Navigational Tools for Interventional Radiology and Interventional Oncology Applications

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Abstract

Keywords

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The interventional radiologist is increasingly called upon to successfully access challenging biopsy and ablation targets, which may be difficult based on poor visualization, small size, or the proximity of vulnerable regional anatomy. Complex therapeutic procedures, including tumor ablation and transarterial oncologic therapies, can be associated with procedural risk, significant procedure time, and measurable radiation time. Navigation tools, including electromagnetic, optical, laser, and robotic guidance systems, as well as image fusion platforms, have the potential to facilitate these complex interventions with the potential to improve lesion targeting, reduce procedure time, and radiation dose, and thus potentially improve patient outcomes. This review will provide an overview of currently available navigational tools and their application to interventional radiology and oncology. A summary of the pertinent literature on the use of these tools to improve safety and efficacy of interventional procedures compared with conventional techniques will be presented.

Objectives: Upon completion of this article, the reader will be able to identify common navigational tools employed for technically challenging interventional radiology/interventional oncology procedures and the potential benefits in terms of procedural accuracy, time, risk, and radiation dose.

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Precise image guidance is critical to the success of interventional radiologic and oncologic procedures. Frequently, these procedures are technically challenging due to poor target visualization, small size, or the proximity of vulnerable regional anatomy. Navigational tools can enhance the interventionalist's precision by improving localization of interventional devices in relation to the target, analogous to navigating a car to its destination using global positioning systems (GPS). Currently available navigational tools for interventional radiology include electromagnetic, optical, laser, and robotic guidance systems. Additionally, the use of image fusion allows for improved visualization of the target lesion by overlying real-time dynamic imaging (e.g.,

ultrasound [US]) on diagnostic quality cross-sectional datasets including contrast-enhanced computed tomography (CT), magnetic resonance imaging (MRI), or fluorodeoxyglucose positron emission tomography (FDG-PET). Knowledge of the navigational tools and image guidance platforms available to the interventionalist can enhance the success of technically challenging procedures with the potential to improve patient outcomes. This article provides an overview of currently available navigational tools and their application to interventional radiology and oncology.

Navigational Tools

Electromagnetic Navigation

Electromagnetic navigation (EMN) applies the philosophy of GPS navigation to the human body.¹ A field generator (analogous to a satellite in space) is placed in proximity to the patient and generates a local magnetic field centered around the lesion of interest² (►Fig. 1). Minute electromagnetic sensor coils embedded within the tips of devices (i.e., the car) can then be localized within the field, with their position calculated relative to fiducial sensors placed on the patient.^{1,3} Additionally, sensors placed within the US transducer used during an intervention can enable real-time device visualization on intraprocedural images.⁴ Integration of this information by a processing computer that can be projected on a monitor can delineate device position on pre- and intraprocedural imaging (i.e., the map) (►Fig. 2).^{3,4} EMN thus facilitates the successful access of targets that would have been deemed inaccessible with conventional techniques. This was exemplified in a study of 40 patients undergoing radiofrequency ablation (RFA) of various lesions where 19 interventions became possible with the use of EM tracking that otherwise would have been impossible to perform.⁵ EMN also has the potential to decrease procedure time and needle passes compared with conventional techniques. In a phantom

lung model, EMN-guided biopsies were shown to require less time and fewer passes than conventional CT alone.⁶ In a human study, combining EM navigation with CT fluoroscopy reduced time for ablation probe placement, number of needle adjustments, skin punctures, and fluoroscopy time.⁷ The use of EM navigation has also been associated with a reduction in procedure-related radiation dose (732 ± 81 mGy/cm³) compared with conventional CT-guided technique ($1,343$ mGy/cm³ $\pm 1,054$), as Penzkofer and colleagues demonstrated in 20 patients undergoing thermal ablation.⁸

Like other technologies, EM tracking is subject to limitations. Target-to-registration error (i.e., the difference between the position of the needle on the screen relative to the actual needle position within the body) has been reported to measure up to 14 mm⁶ with the use of EM tracking; this has been shown to be improved in phantom models to 1.1 mm under optimal conditions with the highest EM field.⁶ Additional limitations include the lack of availability of trackable needles for all procedures, particularly thermal ablation procedures, which may require placement of parallel needles (i.e., a tracked needle next to an ablation needle) or coaxial placement (ablation needle placed through a tracked stylet). In these cases, positioning is not guaranteed as the treatment needle can deviate from the appropriate course. Additionally, to date, experience with EMN in vascular procedures has been very limited.⁹ Finally, the magnetic field created by the field generator can be impeded by an external magnetic field, which currently limits its application with MR guidance.¹⁰

Optical Tracking

Optical tracking is an alternative to EM tracking that utilizes a video camera mounted to the tracked device whose position can be determined based on fiducials placed on the patient's skin.² The mounted system can allow for a simple, reproducible skin incision and trajectory along a controlled path (►Fig. 3). It offers compatibility with any imaging modality, including MRI. Additionally, a freehand system is also available that can be used for CT-guided procedures that may reduce the cost of disposables.¹¹ Numerous studies have demonstrated the benefit of optical tracking with MRI guidance. For example, Wu and colleagues successfully ablated 36 HCC in "difficult-to-treat" locations near the hepatic dome, gall bladder, or liver hilum,¹² and Maeda et al successfully punctured 51 liver tumors, most of which were undetectable by conventional US.¹³ Limitations of optical tracking include the need for an unimpeded pathway between the camera and tracked instrument. This "line of site" precludes the use of nonrigid, inflexible tools, especially when targeting lesions deep within the body.¹⁴

Laser Guidance

Laser tracking systems have also been employed for navigation during image-guided interventions. This method requires a moveable, rotatable laser unit mounted to a 220-degree circular rail that is placed immediately in front of the CT gantry¹⁵ (►Fig. 4). The image processing unit indicates the skin incision site and projects a laser ray for optimal trajectory. The needle follows the laser beam and is monitored by

Fig. 1 Equipment set up for electromagnetic device tracking during percutaneous interventions. Electromagnetic field generator (arrow) with sterile cover is positioned in proximity to the sterile field and directed toward anticipated needle entry site. Sterile fiducials (arrowheads) are placed on skin surface near anticipated skin entry site. (Reprinted with permission from Venkatesan et al.⁴¹)

Fig. 2 Pelvic biopsy facilitated by electromagnetic needle navigation and multimodality image fusion in a 19-year-old woman with undifferentiated round cell of the pelvis. (a) Axial PET/CT scan of pelvis demonstrates focus of FDG avidity within right iliopsoas muscle (arrow). Corresponding unenhanced CT scan (not shown) at the level of abnormal FDG-avid focus demonstrated a large osteolytic soft-tissue mass in the right hemipelvis involving right sacroiliac joint, but no focal anatomic abnormality to correspond to the patient's focus of FDG abnormality along the anterior aspect of this large soft-tissue mass within the right iliopsoas muscle. Intraprocedural CT scans coregistered to preacquired PET scans. Targeted focus of FDG avidity is displayed as a blue dot (arrow); tracked biopsy needle introducer is displayed as green line throughout the intervention. Intersecting red lines can be positioned to highlight either the location of the preselected target (b) or the tip of the tracked needle (c), as per the operator's preference, thereby adding visual conspicuity to either the target or tracked needle tip during the procedure. (d) CT scan confirms actual needle inserted to target immediately prior to sampling (arrowhead). Tracked biopsy facilitated by electromagnetic device tracking and image fusion confirmed necrotic round cell tumor (ghosts of round cells) and no evidence for viable malignancy. (Reprinted with permission from Venkatesan et al.⁴¹)

Fig. 3 Optical tracking using the Actiview CT-Guide needle guidance system (Actiview Ltd., Haifa, Israel now Stryker Corporation, Kalamazoo, MI). (a) A miniature video camera is attached to the needle or device. It identifies the CT-visible fiducial markers in a reference pad attached to the patient's skin. (b) A virtual line guides the probe accurately to the preplanned target, enabling two-dimensional (2D) planning in different planes and even (c) 3D planning. (Reprinted with permission from Appelbaum et al.²⁴)

Fig. 4 ▶ Fig. 1 The Laser Navigation System (laser unit; circular rail; image processing unit). Laser guidance system is mounted in front of the CT intervention scanner (top image). Laser pointer displays the skin incision site (bottom left) and projects the predetermined trajectory angle along which the operator can manipulate a needle during lumbar puncture (bottom right image). (Reprinted with permission from Moser et al.¹⁵)

keeping the laser beam at the distal end of the needle.¹⁵ The theoretical advantage of laser tracking is the improved workflow offered by automatically integrating preprocedural imaging and allowing precise needle placement based on the laser trajectory. In a phantom model of spinal interventions, laser guidance demonstrated technical feasibility similar to freehand technique with reduced procedure time and radiation exposure.¹⁵ The use of laser guidance (Syngo iGuide, Siemens Medical Solutions, Erlangen, Germany) with real-time cone beam CT (Uro Dyna-CT, Siemens Medical Solutions) has been described in an ex vivo model with a proposed role in complex antegrade renal access.¹⁶ However, challenges with both operator learning curve and image misregistration with a moving kidney need to be overcome before mainstream implementation can occur. Laser navigation system can be combined with standard CT to successfully access difficult lung biopsy targets as described in a case report by Hong and colleagues.¹⁷ Limitations to this system currently include added cost and setup time.

Navigational Robots

Navigational robots have the potential to offer the interventionist improved trackability and maneuverability of percutaneous and endovascular tools.¹⁸ Several prototypes have been designed with varying degrees of automaticity. The MAXIO system (Perfint Healthcare, Chennai, India) is a semi-automated robotic platform that is docked at the CT

table side. The robotic arm is positioned over the CT table and is spatially registered with the CT table using a mechanical docking system, optical registration, and tilt sensing. Using a proprietary software package, DICOM CT data are registered with the robotic system, thus allowing the operator to plan and perform CT-guided procedures. Use of this robotic navigation system in a phantom model of percutaneous abdominal ablations demonstrated improved needle accuracy and probe geometry, allowing for a significant reduction in residual target ablation when compared with freehand techniques alone.¹⁹ The FS-02N (Kawasaki Robotics, Detroit, MI) is a fully automated CT-integrated system, capable of image capture, fusion with preprocedure imaging, and needle insertion along a predetermined path.²⁰ The Magellan robot system (Hansen Medical, Mountain View, CA) enables the physician to steer a catheter from a remote workstation with tactile feedback to direct the distal tip of a catheter or needle, thus mitigating operator exposure to ionizing radiation.²¹ Such systems have been described in the arena of peripheral vascular disease with successful deployment of stent grafts for abdominal aortic aneurysms.²² Robotic navigational systems are currently hampered by their large size, as physical docking of the device limits access to the patient and the range of craniocaudal targets. Furthermore, vascular procedures using navigational robots lack the benefit of tactile feedback and require large sheaths. Currently available models are also incompatible with real-time MR guidance.²³

Image Fusion

Image fusion is the process of overlapping imaging datasets into a single composite imaging dataset, including those obtained at different times by the same or different modality. Typically, preprocedural cross-sectional imaging such as contrast-enhanced CT, MRI, or FDG-PET are projected on a monitor with real-time US or noncontrast CT overlay.²⁴ This allows the interventionalists to clearly visualize their target with diagnostic grade imaging while continuously monitoring their needle, catheter, or wire under real-time US guidance. Image fusion has demonstrated improved accuracy in needle placement and can alert the interventionalist to important nearby structures that may not be evident by real-time imaging alone.²⁵ Image fusion can also assist the operator in planning the number and configuration of ablation probes and tailor the composite ablation zone size and shape.²⁶ During ablation, image fusion can enable more confident assessment of the developing zone of ablation than may be apparent with the use of only one form of imaging (e.g., US) guidance.²⁶

The most important aspect of image fusion is the registration or spatial alignment of datasets.³ Because images obtained by different modalities can be projected in different planes or orientations, appropriate alignment of anatomic landmarks is critical to ensuring proper targeting while minimizing nontarget therapy of normal tissue. Image registration is the alignment of pixels between modalities and can be performed manually by the operator, automatically based on the matching of common anatomic landmarks, or semi automatically using a combination of both techniques. Rigid registration is a simple method of registration performed by superimposing static datasets. This provides the ability to pan and rotate one image relative to the other but does not adjust for changes in patient position due to voluntary or involuntary movement, such as breathing. Deformable registration allows the operator to modify images to account for patient and organ movement during a procedure and is thus more adequately suited for fusion technology during image-guided interventions.²⁷ Employing deformable registration to achieve maximum accuracy of coregistered datasets can be extremely time consuming, with reported durations required for image fusion up to 20 minutes for the initial registration and up to 10 minutes for each subsequent registration.²⁸

Image Fusion Techniques

Ultrasound/Magnetic Resonance Imaging Fusion

The ability to obtain multiplanar high-resolution images without ionizing radiation has made MRI a mainstay of diagnostic imaging for organs such as the liver and prostate. In both organs, the exquisite soft-tissue detail obtained with MRI permits detection of small lesions based on their differences in proton signal relative to normal tissue.^{29,30} MRI also has benefit in delineating pathology in the adrenal glands, kidney, or pancreas, especially in cases where CT is equivocal or there is concern about contrast-induced toxicity or allergy. Although real-time MRI guidance is available, images are

especially susceptible to motion artifact. Furthermore, MR-compatible devices, monitoring tools, and communication systems are expensive and cumbersome; even cases of simple MR-guided prostate biopsies may take several hours to set up and perform. Such limitations have limited the widespread use of MRI-guided interventions to specialized centers. On the other hand, US is widely available, portable, and less costly, and does not necessitate any particular space or additional equipment. It allows confident visualization of needle tips with the ability to adjust trajectory in real time. One can clearly appreciate the advantage of US guidance to target a lesion by overlaying images on diagnostic quality MRI (►Fig. 5). When combined, US-MRI fusion and EM tracking has demonstrated nearly double the detection rate of prostate malignancy compared with random biopsies.^{5,31–33} It has also demonstrated utility in prostate cancer brachytherapy planning.³⁴

Ultrasound/Computed Tomography Fusion

CT is commonly used for image-guided procedures, enabling biopsy or ablation of even sub-centimeter targets. However, CT exposes the patient and operator to ionizing radiation, which becomes especially important to those undergoing and performing multiple, time-consuming procedures. Lowering CT parameters such as peak kilovoltage or tube current (mAs) or increasing slice thickness can reduce the total radiation exposure but sacrifices image resolution compared with diagnostic protocols.³⁵ Furthermore, lesions only transiently visible during contrast-enhanced studies (such as arterial phase enhancing hepatocellular carcinomas) may not be resolved during an intraprocedural CT. The expected physiologic clearance of contrast runs the risk of “missing” the lesion or necessitating repeated iodinated contrast infusions. Moreover, the two-dimensional (2D) images of CT make off-axis approaches to lesions in the z-plane difficult. The iterative approach of repeat scanning and needle adjustment is not truly “real time” and can be associated with prolonged procedure time when approaching technically challenging targets.²⁴ CT fluoroscopy is an option that adjusts for this latter limitation but can be associated with increased radiation dose and requires specialized equipment; additionally, institutions without a dedicated CT interventional suite require occupancy of a diagnostic scanner that can cause significant challenges to workflow. The use of US-CT fusion overcomes many of these limitations. Diagnostic quality CT images can be fused to real-time US images to optimize visualization of a target lesion. This combines the practicality of real-time US guidance with the resolution of CT datasets while avoiding the need for a dedicated interventional CT scanner and additional procedural exposure to ionizing radiation or iodinated contrast (►Fig. 6). Numerous studies have been published demonstrating the utility of image fusion with US, especially in the realm of liver tumor ablation. In a study of 1,581 liver tumors ablated using CT/US or US/MRI fusion, 295 lesions were undetectable by US alone. Of these 295 lesions, 266 tumors were successfully ablated.³⁶

Fig. 5 Schematic demonstrating steps to obtain a magnetic resonance imaging/ultrasound (MRI/US) fusion-guided biopsy. ERC, endorectal coil; T2W, T2 weighted; DWI, diffusion-weighted imaging; DCE, dynamic contrast enhanced; TRUS, transrectal ultrasound; 3D, three dimensional. (Reprinted with permission from Minhaj et al. Magnetic Resonance Imaging/Ultrasound–Fusion Biopsy Significantly Upgrades Prostate Cancer Versus Systematic 12-core Transrectal Ultrasound Biopsy. *European Urology* 2013;64(5):713–719.)

Ultrasound/Positron Emission Tomography-Computed Tomography Fusion

Perhaps the most well-known fusion application in diagnostic imaging is the use of functional FDG-PET with attenuation corrected CT for anatomic localization. FDG-PET/CT fusion is a powerful tool used for characterizing malignancy based on tumor metabolic activity while delineating disease that might not otherwise be visualized on conventional anatomic imaging. PET/CT has particular value in assessing subtle foci of disease recurrence within pretreated organs whose parenchyma may be distorted by prior surgery, ablation, embolization, or radiotherapy.³⁷ Real-time PET/CT-guided interventions are available at specialized centers with one center demonstrating successful biopsy of 99/105 lesions in various organs that were not identifiable by other modalities.³⁸ The six unsuccessful biopsies were later determined to be benign by surgical exploration, suggesting a high sensitivity of this technique for malignant lesions.³⁸ Real-time FDG-PET/CT has also been used successfully for guidance during lung tumor ablation³⁹; in one study, 29 ablations were successfully performed with outcomes immediately confirmed by the absence of additional radiotracer uptake using a split bolus technique.⁴⁰

The main limitations to the widespread use of FDG-PET/CT guidance are radiation exposure to the patient and operator as well as long acquisition times following repeated repositioning of needles or catheters. Fusion of preacquired PET/CT data to intraprocedural US or CT imaging, on the other hand, can be very time efficient, necessitating only a single FDG-PET acquisition (→Fig. 7). The combination of PET/CT with real-time US and EM tracking has demonstrated feasibility in directing both biopsy and ablation of tumors deemed inac-

cessible by routine modalities. Venkatesan and colleagues demonstrated successful biopsy of 31/36 FDG-avid target biopsies which were either poorly seen or inconspicuous on conventional imaging modalities used for guidance.⁴¹ In the same study, successful RF ablation of a single FDG-avid hepatic focus not visualized on US or CT was able to be performed, with resolution of FDG avidity and no evidence of local recurrence at short-term follow-up.⁴¹

Cone Beam Computed Tomography

Conventional fluoroscopy has long been the mainstay for imaging during transcatheter intra-arterial therapy. However, poor soft-tissue detail and only 2D projectional capability limit its application in nonvascular interventions. The advent of flat panel detectors has facilitated the ability of a fluoroscopy unit to double as a CT scanner. Multiple radiographic images are obtained while the fluoroscopy unit rotates around the patient, and are then reconstructed into three-dimensional (3D) CT-like datasets known as a cone beam CT (CBCT) in as little as 5 seconds.⁴² CBCT thus allows the operator to perform both vascular and nonvascular interventions in a traditional fluoroscopy suite with cross-sectional imaging capability, without the need for additional equipment or space. In one study, CBCT allowed for safe and effective targeting of small renal masses in hard to reach locations with 95.1% accuracy and no major complications.⁴³ In a phantom model, CBCT with fluoroscopy overlay and needle guidance software demonstrated superior accuracy in targeting small lesions with difficult (double angulated) needle paths compared with routine CT with no significant difference in accuracy of “simpler” in-plane or single angulated trajectories.⁴⁴ In a study of 40 lung tumor ablations,

Fig. 6 CT/US fusion for liver tumor ablation. (a) Coronal, axial, and sagittal views of a contrast-enhanced CT. The tumor and safety margin have been segmented (orange circles). The ablation zones required for complete coverage are also seen (blue circles). The target position for the ablation probe is depicted as the red cross. The virtual probe is seen as the purple line. As the operator advances the tracked probe, the “virtual” probe position adjusts in the software. (b) After the first ablation is completed, the ablation planning software updates the treated areas (as per manufacturer’s specifications) shown as a purple circle. If applicable, the software also adjusts the position of subsequent probes seen as the red and purple crosses. The imaging can also be fused with ultrasound for real-time imaging guidance as seen on the left bottom screen. (Reprinted with permission from Abi-Jaoudeh et al.²)

Fig. 7 Patient with recurrent tumor and recent nondiagnostic biopsy. Graphical user interface showing metabolic activity (blue dots) on PET scan targeted with navigation to sample a viable part of the tumor. PET data were registered to procedural multiplanar reconstructed CT and procedural ultrasound for real-time feedback. Virtual needle represented by blue line. Multiplanar/multimodality navigation is displayed as well as down-the-needle-shaft view (lower left). (Reprinted with permission from Wood et al.³)

CBCT resulted in faster RFA times with similar recurrence rates compared with routine CT-guided RFA.⁴⁵ Use of flat panel CBCT guidance also demonstrated improved accuracy in bone biopsies compared with routine CT guidance, with lower patient and operator radiation doses and no difference in puncture time or diagnostic yield.⁴⁶

Navigational software can also be combined with CBCT to facilitate percutaneous image-guided biopsy and ablation. Needle overlay systems such as Xperguide (Philips Allura Xper FD20; Philips Healthcare, Best, the Netherlands) allow the operator to monitor biopsy needle progress via fusion of fluoroscopic images on the preliminary CBCT dataset. Improved visualization of the needle trajectory can be important for lesions adjacent to critical vessels in organs such as the lung.⁴⁷ To date, CT fluoroscopy-guided biopsy studies have been reported to have an accuracy similar to CT alone without significant increases in radiation dose.^{48,49}

The use of CBCT in vascular procedures has also been described for use during uterine artery embolization,⁵⁰ trans-

jugular intrahepatic portosystemic shunts, stent graft deployment,⁵¹ and endoleak repair.⁵² Preoperative CTA or MR angiography (MRA) may be fused with a low-dose CBCT prior to arterial access,² which allows real-time catheter navigation using fluoroscopic guidance without the need for additional contrast injection. As such, procedures such as placement of stent grafts or associated endoleak repair can be successfully performed with little to no contrast.⁵³ CBCT images can also be combined and co-displayed with conventional 2D angiography images or preprocedural cross-sectional imaging to plan treatment, navigate device position, monitor intraoperative progress, and assess response during intra-arterial therapy. Recent experience with CBCT navigation for transcatheter liver-directed therapy has demonstrated its practical value as a navigational tool. Effective treatment during bland embolization or TACE depends on characterizing tumor location and feeding vessels as well as appropriately positioning the catheter tip to ensure targeted delivery of therapeutic agents. Because of the variable enhancement

characteristics of liver cancers, exact delineation of vascular supply can be difficult on preprocedure cross-sectional anatomic studies alone. CBCT enables the interventionalist to obtain multiphase contrast-enhanced CT datasets with precise contrast bolus timing when the catheter is placed immediately in the supplying vessel, thus more precisely delineating anticipated tumor blood supply immediately prior to embolization. Dual phase (arterial and venous phases) CBCT has demonstrated tumor identification superior to digital subtraction angiography (DSA) of small liver tumors⁵⁴ and can predict up to 94% of lesions observed on contrast-enhanced MRI.⁵⁵ Moreover, tumor segmentation and vessel detection have been shown to be significantly more sensitive with less interobserver variability compared with fluoroscopy alone.⁵⁶

CBCT used during microsphere radioembolization is especially useful in preoperative planning, demonstrating small extrahepatic arteries or areas of extrahepatic enhancement, which are critical in precluding nontarget embolization (►Fig. 8). In a series of 42 cases, Louie et al demonstrated that 33% of salient nontarget extrahepatic arteries detected on CBCT prior to radioembolization were not noted on standard DSA, with 19% also not observed by Tc99m.⁵⁷ Furthermore, the precise arterial detail offered by CBCT has also been used to facilitate catheter placement during nephron sparing embolization of renal tumors⁵⁸ and prostate embolization, avoiding nontarget arteries and enabling identification of collateral vessels⁵⁹(►Fig. 9).

Limitations of cone beam CT compared with traditional CT are its reduced signal-to-noise ratio, with images prone to

artifact from patient positioning (arms at their side) or overlying support tubes or devices (ex. electrocardiographic leads). Additionally, cone beam CT necessitates support staff training to ensure that the appropriate region of interest is included in the field of view, as the field of view is smaller than that of a fluoroscopy unit. Precise positioning and registration may present a logistical challenge especially in the setting of patient motion or when faced with intra-procedural complications such as pneumothorax during lung biopsy.

MRI and Hybrid MRI

Use of interventional MRI has historically been hampered by slow image acquisition times, physical constraints imposed by small bore size, and low signal-to-noise ratio due to relatively weak interventional magnetic field strengths.⁶⁰ Nonetheless, the advantages of intraoperative MRI make it an attractive modality for interventional procedures.

MRA offers particular benefit given its ability to produce 2D and 3D vascular imaging without the need for iodinated contrast. Benefits include evaluation of atherosclerotic plaque burden, barotrauma after angioplasty, and monitoring the release of agents from drug-eluting stents and drug-coated balloons.⁶¹ Dynamic imaging with steady-state free precession sequences allows real-time catheter guidance and steering with dilute gadolinium contrast used for DSA-like angiography. Advanced sequences allow for four-dimensional datasets to provide flexible roadmaps for intravascular procedures. The main limitation to MRI-guided vascular procedures is the invisibility of plastic or metallic guidewires.

Fig. 8 CBCT imaging during Y90 workup in a 60-year-old patient suffering from chemorefractory colorectal liver metastases. (a and b) CBCT during hepatic arterial injection shows masses within the left hepatic lobe. (c) CBCT/fluoroscopic fusion shows catheter manipulation to target vessels. (d) Small hepatocentric vessel feeding the right gastric wall (yellow arrow), which was not identified by angiography alone. Subsequently, proximal coil embolization of the right gastric artery was performed. (Reprinted with permission from Floridi et al.⁵⁸)

Fig. 9 Prostate embolization using CBCT/fluoroscopy fusion. Prostate enhancement on delayed phase where segmentation was performed (top image). EmboGuide software (EmboGuide, Philips Healthcare, Best, The Netherlands) detected one right and one left prostatic artery (a and c) which were seen on 2D arteriography (b and d). (Reprinted with permission from Floridi et al.⁵⁸)

Recently, the use of MRI-compatible 0.035" guidewires made out of fiberglass or polyetheretherketone was described.⁶²

MRI with hybrid X-ray has the potential to offer combined MRI-fluoroscopy that can be used to guide catheters and wires with high spatial resolution and anatomic detail. Combination images can be obtained from different datasets or near real time by switching back and forth between modalities. The latter can be accomplished with platforms that have an X-ray source between two halves of the magnet, or by two separate imaging systems in which the patient table is transferred from one platform to another. Limitations to implementation include deflection of the electron beam by the fluoroscopy unit, and distortion of the image intensifier by the magnetic field. Incorporation of a magnetic shielding system can allow for placement of the X-ray beam source within 1 m of the magnet.⁶³ However, current capabilities preclude routine use, and the challenges of image registration pose an additional challenge.

Conclusion

There is an increasing demand upon the interventional radiologist to successfully access technically challenging anatomic targets for diagnostic and therapeutic purposes. Interventional radiologists must continue to seek tools that improve precision and accuracy. There is increasing evidence that navigational tools such as electromagnetic tracking, optical, CBCT, laser, and robotic navigational techniques, as well as image fusion technologies have the potential to improve the safety and efficacy of interventional procedures. Continued maturation and refinement of these technologies is expected to increase their

practicality and facilitate their integration into everyday practice. Evidence continues to emerge regarding the potential of these technologies to optimize procedure success rates while reducing procedure time, risk, and radiation dose.

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