7 Advanced Tools and Devices: Navigation Technologies, Automation, and Robotics in Percutaneous Interventions

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Introduction

The development and maturation of percutaneous image-guided biopsy techniques over the past three decades has enabled these procedures to supplant open surgical biopsy for a variety of anatomic sites. However, at present conventional techniques have limitations in the amount of pre-biopsy imaging data that may be taken into the interventional suite for real-time guidance [1]. Typically, the optimal use of three-dimensional imaging information is limited by the operator's own mental approximations of needle and target location derived from two-dimensional imaging data [1]. Currently, many minimally invasive biopsies are performed in the CT suite [1]. However, these procedures often require significant CT scanner time (and measurable radiation), are limited to only axial images, and do not directly link images to the needle to enable real-time guidance during insertion and repositioning [1].

Novel tools and devices, including navigation platforms, advanced image-processing software, and robotic needle guidance, have the potential to enable or further enhance the accuracy of percutaneous image-guided biopsy. In certain cases such as PET-guided biopsy, procedures may not have been able to be performed at all without these novel technologies. Navigation and guidance systems have been deployed clinically but primarily in the setting of radiation therapy, brachytherapy, and open surgery such as neurosurgery, orthopedics, or otolaryngology [2]. Minimally invasive image-guided biopsy and tumor ablation procedures have become integral interventions, particularly in the care of the oncology patient. Thus, there is an ongoing need for ever more sophisticated methods of successful targeting of technically challenging or otherwise subtle lesions [3]. Novel navigation platforms facilitating these image-guided interventions offer several advantages. Navigation platforms enable real-time referencing of tracked devices throughout an intervention, as opposed to only intermittent displays of needle angle and position during conventional CT-guided biopsy. Novel image-processing algorithms enable displays of multiplanar, multimodality co-registered imaging data that can offer the interventional radiologist real-time imaging data about multiple modalities (e.g., ultrasound, CT, MRI, PET) simultaneously during a biopsy. Robotic needle guidance may potentially reduce inter-operator variability and procedure time. Use of these technologies has the potential to not only simplify complex spatial relationships for the interventional radiologist but potentially improve lesion targeting and patient care. Tissue characterization via advanced biopsy techniques has the potential to facilitate drug discovery, by enabling assessment of up- or downregulation of biomarker targets, susceptibility to specific pharmacologic regimens, and risk of toxicities based upon genetic variation in drug metabolism. Biopsy guided by metabolic and functional imaging could transform the minimally invasive characterization of human disease, which is of increasing importance as the "personalization" of medical care permeates oncology. Biopsy navigation is anticipated to play an increasingly important role in the evolution of cancer therapies in the future.

Technical Considerations

The use of novel navigation platforms, image-processing algorithms, and medical robots necessitates knowledge of a basic lexicon of key terms, when using these advanced tools

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Table 7.1 Glossary of key terms relevant to device tracking, image fusion, and robotics [4–8]

Term	Definition
Medical global positioning system (GPS)	Localization of a device or image in relation to prior pre-procedural imaging. The electromagnetic field generator is the "satellite" and the needle tip is the "car"
Multimodality or image fusion	Overlapping visual display of multiple imaging modalities during a percutaneous biopsy
Electromagnetic tracking	Mechanism to locate a needle (or ultrasound plane) within a 3D volume of imaging data (like CT, MR, or PET) or to locate a 2D ultrasound plane within a 3D volume
Tracking error/target to registration Error (TRE)	Difference between the real and virtual needle positions. How accurate is the location of the "virtual needle" as displayed on the images?
Registration error (root mean square/RMS)	How well two sets of imaging data or selected anatomic points on each of two imaging modalities match up (ideally <2 mm)
Placement error	How close the needle is placed to the target point
Dynamic reference	Patch or sensor placed on patient that corrects for patient or generator motion. Without this, patient must remain in exact position throughout body intervention
Registration	Matches two (or more) sets of imaging data, or matches image space to "magnetic space"
Rigid registration	Matches two (or more) sets of imaging data based upon fixed anatomic landmarks; it does not, on its own, account for organ shift or tissue deformation between image sets or during the procedure
Deformable/elastic registration	Matches two (or more) sets of imaging data based upon common anatomic landmarks but can deform/warp image sets to account for organ shift or deformation between different images or due to imaging at different times
Medical robot	Mechanical manipulator connected by joints that allow relative motion from one link to another
Robotic arm	Part of the robot that orients the end effectors and/or sensors
End effector	Any attachment on the end of a robot that interacts with the environment, such as a device to lift and position a needle; the robotic "hand" at the end of the robot arm
Degrees of freedom	Axes of movement; reflect the flexibility of an instrument (robot) to achieve positions and orientations. Six degrees of freedom are required for a robotic device to reach, position, and orient an instrument at any point in space. The seventh degree of freedom is inherent to the procedure itself (e.g., cutting, grasping)

and devices. Table 7.1 summarizes some definitions relevant to body interventions employing device tracking, image fusion, and robotic assistance.

Device Tracking

The primary methods for real-time device tracking include electromagnetic tracking and optical tracking. Electromagnetic (EM) and optical tracking are standard techniques used to register devices to preoperative images during neurosurgery and orthopedic surgery, but these technologies have not been widely applied in interventional radiology [3]. Medical devices like needles, catheters, and guidewires may be tracked via placement of minute electromagnetic sensor coils within their tips (PercuNav Image Fusion and Instrument Navigation, Philips Healthcare, Cleveland, Ohio). Tracking of these sensor coils provides spatial information on internal device location in real time during a biopsy, relative to preoperative imaging anatomy (CT, MR, PET). This tracking is analogous to a miniaturized global positioning system (GPS) [3, 9]. The minute size of EM sensor coils allows localization and tracking of internalized medical devices; at present, these can be fitted within coaxial biopsy introducers, stylets, and hollow cannulas as small in diameter as 22 gauge [3]. Optical and infrared tracking of devices requires either optical or infrared cameras, which require direct line of sight that is less practical in the setting of image-guided biopsy [9]. Electromagnetic tracking requires a small EM field generator and software to detect and display the tracked devices (Fig. 7.1). Registration between tracking space and image space may be performed by using reference markers attached to the skin near the planned needle entry point ("fiducials"). These may be either passive fiducial markers or actively tracked fiducials (or patches) with sensors integrated directly inside the fiducial. After identifying the fiducials on intraprocedural CT, the corresponding tracking coordinates may be obtained automatically (or alternatively by pointing the tracked needle to each of the fiducials during the breath hold and averaging the tracking signal for several seconds until a stable reading is obtained). A rigid registration transformation between tracking coordinates and CT image coordinates is computed, and the root-mean-square distance (fiducial registration error) between the CT image coordinates of the fiducials and the transformed tracking coordinates of the fiducials is displayed. The registration with the lowest fiducial registration error is used, typically with a fiducial registration error (FRE) smaller than 2 mm. Sensor coil placement upon an ultrasound probe can also enable tracking of the US transducer. Correction for the moving liver may be attempted with tracking of the hepatic biopsy needle itself or other gating methods. The interventional radiologist is essentially provided with a road map to facilitate needle placement and repositioning, by having information about biopsy needle

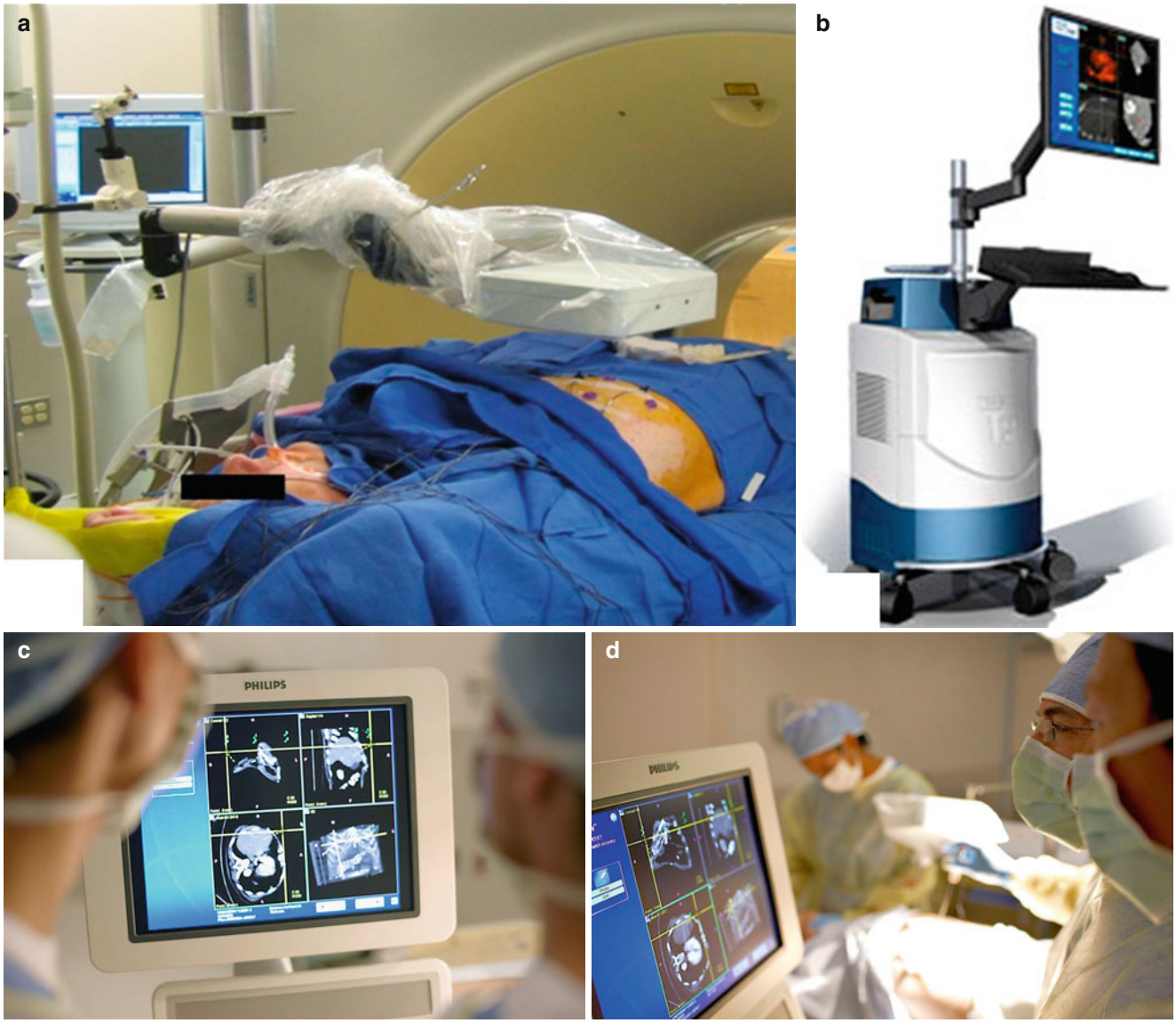


Fig. 7.1 Components for electromagnetic needle tracking during percutaneous biopsy. (**a**) An electromagnetic field generator, sterilely draped, is placed near the working space, directed toward the target and path of needle entry to facilitate image co-registration and device tracking. (**b**) Navigation workstation that enables display of co-registered images and tracked needle during biopsy (PercuNav Image Fusion and Instrument Navigation, Philips Healthcare, Cleveland, Ohio). (**c**) Custom software with display of tracked needle superimposed on multiplanar CT images co-registered to real-time ultrasound. (**d**) Use of needle tracking and multimodality image display facilitates percutaneous biopsy (Image **a** reprinted with permission from Venkatesan et al. [10], Radiological Society of North America (RSNA). Images **b**–**d** reprinted with permission from Philips Healthcare, Cleveland, Ohio)

location, referenced within pre-procedural imaging. Use of this technology has the potential to be superior to the use of conventional biopsy technique, particularly for lesions whose intra-procedural visualization is suboptimal relative to pre-acquired images, e.g., tumors that are only briefly seen during arterial-phase CT (Fig. 7.2).

Early clinical trials suggest good spatial accuracy and feasibility of electromagnetic needle tracking. Kruecker et al. evaluated the spatial accuracy of electromagnetic needle tracking and demonstrated the feasibility of US to CT fusion during CT- and US-guided biopsy and radiofrequency ablation (RFA) procedures, performing a 20-patient clinical trial to investigate electromagnetic needle tracking during interventional procedures [11]. Eight patients underwent RFA; the remainder underwent needle biopsy of sites in the liver, kidney, lung, chest wall, and retroperitoneum [11]. Needles were positioned by using CT and US guidance, and an electromagnetic tracking system was used consisting of internally tracked needles and software to record needle positions relative to previously obtained CT scans (Philips Healthcare,

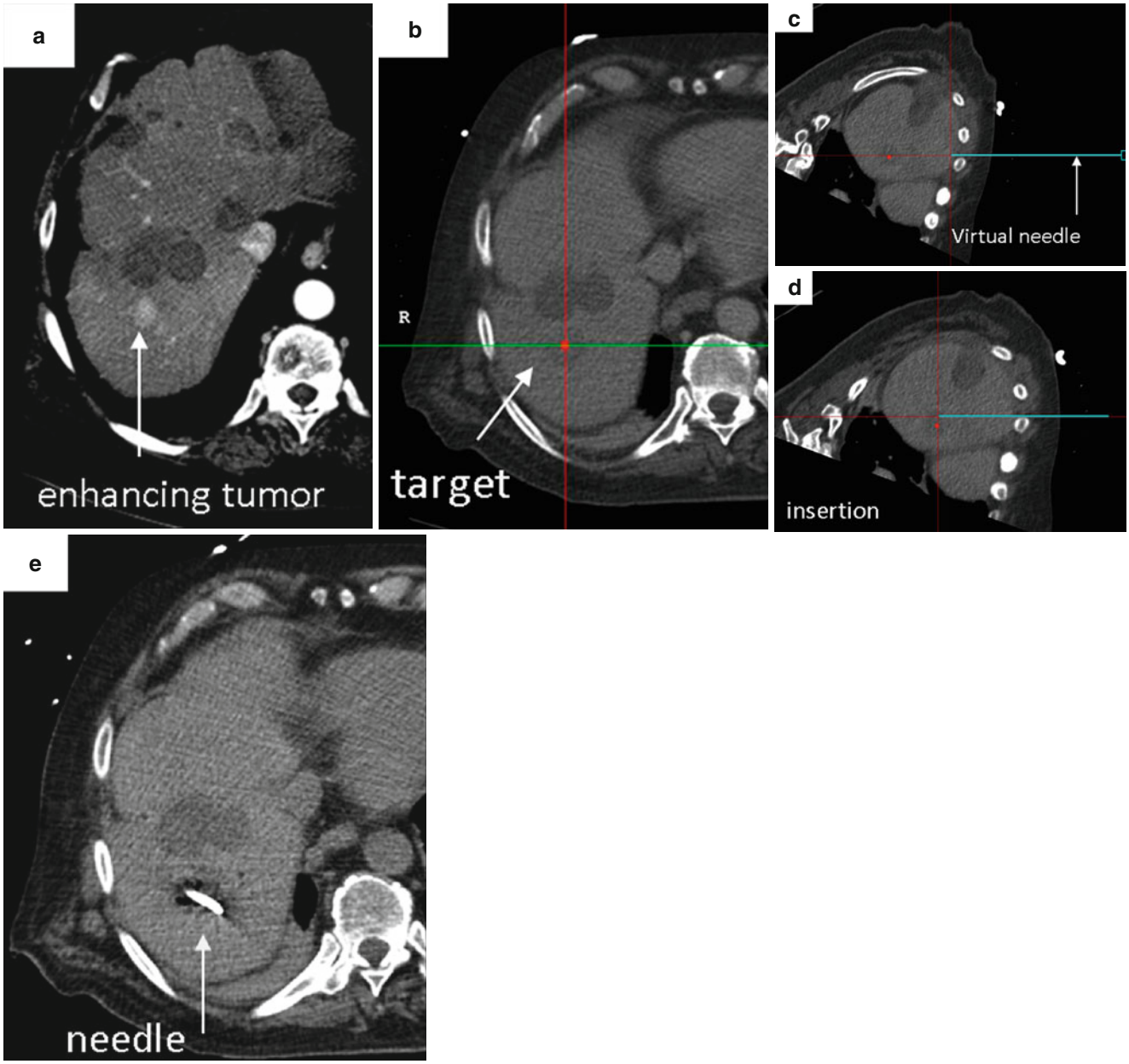


Fig. 7.2 Representative case using image fusion and needle tracking to facilitate percutaneous biopsy. (**a**) Pre-procedural imaging demonstrates the target, a briefly apparent 1 cm arterially enhancing lesion that was not well seen on non-contrast CT, venous phase CT or ultrasound. (**b**) Intra-procedural CT with selected location of target highlighted as a *red dot* on the navigation workstation. The location and orientation of the tracked needle is displayed as a *blue* "virtual needle." (**c** and **d**) Serial images demonstrate location and position of tracked needle relative to target during needle insertion. (**e**) Intra-procedural CT confirms needle tip within location of target. Percutaneous biopsy of this small (1 cm) nodule yielded a diagnosis of hepatocellular carcinoma (Reprinted with permission from Wood et al. [8])

Cleveland, Ohio, formerly Traxtal, Inc., Toronto, CA and Philips Research, Briarcliff, NY) [11]. The electromagnetic field generator was mounted on an articulated mechanical arm, which was attached to a stereotactic frame connected to the CT gantry or simply mounted on a nearby structure such as the ultrasound itself or table [11]. Position tracking data were acquired to evaluate the tracking error [11]. Registration between tracking space and image space was obtained by using reference fiducial markers (or patches) attached to the skin [11]. The US transducer was tracked to demonstrate real-time US-CT fusion for imaging guidance, where the needle is displayed on the ultrasound as well as the pre-procedural CT image [11]. The basic tracking error was 3.5 mm ± 1.9 with use of nonrigid registrations that used previous internal needle positions as additional fiducials reference markers and more recently was found to be 2.7 ± 1.6 mm in a more recent

35-patient study [11, 12]. Fusion of tracked US with CT was successful; patient motion and distortion of the tracking system by the CT table and gantry were identified as sources of error [11]. The spatial tracking accuracy of this system was sufficient to display clinically relevant pre-procedural imaging information during needle-based procedures. Particular benefit was noted for virtual needles displayed within pre-procedural images of transiently apparent targets, such as arterial-phase enhancing liver lesions, or during thermal ablations when obscuring gas is released [11].

Santos et al. evaluated an electromagnetic (EM) navigation system (Veran Medical Technologies Inc, St. Louis, MO) to assess its potential to reduce the number of skin punctures and instrument adjustments during CT-guided percutaneous ablation and biopsy of small (<2 cm) lung nodules [12]. Nineteen EM interventions were performed, including 6 biopsies, 9 radiofrequency ablations (RFAs), 1 combined biopsy with an RFA, and 3 microwave ablations [12]. Median nodule diameter was 1.95 cm (range, 1.2–2.4 cm), and median distance from the skin to lesion was 7.6 cm (2–18 cm) [12]. When an EM-guided biopsy was performed, the intervention was done immediately prior to ablation. For all 19 EM interventions, only one skin puncture was required. The mean number of instrument adjustments required was 1.2 (range, 0–2) [12]. The mean time for each EM intervention was 5.2 min (range, 1–20 min) [12]. Pneumothorax occurred in five patients (50 %), with only the number of instrument adjustments being significantly related to the pneumothorax rate ($p \leq 0.005$) [12]. The authors concluded that the EM navigation is feasible and a useful aid for image-guided biopsy and ablation of small pulmonary tumors [12]. Their experience suggests the EM navigation system might require fewer skin punctures and instrument adjustments for lung biopsies than using CT fluoroscopy guidance alone [12].

The use of fusion-guided biopsy and ablation has demonstrated improvement over conventional CT and US guidance in terms of improved angle selection compared to conventional technique. Kruecker et al. reported that the addition of needle and ultrasound tracking improved needle path "off-target error" from 17.8 ± 17.1 mm to 3.3 ± 3.1 mm and changed insertion angle by 13.3° ± 6.5°. This added accuracy has the potential to translate into improved outcomes, particularly for biopsy or ablation of occult targets, where targeting accuracy is crucial [13].

A recent clinical study has evaluated this potential, by assessing the feasibility of combined electromagnetic device tracking and computed tomography (CT)/ultrasonography (US)/fluorine-18 fluorodeoxyglucose (FDG) positron-emission tomography (PET) fusion for real-time feedback during percutaneous and intraoperative biopsies and hepatic radiofrequency ablation [10]. Targets demonstrated heterogeneous FDG uptake or were not well seen or were totally inapparent at conventional imaging and were thus considered technically challenging or impossible to target using conventional imaging guidance [10]. In this study, pre-procedural FDG-PET scans were rigidly registered using a semiautomatic method to intra-procedural CT. Real-time US scans were registered through a fiducial-based method, allowing US scans to be fused with intra-procedural CT and pre-acquired FDG-PET scans. A visual display of US-CT image fusion with overlaid co-registered FDG-PET targets was used for guidance [10]. Navigation software enabled real-time biopsy needle and needle electrode navigation and feedback, employing coaxial biopsy needle introducer tips and RF ablation electrode guider needle tips containing electromagnetic sensor coils spatially tracked through an electromagnetic field generator [10]. Successful fusion of real-time US to co-registered CT and FDG-PET scans was achieved in all patients, with 31 of 36 biopsies being diagnostic and one case of RF ablation resulting in resolution of targeted FDG avidity, with no local treatment failure over a short follow-up period [10].

Additional Navigation Tools for Device Tracking

Additional tools facilitating needle tracking for percutaneous biopsy include mechanical devices, optical devices, and rotational CT-based tools. Mechanical devices include commercial needle stabilizers, which may be fixed to a patient's skin via adhesive and which contain a central needle guide, into which a biopsy needle may be inserted, with the initial biopsy needle angle selected by the operator being able to be "locked" into position within the stabilizer, enabling maintenance of the same needle angle throughout the process of needle insertion to the desired target. Commercial devices facilitating needle angle precision include the SeeStar (St. Jude Medical, formerly Radi Medical Systems, St. Paul, MI) and the Simplify (NeoRad, Oslo, Norway) (Fig. 7.3).

Optical tracking devices for percutaneous biopsy involve optical sensors which may be mounted on needles or probes that may be paired with custom software enabling multiplanar display of patient anatomy, including the location of the desired target in relation to the needle during needle insertion, thereby potentially minimizing the number of serial CT scans required to perform a biopsy, reducing procedure time and radiation dose. The CT-Guide® optical guidance system (approved for marketing in USA, China, Europe, Canada, and Israel) is one example of an optical guidance system for use in CT-guided needle procedures (ActiViews Ltd., Haifa, Israel). Components of this system include a disposable, miniature video camera that may be mounted on any commercial needle or probe, fiducial markers printed on a flexible adhesive pad, and a custom computer graphical user interface. The pre-procedural CT images with overlying

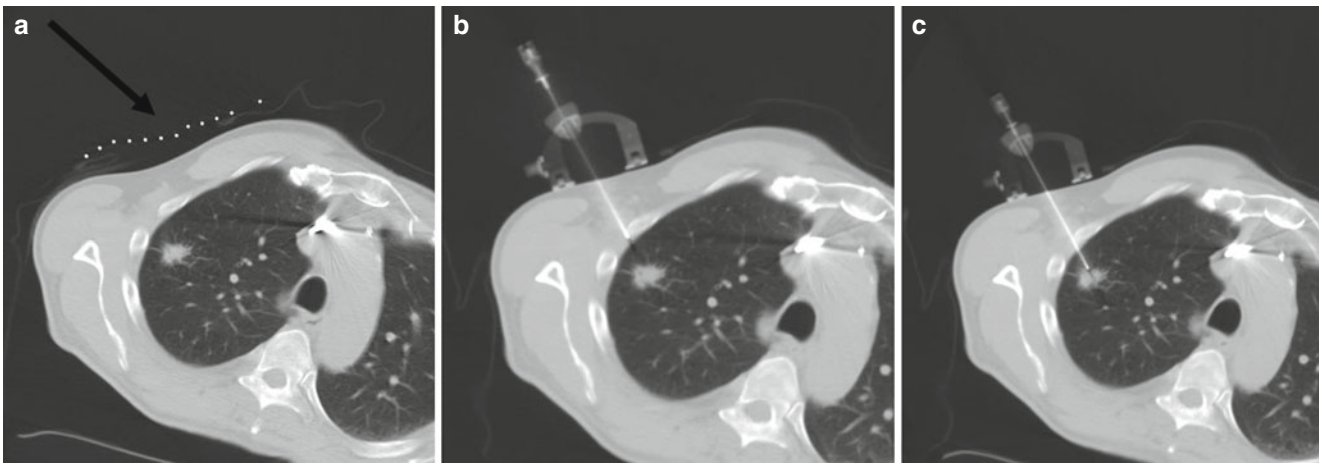


Fig. 7.3 Representative images during percutaneous lung biopsy using the Simplify (NeoRad, Oslo, Norway). (**a**) Grid placement and initial CT scan confirms right upper lobe lung nodule for biopsy. A grid is placed on the overlying skin to mark the target at the level of the skin (*black arrow*). (**b**) Simplify placed on the skin enables maintenance of initial needle angle throughout needle insertion. (**c**) Successful percutaneous needle biopsy of the targeted lesion

fiducial markers are imported into the custom planning software and used for target and angle selection and real-time guidance (see Fig. 7.4).

Rotational CT for navigation may be referred to by many terms, including cone-beam CT (CBCT), C-arm CT, cone-beam volume CT, angiographic CT, flat-panel CT, rotational angiography CT, rotational fluoro CT, and C-arm CBCT. These systems can function in at least two modes: conventional CT intermittent guidance and a fluoroscopy overlay tool that overlays the intended pathway over a live fluoroscopy image. In one iteration, a live triplanar needle guidance image tool creates overlays of live fluoroscopy with triplanar CT displays which provide information on planned needle path and target not available with the use of fluoroscopic guidance alone. Real-time advancement of needle may be performed based on a planned needle trajectory, with live feedback provided by intra-procedural rotational CT images. Advantages of rotational CT compared to multi-detector CT include the lack of requirement for a CT gantry and no need to transfer patients between CT and a fluoroscopy table, as well as lower radiation dose [14, 15]. Drawbacks include much smaller field of view, less control over parameters like mAs and kVp, higher scatter radiation, lower spatial and contrast resolution, and longer acquisition time [14]. Commercial examples of rotational CT navigation platforms include Xper Guide (Philips Healthcare, Best, Netherlands), the iGuide system (Siemens, Erlangen, Germany), and the InnovaCT (GE Healthcare, Waukesha, WI).

Early studies have described the feasibility of using CBCT for common interventions. Hirota et al. have reported the feasibility of employing CBCT angiography during abdominal interventions, including trans-arterial chemoembolization (TACE), splenic embolization, and implantation of intra-arterial port systems [15]. More recent investigations describe the potential for CBCT to facilitate technically challenging interventions, including successful biopsy of technically challenging FDG-PET avid targets [16]. The ability of CBCT to enable real-time, intra-procedural assessment of the effectiveness of TACE has also been described [17]. A recent study described the integration of CBCT with PET/CT for biopsy and ablation in seven patients, who underwent a total of two ablations and six biopsies without the need for additional specialized hardware [16]. Loffroy et al. describe the ability of intra-procedural dual-phase CBCT to predict tumor response at 1-month follow-up in 29 patients with 50 targeted hepatocellular carcinoma lesions undergoing TACE with doxorubicin-eluting beads, when compared against 1-month posttreatment MRI [17]. The decrease in tumor enhancement observed with dual-phase cone-beam CT after TACE showed a linear correlation with MR findings, assessed according to European Association for the Study of the Liver (EASL) guidelines. A significant relationship between tumor enhancement at cone-beam CT after TACE and complete and/or partial tumor response at MR imaging was found for both arterial (odds ratio, 0.95; 95 % confidence interval [CI], 0.91, 0.99; $p = .023$) and venous (odds ratio, 0.96; 95 % CI, 0.93, 0.99; $p = .035$) phases using a multivariate logistic regression model [16]. As the authors note, the ability of intra-procedural C-arm dual-phase CBCT to predict future tumor response may be especially beneficial, given that treatment response has been identified as an independent predictor of survival [17, 18].

Image Fusion/Co-registration Methods

Multimodality image fusion, including US, CT, MRI, and FDG-PET, has the potential to enhance the utility and indications for biopsy and may be superior to conventional imaging guidance in specific settings. Co-registration between patient anatomy and pre- and intra-procedural data enables simultaneous display of multiplanar anatomic details from CT and MRI and the functional imaging of FDG-PET while providing real-time anatomic data obtained from US [3]. The operator has the useful imaging information available from each modality when he or she needs it most.

Use of a single imaging modality for guidance may not be ideal during image-guided biopsy. This can be especially true for targets seen only fleetingly during contrast-enhanced CT and/or targets that are in proximity to large blood vessels, where real-time sonographic information about vulnerable anatomy is useful [3]. Registration and fusion of real-time US

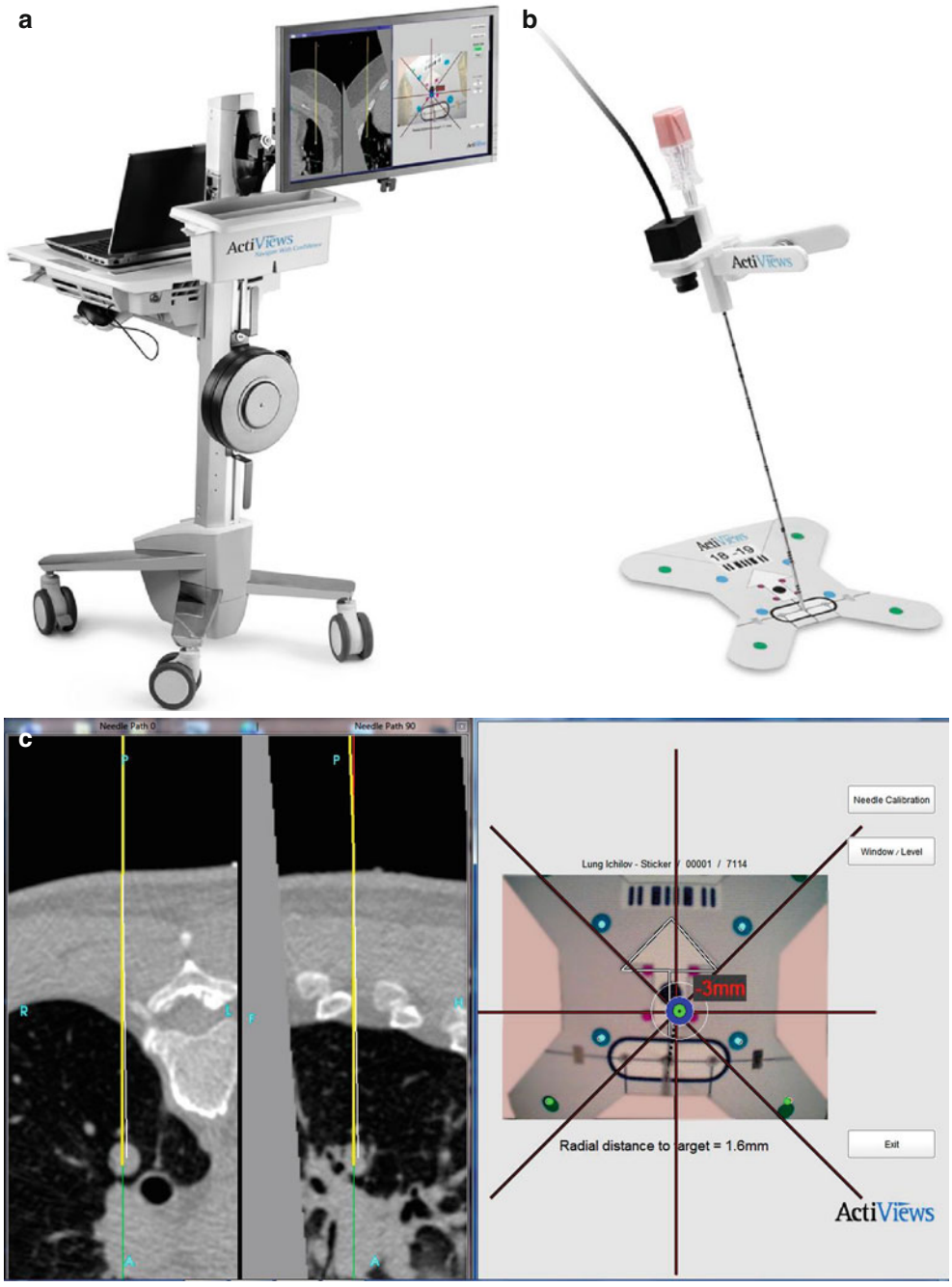
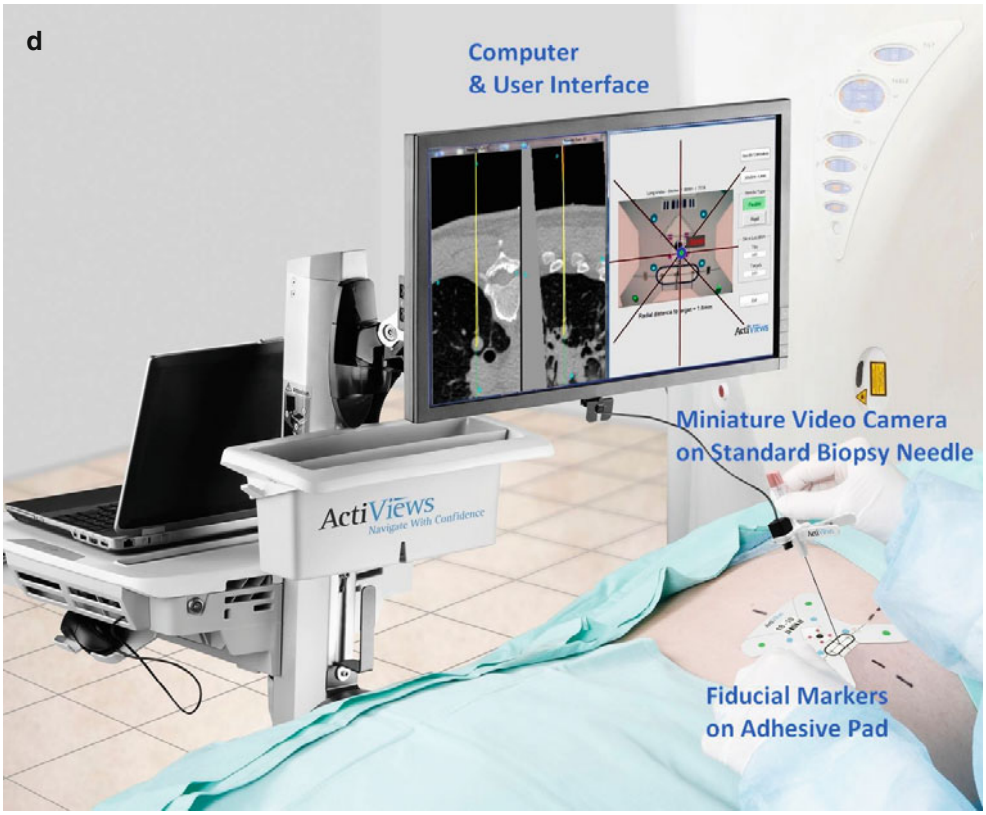


Fig. 7.4 Representative images of the CT-Guide® (ActiViews Ltd, Haifa, Israel) optical guidance system. (**a**) Custom computer with graphical user interface enables target and angle selection and real-time guidance. (**b**) Biopsy needle with miniature video camera (*black square*) clipped to needle hub. (**c**) Close-up of custom graphical user interface with display of tracked needle superimposed on multiplanar CT images, providing the operator with real-time feedback based upon selection of initial skin entry site and target location. (**d**) Use of optical needle tracking and image display facilitates during percutaneous biopsy (Images reprinted with permission from Activiews Ltd., Haifa, Israel)

Fig. 7.4 (continued)



imaging with a pre-acquired 3D image such as CT address these technical challenges [3]. Combining these two modalities also increases the likelihood of target lesion visualization, as the contribution of several modalities can be adjusted and blended to maximize lesion contrast [3]. Superimposing a display of the real-time image of the needle within the larger, higher-resolution CT image may also assist in using other internal anatomic landmarks for navigation even if the target lesion cannot be visualized well with either modality during biopsy [3]. Real-time US and CT image fusion is enabled by electromagnetic tracking of the US probe. The two-dimensional (2D) US image is superimposed with variable opacity and windowing with blending onto the corresponding slice in the CT volume. Alignment of the two image data sets is maintained as the US transducer is moved with real-time updating of fused US and CT images to visualize lesions in both modalities. In this fashion, the ultrasound transducer becomes a "multiplanar reconstruction (MPR) 2D plane selector," and the MPRs are updated in real time with the needle location displayed on all images. Sonography systems for which a pre-acquired CT or MRI may be displayed and co-registered with ultrasound are commercially available from an increasing number of vendors (Hitachi Real-time Virtual Sonography (HI-RVS), Hitachi Medical Systems, Tokyo, Japan; PercuNav Image Fusion and Instrument Navigation, Philips Medical Systems, Cleveland, Ohio; Virtual Navigator, Esaote, Genoa, Italy; Veran ig4 Navigation System, Veran Medical Technologies, St. Louis, Missouri; SonixGPS, Medical Corporation; Logiq E9 Ultrasound System, General Electric Healthcare, Little Chalfont, Buckinghamshire, UK, Milwaukee, WI).

Indications and Patient Selection

Multimodality image fusion and needle tracking are particularly useful to facilitate percutaneous biopsy of lesions that are not consistently seen across imaging modalities. Examples of targets that are very difficult to target with conventional technique include lesions apparent only on a single (e.g., T2-weighted) MR pulse sequence and lesions seen only as a focus of FDG abnormality on FDG-PET scan or only momentarily seen during an arterial-phase CT and occult on ultrasound. Successful biopsy is sometimes enabled by co-registering the images that demonstrate the target lesion in relation to the patient's intra-procedural imaging and anatomy [13]. Lesions that are heterogeneous in their imaging appearance can also be difficult to successfully target with conventional technique, such as tumors with heterogeneous FDG uptake where biopsy of the highest PET activity should relate to validity and integrity of the tissue sample (or biomarker), including diagnostic material-yielding genomic and proteomic data, which is key information

in today's era of personalized targeted therapies. These abnormalities can be successfully biopsied with tracking and image fusion; the image fusion technology can display the location of focal areas of FDG avidity, and real-time device tracking can display needle position in relation to the desired target. Tracking and image fusion are also useful when CT, MR, or FDG-PET imaging is not available in the procedure room for real-time intra-procedural guidance. It can also be used to facilitate training or potentially even compensate for lack of experience, normalizing the operator for variabilities in experience or broadening the capabilities of the less experienced operator.

Robotics

In contrast to the aforementioned device tracking and multimodality image fusion techniques, the use of medical robots to facilitate IR procedures is, at present, far more experimental, albeit promising. Medical robots are typically mechanical device manipulators connected by joints that allow active or passive motion from one link to another [4, 5]. The use of medical robots to assist or to perform intraoperative procedures has been motivated by goals of patient safety, enhanced precision and accuracy, and reduced inter-operator variability and procedure time. It is important to point out that typical "medical procedural robots" are often thought of in the surgical tele-robotics setting, where the surgeon sits at a nearby console and performs the surgery through laparoscopic manipulators and end effectors (arms and hands), such as with the *da Vinci* Surgical System (Intuitive Surgical Inc., Sunnyvale, CA). Robots have been used in neurosurgery, orthopedics, and urology; however, their use is still not considered as a standard of care practice [5], although urological applications for prostatectomy and certain cardiac procedures have seen broadened use of the *da vinci* Surgical System in particular (Intuitive Surgical Inc., Sunnyvale, CA). It is important to note that these surgical robots are quite different and significantly more expensive from any robot that might be used in CT or MRI *da vinci* Surgical System. IR robots that may become standard for CT-guided procedures someday are distinct entities, potentially very inexpensive and directly integrated to the CT software and CT imaging data. The potential for medical robots to facilitate percutaneous interventions remains an area of ongoing research, with relatively little clinical experience to date. As noted by Cleary et al, there remain ongoing challenges to implement a robot in the clinical setting, with medical robots needing to adhere to strict safety and application requirements [5, 19].

There is promising preclinical research demonstrating the ability of medical robots to facilitate percutaneous biopsy. Kettenbach et al. developed a robotic system for ultrasound (US)-guided biopsy and validated its feasibility, accuracy, and efficacy using phantoms [20]. The authors conclude that robotic-assisted biopsies in vitro using US guidance are feasible with high accuracy [20].

Sun et al. have also described in vitro use of a robotic end effector for driving needles during simulated image-guided liver biopsy [21]. This design involves a single articulating arm mounted on a stereotactic frame with a needle gripper on its distal tip that tenses and relaxes based on electronic signals conveyed to it via operator instructions. Operators are able to control not only needle angle and insertion but also two activation states, rigid mode and relaxed mode, to be used throughout the duration of the procedure [21]. Actual needle driving and gripping utilizes the rigid activation state, during which the articulating arm of the end effector is locked to inhibit non-controlled movement [21]. In the relaxed mode, the articulations along the length of the end effector facilitate concurrent movements of the engaged needle with the liver along the craniocaudal axis and potentially any other axes that the liver may travel during respiration [21]. Any shear injury to the liver and adjacent soft tissues would be eliminated as the end effector adjusts its position in accordance with respiration-induced liver motion [21]. A simulation study was performed to define these processes using tissue phantoms with mechanical properties in the range of hepatic tissue and the overlying abdominal wall. A series of tests using a moving bovine liver sample compared performances during the flaccid and rigid modes, demonstrating the design's ability to accommodate soft tissue and organ motion in a single direction [21]. The flexibility offered by the flaccid state of the end effector was found to effectively eliminate the tearing that could occur if a rigid needle-driving end effector was used alone [21]. As the authors conclude, such a switchable and flexible mode for a robotic arm could overcome existing limitations of automated needle placement within a mobile target, minimizing sheer stress upon organ capsules and thereby enhancing patient safety [21].

Several CT- and MRI-compatible robots are being developed for percutaneous image-guided interventions within the existing environments of the CT gantry and closed-bore magnet. Melzer et al. describe development of a CT- and MRI-compatible robotic system, termed "INNOMOTION" (Synthes Inc., formerly Innomedic, Oberdorf, Switzerland) [22]. This pneumatic robotic system consists of a robot arm which can be manipulated in six degrees of freedom, with the device has carefully optimized for use in closed-bore MRI scanners and the CT gantry [5, 22]. The robot arm is attached to a 260° arch that is mounted to the patient table of the scanner and can be passively repositioned on either side of the arch at 0°, 30°, and 60° to the vertical according to the region of interest (e.g., spine, liver, kidney, breast) [5]. Active positioning measurements are achieved via fiber optic coupled switches, along with rotational and linear incremental sensors [5]. The mobile arch can be fixed to the patient table of the MR system [5]. A module for application of coaxial

probes (e.g., cannulas for biopsies) provides two degrees of freedom in X and Z axes and is attached to a robotic arm with five degrees of freedom [5]. This design assures stable positioning of the instrument. A pneumatic drive enables controlled insertion of the cannula in incremental steps of 1–20 mm [5]. A graphical user interface provides trajectory planning directly on the MRI images [5].

Chellaturai et al. describe the clinical use of an automated guiding apparatus for CT-guided interventions, which calculates coordinates on DICOM images from a CT scanner and guides physician needle placement [23]. The system includes an electromechanical robotic guide arm that provides five degrees of freedom, a computer console for receiving CT images and calculating coordination, and an interface for data communication between the guide arm and computer console (PIGA-CT, Perfint Healthcare Pvt. Ltd, Chennai, India) [23]. After the physician operator selects skin entry and target points, the apparatus positions itself over the patient and aligns its needle guide accordingly. The needle is subsequently inserted via the guide by the operator [23].

Stoianovici et al. describe the development of a fully automated MRI-compatible robot, termed the "MrBot." This robot has been optimized specifically for transperineal access during MRI-guided prostate biopsy and is fully MRI compatible, with components that are nonmagnetic and dielectric [24]. As the homogeneity of the magnetic field is not affected by the presence of MrBot in the scanner's bore, spectral data from tissues can also be acquired and incorporated into precise targeting of focal metabolic abnormalities [24]. Fitted with optical sensors, the robot operates independently of an electrical source [24]. Its robotic needle possesses six degrees of freedom—five for positioning and orienting and one degree of freedom for setting the depth of needle insertion [24]. In addition, the needle driver presents several additional degrees of freedom for operating the needle, stylet, and loading the markers and can automatically place brachytherapy seeds [24]. The robot is constructed in the form of a platform supported by articulated linear actuators in a five-degree-of-freedom parallel link structure, with significant rigidity inherent within this structure facilitating targeting precision [24]. Although the MrBot is invisible in MRI, a high-contrast marker is built in the robot to enable registration. The accuracy of registration demonstrates targeting errors due to registration to be as low as 0.3 mm [24]. This robot has been tested on a canine model with images acquired for registration, organ visualization, and target specification [24]. Needle targeting error using this experimental model was less than 1 mm [24]. Robotic targeting tests are currently underway using this device to target simulated cancer lesions and to pursue a pilot clinical feasibility study for MRI-guided biopsy [24].

Early clinical experience using robots for percutaneous interventions has been promising. Su et al. evaluated the efficiency, accuracy, and safety of robotic percutaneous access to the kidney (PAKY) for percutaneous nephrolithotomy compared to conventional manual technique [25]. Intraoperative access variables including the number of access attempts, time to successful access, estimated blood loss and complications of 23 patients who underwent robotic PAKY with a remote center of motion device (PAKY-RCM) were compared with the same data from a series of 23 patients who underwent conventional manual percutaneous access to the kidney [25]. The PAKY-RCM incorporates a robotic arm with an axial loading system to accurately position and insert a standard 18-gauge needle percutaneously into the kidney [25]. When comparing PAKY-RCM with standard techniques, no significant difference was noted in the mean number of attempts to biopsy nor in the estimated blood loss score; the difference in the time to access the target approached statistical significance, being lower with use of the robotic system (10.4 ± 6.5 min vs. 15.1 ± 8.8 min ($p = 0.06$) [19]. The PAKY-RCM was successful in obtaining access in 87 % (20 of 23) of cases. The other three patients (13 %) required conversion to manual technique [25]. No major intraoperative complications were observed in either group, suggesting that this robotic system is a feasible, safe, and efficacious method of obtaining renal access for nephrolithotomy, demonstrating a number of attempts and time to access that was comparable to those of standard manual percutaneous access techniques [24]. As noted by Su et al, these data support the prospect of a completely automated robot-assisted percutaneous renal access device [25].

Chokkappan et al. describe the feasibility and preliminary efficacy of the PIGA-CT automated guiding apparatus in the performance of CT-guided lung biopsy as compared with conventional technique in a cohort of 72 consecutive CT-guided biopsies, 36 each performed with manual planning vs. the automated biopsy system [26]. Fewer mean needle repositionings were observed with the assistance platform (1.3) compared to conventional technique (2.9) ($p < 0.001$). Twenty-five biopsies yielded sufficient tissue for pathologic evaluation using the assistance platform vs. 23 using conventional technique ($p = 1.00$). Average number of verification scans was significantly lower with the use of the assistance platform (1.3) compared to conventional technique (3.6) ($p < 0.001$). Procedure time was also notably reduced with the assisted approach (30.8 min) compared to conventional technique (58.7 min) ($p < 0.001$). Complication rates were not statistically significant ($p = 0.15$) [26]. The authors conclude that both manual and automated planning offer comparable diagnostic yield and incidence of complications, with the assisted approach facilitating fewer needle passes, reduced procedure time, number of check scans, and hence the patient's radiation dosage [26]. Promising preliminary results such as these, employing robotic assistance platforms, remain of ongoing interest for future clinical

investigation. Additional prospective randomized clinical studies in the future are anticipated to further define the specific benefits of these technologies.

Summary

Many novel tools and devices are available or being investigated to facilitate percutaneous image-guided interventions. These include software for image registration and fusion, electromagnetic tracking, mechanical, optical, and rotational CT-based methods of device tracking, multimodality imaging, and semiautomated robotic needle guidance integrated to the CT. The use of these innovative device tracking techniques and CT robot systems has the potential to improve patient safety and procedural efficiency while potentially reducing procedure time, radiation dose, and inter-operator variability. Many of these novel tools are available to the interventional radiologist, and prospective clinical studies should soon further define the specific clinical benefits of these technologies.

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