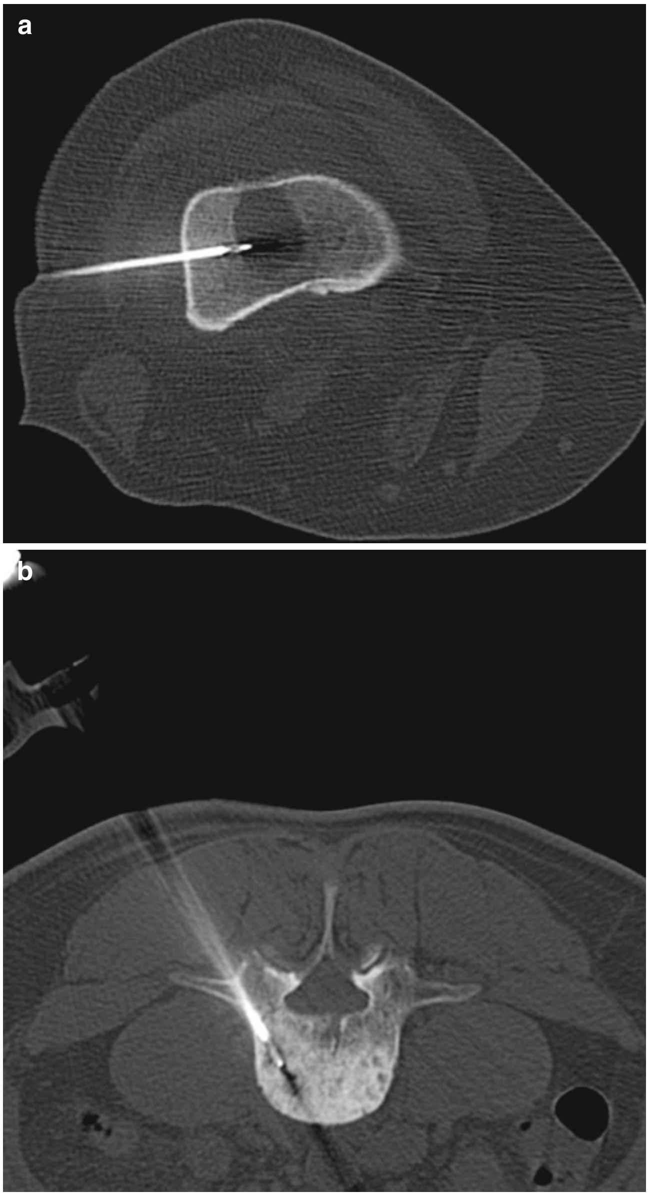

Fig. 2.9 Both lytic (**a**) and sclerotic (**b**) bone lesions can be visualized and targeted for biopsy. Biopsy of the lytic lesion in the distal right femur (**a**) showed metastatic cervical cancer. Biopsy of a sclerotic lumbar vertebral body tumor (**b**) showed metastatic neuroendocrine carcinoma

safe approach to a lesion [27–29], and injection of saline can help widen existing narrow spaces [30, 31]. Paravertebral or paramediastinal spaces can be artificially widened by injection of saline to allow safe placement of a biopsy needle without puncturing the visceral pleura.

Breath-Hold Monitoring and Feedback

Respiratory motion poses a problem in targeting small lesion in the lower thorax and upper abdomen [32]; however, breathing instructions may help avoid this problem in compliant patients [33]. Respiratory gating and breath-hold monitoring and feedback systems have been developed to synchronize intermittent CTF imaging with specific phases of respiration [32, 34, 35]. One such system monitors changes in body-wall girth and provides immediate feedback to patients so that they can adjust their breath-hold levels accordingly [34]. All of these strategies require some degree of patient training and cooperation and are less reliable in sedated patients.

Image Fusion with Positron Emission Tomography (PET)-CT

All cross-sectional modalities, including CT, provide excellent anatomical information about the extent of disease, but they have limited capability in differentiating viable from nonviable tissues. Sampling of nonviable regions within the tumor may lead to false-negative results and delay therapy. Functional imaging with PET using 2-fluoro-2-deoxy-D-glucose (FDG) relies on differences in the metabolic activity of different tissues and allows for more reliable detection of viable tumor tissue [36]. The limited anatomic information provided by PET can be overcome by fusing functional PET data with morphologic CT data; this fusing of PET and CT data is possible with dual modality PET-CT imaging systems [37, 38]. Similarly, PET can be used in patients with multiple lesions to identify the lesions with the highest FDG uptake for sampling. Frequently, a simple review of previously acquired PET-CT images provides sufficient information for CT-guided biopsies based on morphologic findings or anatomic landmarks (Fig. 2.12). In more subtle cases such as smaller targets, previously acquired PET-CT images can be coregistered with intraprocedural CT scans to guide the biopsy [39]. Other investigators have demonstrated the feasibility of PET-CT-guided interventions, taking advantage of PET imaging and CT-guided navigation in the same setting [40]. In very subtle cases, this combination allows for detection of metabolically active lesions and for placement of the needle at the same time.

Methods of Reducing Radiation Exposure from CTF

Several strategies have been developed to make CTF safer by lowering radiation exposure to the operator and patient [5–9, 11]. Dedicated needle holders have been developed to keep the operator's hands away from the primary CT beam [22]. The use of a needle holder is associated with the loss of tactile feedback, resulting in reduced control over the needle, difficulty with needle advancement through resistant tissue planes, artifacts from some metallic needle holders, difficulty in keeping the needle in the scan plane, and a tendency for thin needles to bend during insertion.

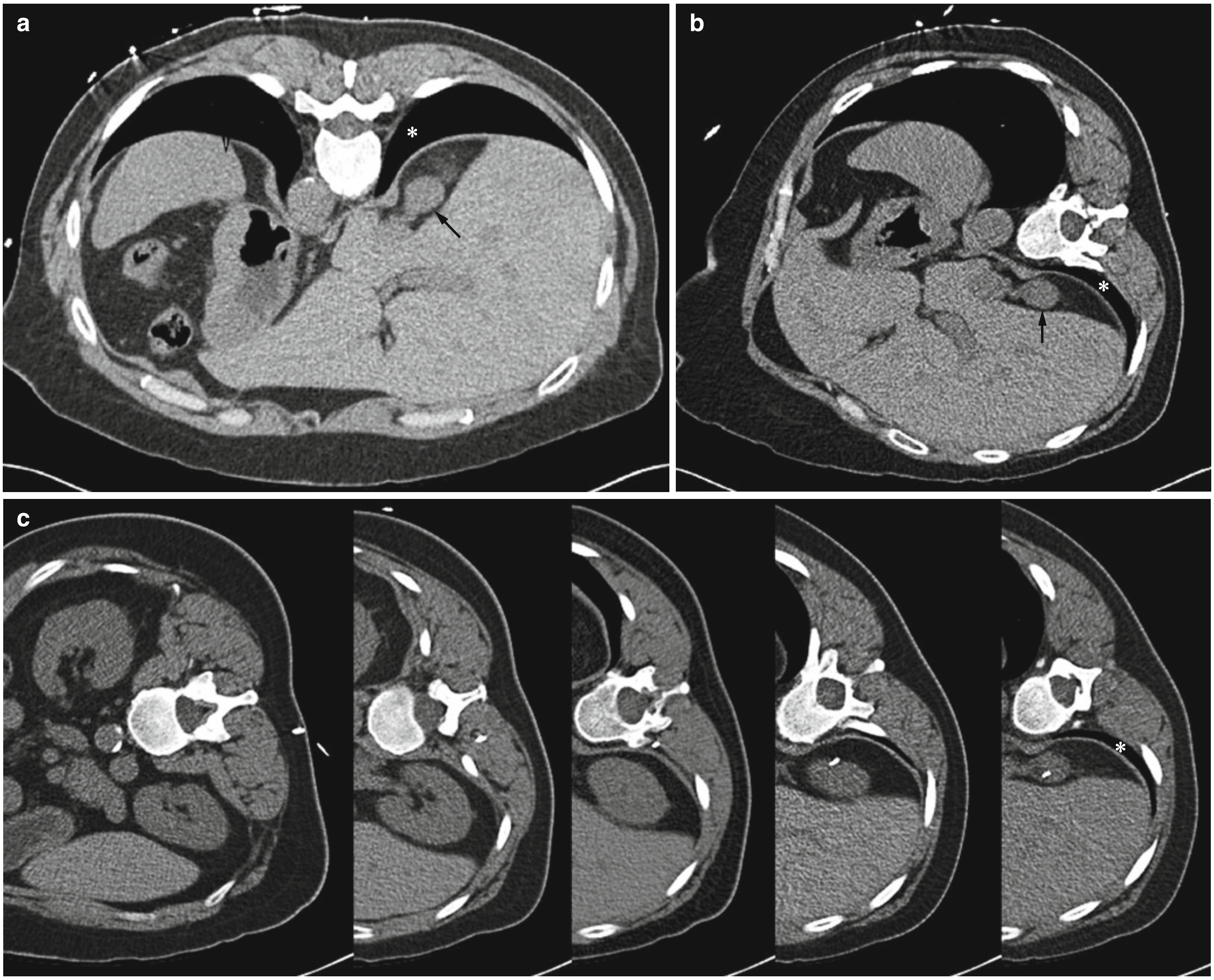

Fig. 2.10 A 56-year-old woman with history of melanoma was referred for a biopsy of right adrenal gland. Axial CT image of the abdomen in prone position (**a**) shows the adrenal mass (*arrow*). Intervening lung parenchyma (*asterisk*) precludes safe needle insertion in this position. Often placing the patient in the ipsilateral decubitus position helps decrease the lung volume and provides a safe path for needle. In this case, axial CT image of the abdomen in right lateral decubitus (**b**) still shows the intervening lung (*asterisk*). A needle insertion site was selected approximately 9 cm inferior to the lesion. Multiple axial images (**c**) show the path of the needle extending cephalad and avoiding the lung base (*asterisk*)

Imaging techniques have been modified using lower tube potential and current and thinner slices. Placement of a lead drape next to the imaging plane helps reduce scatter radiation. Finally, using "quick-check" CTF intermittently between needle advancements instead of continuously during the entire biopsy has been shown to reduce radiation exposure to well within acceptable limits [11, 41].

In summary, CT is well suited to guide percutaneous biopsies. It is widely available, and its high spatial and contrast resolution help detect the targets easily. Although most CT-guided biopsies are performed without the need for administration of intravenous contrast medium, review of a contrast-enhanced diagnostic CT scan is essential for planning a safe and effective biopsy procedure. At times, intravenous contrast medium can be administered immediately prior to the biopsy to help localize the lesion, but the resulting enhancement is often short lived. The learning curve is short, but mastering the art of CT-guided biopsy to target small, mobile, or difficult to reach lesions and to obtain viable and adequate samples requires attention to details, use of various ancillary techniques, and practice.

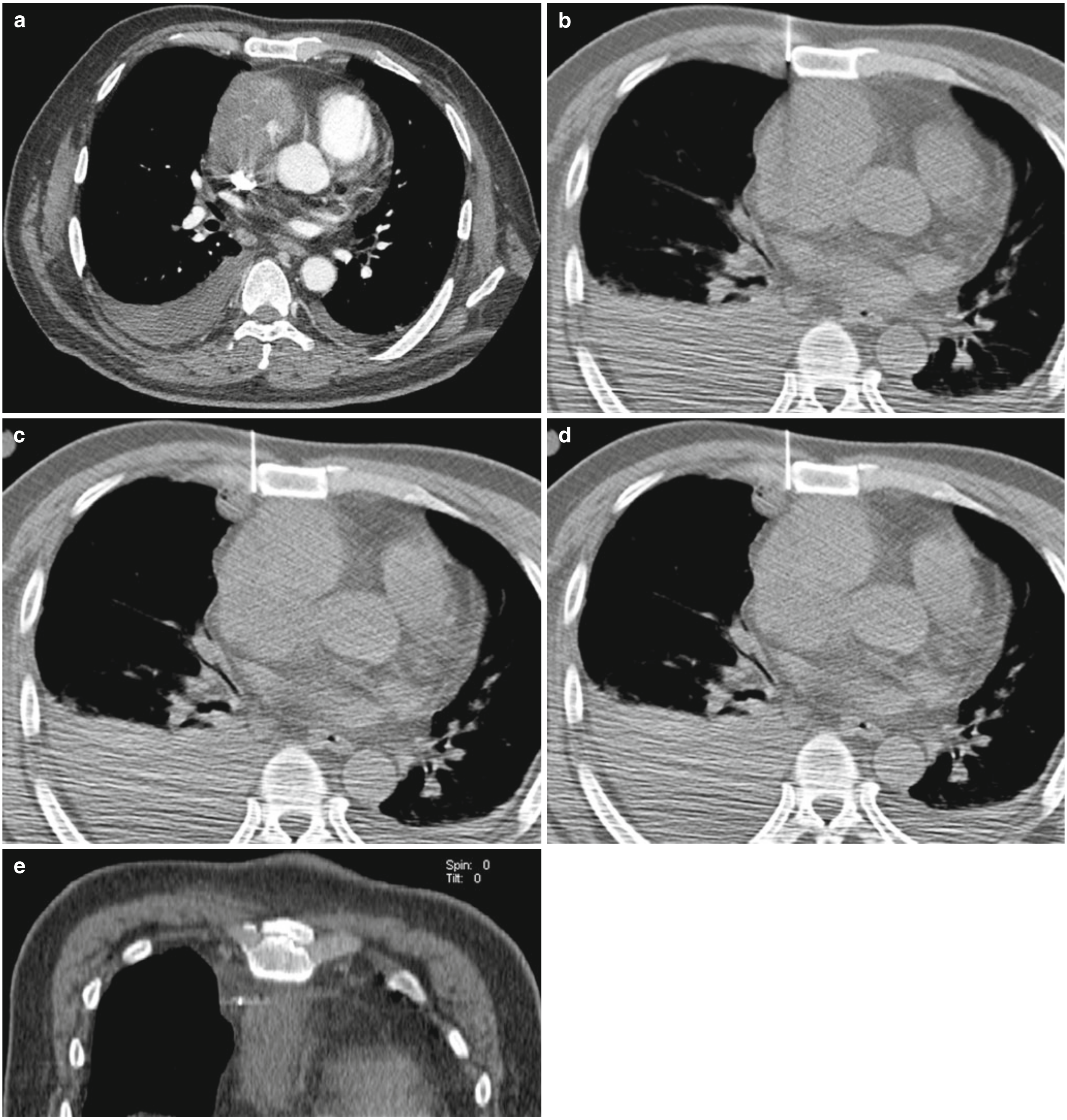

Fig. 2.11 A 53-year-old man was referred for biopsy of a mediastinal mass (**a**). Axial CT image of the chest shows the path of the biopsy needle traversing the pleura (**b**). After injection of 10 mL of saline (**c**), the mediastinal window was widened to advance the needle without traversing the pleura (**d**). A coronal reformatted image shows the lung displaced laterally and the needle traversing the "salinoma" (**e**)

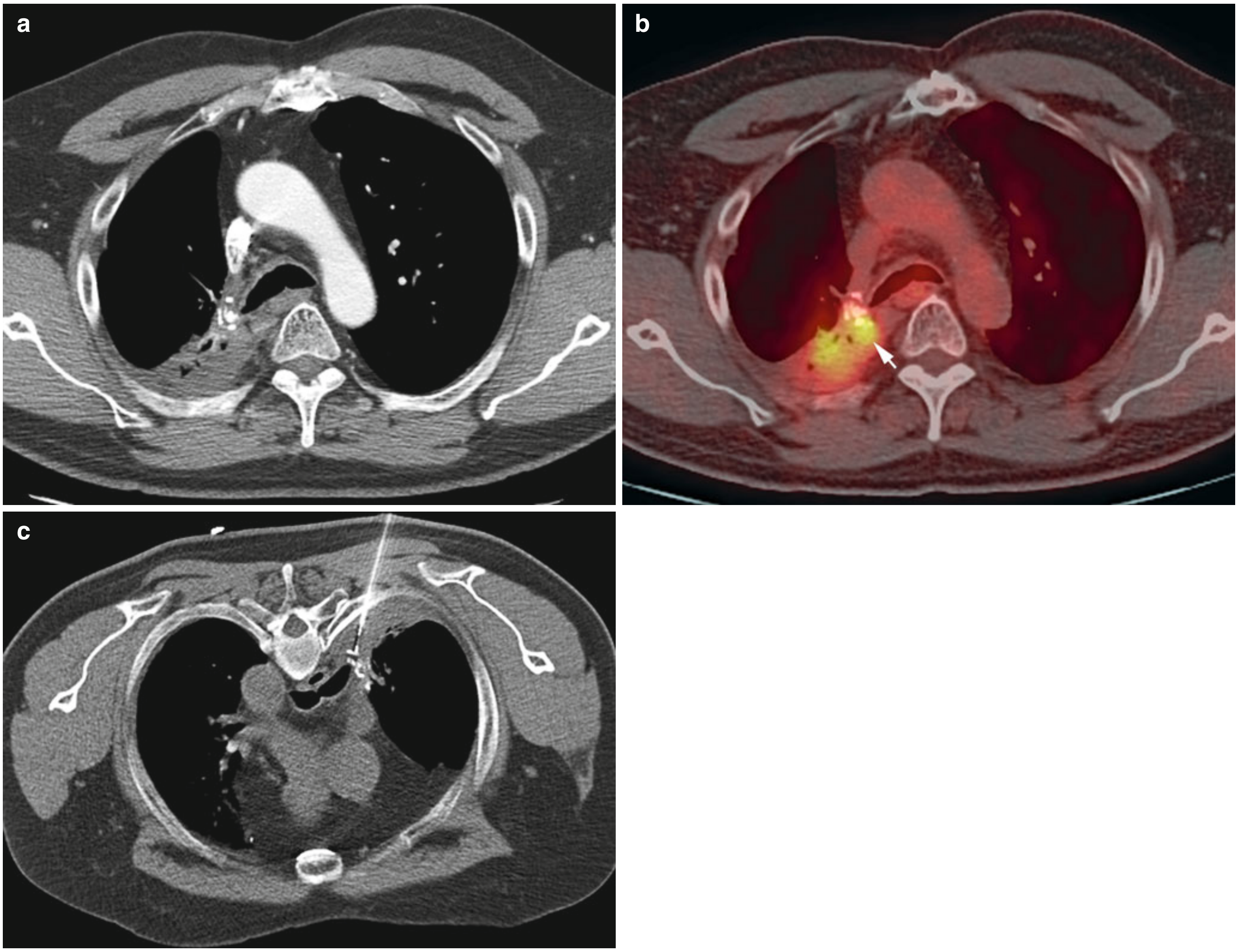

Fig. 2.12 A 72-year-old man with history of non-small cell lung cancer and right upper lobectomy underwent surveillance CT imaging. Axial CT image of the chest (**a**) shows a new soft tissue mass in the posterior aspect of the right chest. PET/CT image of the same area (**b**) shows a focal area of high metabolic activity (*arrow*). This particular spot was targeted for CT-guided biopsy based on anatomical and surgical landmarks (**c**). Pathology showed recurrent adenocarcinoma

References

1. Silverman SG, Bloom DA, Seltzer SE, Tempany CM, Adams DF. Needle-tip localization during CT-guided abdominal biopsy: comparison of conventional and spiral CT. Am J Roentgenol. 1992; 159:1095–7.
2. Katada K, Kato R, Anno H, Ogura Y, Koga S, Ida Y, et al. Guidance with real-time CT fluoroscopy: early clinical experience. Radiology. 1996;200:851–6.
3. Gupta S. Role of image-guided percutaneous needle biopsy in cancer staging. Semin Roentgenol. 2006;41:78–90.
4. Collins JM, Kriegshauser JS, Leslie KO. CT-guided biopsy of perivascular tumor encasement using simultaneous IV contrast enhancement. Am J Roentgenol. 2009;193:W283–7.
5. Kato R, Katada K, Anno H, Suzuki S, Ida Y, Koga S. Radiation dosimetry at CT fluoroscopy: physician's hand dose and development of needle holders. Radiology. 1996;201:576–8.
6. Paulson EK, Sheafor DH, Enterline DS, McAdams HP, Yoshizumi TT. CT fluoroscopy–guided interventional procedures: techniques and radiation dose to radiologists. Radiology. 2001;220:161–7.
7. Nawfel RD, Judy PF, Silverman SG, Hooton S, Tuncali K, Adams DF. Patient and personnel exposure during CT fluoroscopy-guided interventional procedures. Radiology. 2000;216:180–4.
8. Daly B, Templeton PA. Real-time CT fluoroscopy: evolution of an interventional tool. Radiology. 1999;211:309–15.
9. Froelich JJ, Wagner HJ. CT-fluoroscopy: tool or gimmick? Cardiovasc Intervent Radiol. 2001;24:297–305.
10. Nishizawa K, Uruma T, Takiguchi Y, Kuriyama T, Yanagawa N, Matsumoto M, et al. Dose evaluation and effective dose estimation from CT fluoroscopy-guided lung biopsy. Igaku Butsuri. 2001; 21:233–44.
11. Irie T, Kajitani M, Yoshioka H, Matsueda K, Inaba Y, Arai Y, et al. CT fluoroscopy for lung nodule biopsy: a new device for needle placement and a phantom study. J Vasc Interv Radiol. 2000; 11:359–64.
12. de Mey J, Op de Beeck B, Meysman M, Noppen M, De Maeseneer M, Vanhoey M, et al. Real time CT-fluoroscopy: diagnostic and therapeutic applications. Eur J Radiol. 2000;34:32–40.
13. Froelich JJ, Ishaque N, Regn J, Saar B, Walthers EM, Klose KJ. Guidance of percutaneous pulmonary biopsies with real-time CT fluoroscopy. Eur J Radiol. 2002;42:74–9.

14. Kirchner J, Kickuth R, Laufer U, Schilling EM, Adams S, Liermann D. CT fluoroscopy-assisted puncture of thoracic and abdominal masses: a randomized trial. Clin Radiol. 2002;57:188–92.
15. Muehlstaedt M, Bruening R, Diebold J, Mueller A, Helmberger T, Reiser M. CT/fluoroscopy-guided transthoracic needle biopsy: sensitivity and complication rate in 98 procedures. J Comput Assist Tomogr. 2002;26:191–6.
16. White CS, Meyer CA, Templeton PA. CT fluoroscopy for thoracic interventional procedures. Radiol Clin North Am. 2000;38: 303–22, viii.
17. Gianfelice D, Lepanto L, Perreault P, Chartrand-Lefebvre C, Milette PC. Value of CT fluoroscopy for percutaneous biopsy procedures. J Vasc Interv Radiol. 2000;11:879–84.
18. Silverman SG, Tuncali K, Adams DF, Nawfel RD, Zou KH, Judy PF. CT fluoroscopy-guided abdominal interventions: techniques, results, and radiation exposure. Radiology. 1999;212:673–81.
19. Liermann D, Kickuth R. CT fluoroscopy-guided abdominal interventions. Abdom Imaging. 2003;28:129–34.
20. Schweiger GD, Brown BP, Pelsang RE, Dhadha RS, Barloon TJ, Wang G. CT fluoroscopy: technique and utility in guiding biopsies of transiently enhancing hepatic masses. Abdom Imaging. 2000;25:81–5.
21. Schweiger GD, Yip VY, Brown BP. CT fluoroscopic guidance for percutaneous needle placement into abdominopelvic lesions with difficult access routes. Abdom Imaging. 2000;25:633–7.
22. Daly B, Templeton PA, Krebs TL, Carroll K, Wong-You-Cheong JJ. Evaluation of biopsy needles and prototypic needle guide devices for percutaneous biopsy with CT fluoroscopic guidance in simulated organ tissue. Radiology. 1998;209:850–5.
23. Kim GR, Hur J, Lee SM, Lee HJ, Hong YJ, Nam JE, et al. CT fluoroscopy-guided lung biopsy versus conventional CT-guided lung biopsy: a prospective controlled study to assess radiation doses and diagnostic performance. Eur Radiol. 2011;21:232–9.
24. vanSonnenberg E, Lin AS, Casola G, Nakamoto SK, Wing VW, Cubberly DA. Removable hub needle system for coaxial biopsy of small and difficult lesions. Radiology. 1984;152:226.
25. Hussain S. Gantry angulation in CT-guided percutaneous adrenal biopsy. Am J Roentgenol. 1996;166:537–9.
26. Yueh N, Halvorsen Jr RA, Letourneau JG, Crass JR. Gantry tilt technique for CT-guided biopsy and drainage. J Comput Assist Tomogr. 1989;13:182–4.
27. Haaga JR, Beale SM. Use of CO_2 to move structures as an aid to percutaneous procedures. Radiology. 1986;161:829–30.
28. Langen HJ, Jochims M, Gunther RW. Artificial displacement of kidneys, spleen, and colon by injection of physiologic saline and CO_2 as an aid to percutaneous procedures: experimental results. J Vasc Interv Radiol. 1995;6:411–16.
29. Langen HJ, Klose KC, Keulers P, Adam G, Jochims M, Gunther RW. Artificial widening of the mediastinum to gain access for extrapleural biopsy: clinical results. Radiology. 1995;196:703–6.
30. Carlson P, Crummy AB, Wojtowycz M, McDermott JC. A safe route for deep pelvic biopsy with distention of the iliacus muscle. J Vasc Interv Radiol. 1991;2:277–8.
31. Karampekios S, Hatjidakis AA, Drositis J, Gourtsoyiannis N. Artificial paravertebral widening for percutaneous CT-guided adrenal biopsy. J Comput Assist Tomogr. 1998;22:308–10.
32. Carlson SK, Felmlee JP, Bender CE, Ehman RL, Classic KL, Hoskin TL, et al. CT fluoroscopy-guided biopsy of the lung or upper abdomen with a breath-hold monitoring and feedback system: a prospective randomized controlled clinical trial. Radiology. 2005;237:701–8.
33. Schaefer PJ, Schaefer FK, Heller M, Jahnke T. CT fluoroscopy guided biopsy of small pulmonary and upper abdominal lesions: efficacy with a modified breathing technique. J Vasc Interv Radiol. 2007;18:1241–8.
34. Carlson SK, Felmlee JP, Bender CE, Ehman RL, Classic KL, Hu HH, et al. Intermittent-mode CT fluoroscopy-guided biopsy of the lung or upper abdomen with breath-hold monitoring and feedback: system development and feasibility. Radiology. 2003;229:906–12.
35. Tomiyama N, Mihara N, Maeda M, Johkoh T, Kozuka T, Honda O, et al. CT-guided needle biopsy of small pulmonary nodules: value of respiratory gating. Radiology. 2000;217:907–10.
36. Reading CC, Charboneau JW, James EM, Hurt MR. Sonographically guided percutaneous biopsy of small (3 cm or less) masses. Am J Roentgenol. 1988;151:189–92.
37. Aquino SL, Asmuth JC, Alpert NM, Halpern EF, Fischman AJ. Improved radiologic staging of lung cancer with 2-[18 F]-fluoro-2-deoxy-D-glucose-positron emission tomography and computed tomography registration. J Comput Assist Tomogr. 2003;27:479–84.
38. Schwartz DL, Ford E, Rajendran J, Yueh B, Coltrera MD, Virgin J, et al. FDG-PET/CT imaging for preradiotherapy staging of head-and-neck squamous cell carcinoma. Int J Radiat Oncol Biol Phys. 2005;61:129–36.
39. Tatli S, Gerbaudo VH, Mamede M, Tuncali K, Shyn PB, Silverman SG. Abdominal masses sampled at PET/CT-guided percutaneous biopsy: initial experience with registration of prior PET/CT images. Radiology. 2010;256:305–11.
40. Klaeser B, Mueller MD, Schmid RA, Guevara C, Krause T, Wiskirchen J. PET-CT-guided interventions in the management of FDG-positive lesions in patients suffering from solid malignancies: initial experiences. Eur Radiol. 2009;19:1780–5.
41. Carlson SK, Bender CE, Classic KL, Zink FE, Quam JP, Ward EM, et al. Benefits and safety of CT fluoroscopy in interventional radiologic procedures. Radiology. 2001;219:515–20.