Oncology patients, particularly those with breast, colorectal, prostate, renal and pancreatic cancers, are living longer due to advances in detection, and treatment. Unfortunately, this has come with a commensurate increase in the prevalence of osseous metastases and skeletal related events approaching 100,000 new patients each year. Patients are now experiencing serious morbidity and mortality due to pathologic fractures, altered structural mechanics, and cancer related bone pain. This patient population poses challenges for conventional open surgical and/or medical management often due to disease extent, location, and, in general, poor surgical candidacy. Percutaneous techniques may also be challenging under image guidance due to limited ability to use traditional orthopedic corridors, loss of cortical landmarks with destructive lesions, and need for live image guidance. Modern angiography suites with cone beam computed tomography (CBCT) and advanced imaging applications including needle guidance, 3D fusion, tumor segmentation, and angio-CT have facilitated the development of novel minimally invasive techniques for pain palliation and stabilization. The interventional radiologist is uniquely positioned to harness these advanced imaging applications and offer effective, safe, minimally invasive treatment options to patients with neoplastic disease within the axial, and appendicular skeletons. The focus of this article is to address the technical aspects of patient preparation, positioning, advanced imaging system capabilities, guidance strategies, and pitfalls during osteoplasty and fixation procedures.

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Patient considerations/indications

Approach to these complex patients should be multidisciplinary with involvement from interventional radiology, orthopedics, medical oncology, radiation oncology, and palliative care.

Patients with skeletal involvement experience pain and disability due to cancer related bone pain, mechanical instability and altered biomechanics, pathologic fracture, and tumor extension into adjacent structures. Available treatment options for pain palliation, local tumor control, and/or structural stability include ablation, osteoplasty, and/or screw fixation. For the complex pelvic metastases and fractures, Orthopedic Surgery, and Interventional Radiology (Interventional Oncology) act as a treatment team. While this is not a requisite, we have found valuable exchange of ideas, knowledge, and refinement of our techniques through this collaboration. Choice and sequencing of treatment is dependent upon extent of disease, physical exam findings, degree of disability, prognosis, and goals of care. With respect to tumor...
type, our experience has been predominately with metastatic disease, and myeloma. Primary bone sarcoma is considered a relative contraindication, as surgical resection is regarded as the gold standard. There are only a few absolute contraindications which include inaccessibility of target lesion, uncorrectable coagulopathy, and active systemic and/or surgical site infection.

Technical procedural details
Patient preparation and positioning
Correct patient positioning when performing these cases can be challenging and may vary from case to case based on several factors including anatomy, lesion size, patient body habitus, and targeted site for screw fixation. Given the intent is often to place metallic implants, strict adherence to sterile preparation and technique is paramount. We have adopted a hybrid surgical preparation of the patient with bolstering under the pelvis and shoulder to stabilize the area of interest and simplify screw corridors when possible. When planning corridors, the reachable angles are generally 30° cranial or caudal at angles up to 60° LAO and/or RAO. This knowledge can aid in determining appropriate patient positioning before the case. One example is buttressing under the sacrum when needed to help elevate the sacrum, so it is not flat and/or parallel with the table. Wrapping the arms facilitates obtaining additional CBCT during the procedure without having to remove the arm boards and minimizing patient movement. Strapping the patient also minimizes motion and helps prevent future misregistration and error. Prior to prepping the patient, we perform a trial CBCT to determine whether the target anatomy can be adequately imaged and to ensure the CBCT can be safely acquired. Once verified, we utilize a large sterile field and Ioban (3M St. Paul, MN) adhesive barriers to secure sterile towels and drapes (Fig. 1). Lastly, while performing CBCT, we will cover the operative field with a half drape which is then discarded immediately after image acquisition to maintain sterility.

Advanced imaging applications
Modern angiography suites have made it possible to treat complex metastases through the application of advanced navigation, tumor segmentation, and real-time multiplanar reformats for which we have termed “augmented fluoroscopy.” We use augmented fluoroscopy for the placement of screws, ablation probes, bone trocars, fiducial markers at points of interest, and to outline vital structures.

After the planning CT or MRI has been reviewed, and trajectories chosen, the patient is then bolstered, positioned, and prepped. (Fig. 1) At this point the patient is registered to the table, if no further movement occurs, the patient is rescanned with a CBCT which will then be fused to the planning imaging study. During the planning sequence initial registration and fusion of the 2 data sets is performed using easily identified bone contours (iliac crests, spinous processes, ribs, pubic rami) to ensure the 2 data sets are as closely fused as possible (Fig. 2). Prepping the patient first and then obtaining the CBCT is critically important to minimize patient movement and reduce the chance of prolonged time between data acquisition and commencing the placement of needles or probes.

The navigated lines used to plan and place guide pins, probes, bone cannulas, and screws are the workhorse of the imaging software techniques (Fig. 3). Planning these lines ahead of the case determines number, size, and order of placement of the above devices. In addition to the navigated corridor lines, advance planning software allows tracing of tumor borders and volumes, vital structures such as nerves, arteries, and joint lines. The principal advantage of augmented fluoroscopy is that the drawn lines and segmented volumes are projected and rotate in space as we rotate the imaging chain around the patient giving infinite views with the trajectories tracking in real time. (Fig. 4) This allows non-traditional views of pelvic corridors when tumor or pathologic fracture has disrupted those relationships. Despite this technological advantage, the immediate view is still only a 2-dimensional (2D) view of a 3-dimensional (3D) volume. For example, the iliac wing is a complex curved structure with

Figure 1 Intra-procedural image demonstrating patient preparation. (Color version of figure is available online.)
**Figure 2** Registration and 3D-3D fusion of pre-procedural planning CT pelvis and on-table CBCT. The images are fused in the axial (A), coronal (B), and sagittal (C) planes via translation, and rotation of the acquired CBCT which is superimposed on the pre-procedural CT. (Color version of figure is available online.)

**Figure 3** Patient with extra-skeletal myxoid chondrosarcoma and hip pain. Image A. Initial coronal planning CBCT image with ablation and/or first screw navigation line (orange). Image B. Cannulated screw partially advanced with microwave ablation probe positioned in the lesion. Image C. Subsequent augmented fluoroscopic image demonstrating screw navigation lines for placement of femoral neck screws in a triangular pattern (Color version of the figure is available online.)

**Figure 4** Image A. Post fusion procedural planning image in an orthogonal plane to the needle trajectory (yellow line). Fiducial (green crosshair) marks the osseous entry site and tumor segmentation (magenta). Image B. Generated augmented fluoroscopic view of image A. Image C. Intra-procedural augmented fluoroscopic image demonstrating the use of fiducials to plan overlapping ablation zones, and a poly line to trace the sciatic nerve (green) (Color version of the figure is available online.)
multiple cortical lines, and entering it along this curved surface to target the anterior superior pubic ramus corridor or sacral corridors is challenging. This is further complicated by the fact that a “bullseye” down the needle view can be difficult to perform due to clearance issues under the flat panel detector with long guide pins or bone cannulas. One way to add additional volumetric or third dimension information to the fluoroscopic image is to place fiducials at the bone entrance points along the planned lines (Figs. 4 and 5) which allow positioning a guide pin or cannula at a precise point on a 2D image with the fiducial supplying a “depth” or additional point of reference. Fiducial marks should be placed at key bone entrance points, and helpful bony prominences. The latter allows for quick identification of misregistration errors as the fiducial will float off or pass deep to the bone interface when misregistration has occurred.

Pitfalls learned along the way include the gradual and often unrecognized misregistration that can occur with hammering, drilling, or passing devices into the body. Even the passage of a 20-gauge needle can tilt the patient slightly causing misregistration and errors. Further, the body slowly heats the tabletop cushion, which compresses over time resulting in the body sinking into the table. This results in misregistration with the actual anatomy translating toward the floor relative to the acquired dataset and planning lines which remain static. A classic example of this occurs in the prone patient when targeting the trans-sacral S1 and S2 corridors (Fig. 6). If this settling is not accounted for, the needle or guide pin will pass more posterior in the corridor than appreciated putting the S1 or S2 neuroforamen in jeopardy. It is important to remember that augmented fluoroscopy lines are aids especially helpful when cortices are disrupted by fracture or tumor, but our fundamental knowledge of the anatomy, and fluoroscopic landmarks should always supersede these navigational aids. Frequent “control” CBCTs will allow for checking needle paths and re-registering the datasets.

**Imaging review and procedural planning**

Percutaneous probes and screws can be placed with “traditional” orthopedic views using standard c-arm fluoroscopy. For placement of the superior pubic ramus screws, the pelvic inlet and combination obturator oblique-outlet views can be used to safely place a guidewire and screws. The starting point for an antegrade screw is typically near the base of the gluteus medius pillar in the supra-acetabular region. For a retrograde screw, the starting point is on the anteromedial portion of the parasymphysis bone. Views used for safe placement of the ischial screw and/or posterior column screw are the pelvic outlet, iliac-oblique, and lateral sacrum.

![Figure 5](image.png)

**Figure 5** Fused axial (A) and sagittal (B) images of a posterior to anterior supra-acetabular corridor navigation line (yellow), fiducial marker at the bone entry site (green crosshair) and segmented tumor volume (green). Completion sagittal and coronal CBCT images after tandem cannulated screw placement and osteoplasty (Color version of the figure is available online.)
Anterior to posterior and/or anterior inferior iliac spine to posterior ilium screws can be safely placed with the combination obturator-oblique outlet, combination obturator-oblique inlet, and iliac oblique views. Trans-sacral screws can be placed with the pelvic inlet, pelvic outlet, and lateral sacrum views. Efficiency is highly dependent upon surgeon and radiology technologist experience. Recognition of pelvic dysmorphism is of critical importance as well. Limitation of standard fluoroscopic c-arm occur with obese patients and those with greater metastatic disease burden.

Navigation can facilitate safer placement of screws when anatomy is distorted by advanced metastatic disease. The tactile feedback is greatly diminished when there is extensive involvement of the osseous fixation pathways. This can be particularly problematic in the supra-acetabular region and superior pubic ramus. Some physicians may not have access for combination procedures with interventional radiology. CT-guided navigation can be performed in the operating suite with the O-Arm and stealth navigation. This methodology allows for percutaneous screws placement while using 3D reconstruction and optical navigation with optical fiducials mounted on each instrument. The benefit of this system is that a fiducial is secured to a bony prominence which allows for automated re-registration. A limitation of this is the large size of the imaging device, higher per acquisition dose, and slower speed of obtaining multiple CT scans.

The use of augmented fluoroscopy in the interventional radiology suite provides some critical advantages. CT scan and MRI can used to map out critical neurovascular structures that may be at danger during ablation. Tumor volume can be mapped out and provide better idea of the volume to ablate and then subsequently augment with cement. Augmented fluoroscopy allows for screw trajectories to be pre-planned and measured. Guide pins can be placed safely with combination of tactile and visual feedback. CT scans can be obtained quickly to confirm safe placement in a more efficient manner than the O-arm. The interventional radiology environment does not lend itself as well to cases of fixation in severely displaced fractures and is best suite in the prophylactic manner.

Figure 6 Fused axial images demonstrating the tumor segmented with polylines (A), needle trajectory (yellow line) through the S1 corridor (B), and post guide pin placement (C). Sagittal procedural CBCT images with guide pins placed through the S1 and S2 corridors (D) and post final screw placement (E). Misregistration due to the body settling into tabletop pad resulted in guide pin path through S1 corridor more posterior and superior to the plotted needle trajectory (images B, C, and D). Control CBCT was performed and fused to the planning CT. Guide pins were repositioned and screws were placed along the intended trajectory. Note the changes in position of the S1 guide pin (D) and final screw position (E) (Color version of the figure is available online.)
Planning trajectories

Lesion location dictates the type and number of screws required for fixation. Sacral lesions are often treated with multiple trans-sacral screws depending on the quality and size of the S1 and S2 corridors. Lesions primarily involving the anterior column and/or superior pubic ramus can be treated with a superior pubic ramus screw. Lesions within the posterior column can be treated with an ischial and/or posterior column screw. Some supra-acetabular and/or iliac lesions can be treated with an anterior to posterior and/or anterior inferior iliac spine to posterior ilium screws. Advanced supra-acetabular lesions can require all 3 screws resulting in a “tripod” construct. The tripod construct can be beneficial in patients with longer survivorship who develop osteoarthritis. The strength of the construct allows and facilitates a later (staged) more traditional total hip arthroplasty as opposed to more extensive Harrington type reconstructions that carry greater morbidity.

Ablation and osteoplasty

Trajectories for ablation and osteoplasty are nuanced and vary depending on ablation modality, intent of ablation, extent of disease, adjacent critical structures, and concurrent plan for screw fixation. The majority of combination ablation, osteoplasty, and fixation cases are performed with palliative intent and/or local targeted tumor control. Ablation guidance lines and zones are primarily planned to target strategic corridors and margins to inhibit local disease progression in regions and/or pathways which could contribute to potential hardware failure or worsening mechanical instability. The ablation probe is often inserted through an access cannula or partially inserted screw. Advantages of performing the ablation with needle guidance and augmented fluoroscopy, especially when combined with screw fixation, are flexibility with working room, potentially reduced radiation dose, real time imaging, live tumor segmentation overlays, and fiducial markers (Fig. 4).

Osteoplasty can be performed via cement cannula through the ablation access, a partially inserted screw or via an additional access after screw placement. Obtaining this access can be challenging due to adjacent critical structures and limited unobstructed corridors to the target zone after screw placement (Fig. 7, Image A). In this scenario needle guidance, tumor segmentation, and live fluoroscopy in combination are invaluable tools for performing osteoplasty. Needle guidance lines are drawn after a control CBCT is obtained to avoid potential misregistration due to patient movement during screw placement and to safely target the intended region for osteoplasty. Tumor segmentation with overlay allows for live visualization of cement fill within and around the borders of the tumor during cement delivery (Fig. 8). It also facilitates manipulation of a curved needle for optimization of cement delivery to portions of the lesion and/or bone that are inadequately filling and/or cement delivery to strategic regions and/or pathways to bolster the construct (Fig. 7, Images B, C).

Augmented fluoroscopy cases

An in-depth review of all the available medical imaging systems with augmented fluoroscopy capabilities is beyond the scope of this article. Therefore, we have chosen the most widely available fluoroscopy platforms, General Electric
Sixty-year-old female with history of stage I invasive ductal carcinoma of the breast status post lumpectomy and adjuvant radiation therapy. The patient presented with acute right hip pain and was found to have a lytic and/or destructive lesion involving the right acetabulum. Computed tomography images demonstrated tumor involvement of the anterior column, posterior column, supra-acetabular region, and medial wall. (Fig. 9). After a multidisciplinary discussion the decision was made to proceed with fixation of the acetabulum via superior ramus, ischial, and supra-acetabular screws followed by osteoplasty. The patient’s pre-procedural cross-sectional imaging was uploaded in the Syngo workstation in the interventional radiology suite. Trajectories for guide pin placement and osteoplasty were planned prior to the patient entering the interventional radiology suite. Of note, when approaching cases with multiple screw placements it is helpful to start with what is usually the most difficult corridor, the superior pubic ramus. Within the 4D tab a 4-pane window is activated with axial, coronal, sagittal, and 3D reconstructions. These image volumes are manipulated to produce orthogonal views to the intended corridor. Prior to manipulation of the imaging, it is important activate the needle guidance software. Failure to do this will result in loss of manipulated views as when the software is activated it resets all planes back to the original acquisition. After the needle guidance software is activated, the volumes can be manipulated, and trajectories planned. Two very helpful features within the “Define Path” menu are the “Switch to In-Plane view” and “Switch to Ortho view” buttons which when selected automatically create reformats centered on the needle path or target, respectively.

Within the “Measure” tab the operator can select and place green crosshairs (fiducials) or polylines that are overlayed on live fluoroscopic images. We have found the use of the fiducial marker to be tremendously helpful when the bullseye view cannot be obtained due to the steep angles of the intended trajectories. The fiducial markers provide a visual confirmation to correspond with tactile feedback of engaging the bone at the intended site, a task which has proven difficult at times due to the combination of complex pelvic osseous anatomy, and 2D fluoroscopic views. Next, we center the imaging planes on the tumor and segment the tumor by drawing polylines around the border in multiple planes (Fig. 7, Image A, and C). Adjacent critical structures such as nerves, neural foramen, and joint lines can also be marked with polylines or fiducial markers. Depending on the entry angle, the working room under the flat panel detector may preclude direct entry with a guide pin, in these instances we use an 8-gauge Stryker (Kalamazoo, MI) bone trocar to gain access as it accommodates a 3.2 mm guide pin. To minimize radiation exposure, the acquisition fluoroscopy rate is set to 1-2 frames per second and live augmented fluoroscopy in progression and traditional orthopedic views is utilized during device placement in favor of multiple repeat CBCT. However, intermittent CBCT are also performed to ensure appropriate position of devices, as needed on a limited basis. (Figure 7) images A and C, are examples of the use of augmented fluoroscopy to navigate guide pin
placement through a tight corridor as well as facilitate osteoplasty of the acetabular lesion with a curved needle.

Phillips healthcare imaging system

Seventy-seven-year-old female with metastatic rectal cancer who presented to the hospital with new onset low back pain. Magnetic resonance imaging (MRI) of the lumbar spine was obtained demonstrating multiple osseous metastases an asymmetric left sided fracture pathologic fracture of L4. After a multidisciplinary review with neurosurgery and medical oncology, the decision was made to pursue ablation of the lesion followed by vertebral augmentation. With the patient in the prone position, prepped, and under general anesthesia, a CBCT was obtained. The data set was reviewed in XperCT and trajectories for the ablation and augmentation via bi-pedicular access were planned with XperGuide. Use of guidance in this case was of particular importance because of the necessity to precisely position the needle within an asymmetric left sided fracture. The bullseye view was selected for initial needle placement as this gives a live fluoroscopic image of the target and skin entry points superimposed over each other allowing for “down-the-barrel” technique when advancing the needle. Depth was determined by switching to a secondary progression view which highlights the target point. In this view the entire length of the needle can be visualized superimposed over the line previously drawn. The needle can then safely be advanced to the appropriate depth provided there has not been any significant patient movement. CBCT was then obtained post probe placement to confirm appropriate position.

General electric healthcare imaging system

Patient with intractable lower back found to have S1 metastatic lesion and post radiation insufficiency fractures of the sacrum. After proper positioning a planning CBCT was obtained. 3D point-in-space markers were placed on the S1 nerve root. The S1 neuroforaminal wall, S1 and S2 neuroforaminal lateral contours, and the leading edge of the target tumor were traced for enhanced conspicuity during the procedure. (Fig. 10, Images A and B). Vectors for radiofrequency ablation (RFA) of the target lesion and coaxial 27-gauge thermocouple via 17-gauge cannula needle were determined and ultimately placed under augmented fluoroscopy (Fig. 10, Image B). CBCT was then obtained to confirm proper position of the RFA probe and thermocouple (Fig. 10, Image C, and D). Bilateral sacroplasies were then performed under augmented fluoroscopy via planned vectors for cannula placement and tracings of S1 and S2 neuroforaminal contours for visualization during both cannula placement and injection of cement.

Conclusion

Osseous metastases and skeletal related events are increasing in prevalence as patients are surviving their cancers. Patients are increasingly experiencing serious morbidity and mortality
due to pathologic fractures, altered structural mechanics, and cancer related bone pain. The interventional radiologist, in collaboration with our Orthopedic colleagues and other specialists, is uniquely positioned to expand upon minimally invasive techniques used in osteoplasty and fixation by harnessing the capabilities of advanced imaging suites and augmented fluoroscopy for treatment of complex debilitating osseous pathologies in a safe and effective manner. The imaging system vendors continue to innovate and refine the imaging systems reducing dose to patient and operators, adding software functionality, and improving patient safety and outcomes. This collaboration is equally important.

References

Figure 10  Sixty-year-old female with history of stage I invasive ductal carcinoma of the breast with acute right hip. Axial (A), sagittal (B), and coronal (C) computed tomography images demonstrated tumor involvement in the anterior column, posterior column, and supra-acetabular region with cortical destruction of the medial wall.