Integrated CT–Fluoroscopy Equipment: Improving the Interventional Radiology Approach and Patient Experience for Treatment of Musculoskeletal Malignancies

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Abstract

Integrated CT–fluoroscopy equipment augments the comprehensive approach to the treatment of musculoskeletal (MSK) malignancy by interventional radiology techniques. As the role of minimally invasive treatment expands to meet the highly variable presentation of MSK malignancy, creative solutions to treatment challenges are required to improve locoregional tumor control and durability of pain palliation. Challenges to effective treatment can often be attributed to a combination of aggressive tumor biology, large size, forbidding location, and adverse vascularity. In these cases, a tailored treatment approach may necessitate the application of multiple interventional radiology (IR) techniques that require different image guidance capabilities. Integrated CT–fluoroscopy equipment provides the means to leverage both imaging modalities within the same procedural setting to facilitate the simultaneous application of multiple synergistic treatments and protective measures. This article examines the potential role of hybrid units in the IR treatment of challenging MSK malignancies as a means to empower a paradigm transition for a more comprehensive and patient-tailored approach.

Keywords

- integrated
- hybrid
- musculoskeletal
- malignancy
- interventional radiology

Objectives: Upon completion of this article, the reader will be able to demonstrate potential applications of integrated CT–fluoroscopy equipment for the expansion of the current interventional radiology approach to overcome treatment challenges for musculoskeletal malignancies.

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Over 50% of cancer patients develop musculoskeletal (MSK) metastases,^{1,2} which portend substantial morbidity.^{3–5} Periosteal inflammation due to tumor infiltration can result in pronounced pain that is poorly responsive to pain medications, while cortical bone erosion can lead to structural instability and fracture. Moreover, the bone microenvironment can provide sanctuary for tumor cells, shielding metastases from

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systemic anticancer therapies. As such, minimally invasive locoregional therapies are a cornerstone in the management of MSK malignancies.

Treatment goals are often individualized and include palliative pain amelioration, local tumor control, structural reinforcement of weight-bearing bones, prevention of skeletal-related events, or a combination of the preceding. Procedural planning and outcome expectations often require careful consideration of tumor biology, size, location, and vascularity. The highly variable combinations of these four factors can result in treatment challenges even for the same tumor type within the same patient. Lateral thinking may be required to promote tailored strategies that overcome these challenges through the combination of multiple IR techniques.

Integrated CT–fluoroscopy equipment (hybrid unit) expands the IR treatment potential for MSK malignancies. These units marry the potential applications of high-resolution multidetector CT image guidance with the real-time spatial capabilities of fluoroscopy image guidance in the same procedural suite.

Many unique treatment challenges can be overcome through the expanded potential of the dual-modality design. Comprehensive treatments that would not otherwise have been safely feasible in the same procedural setting can be performed due to the ability to seamlessly switch back and forth between CT and fluoroscopic guidance. The most useful imaging modality may be quickly and easily selected for each portion of the procedure without relocating the patient. The utility of hybrid units also improves the patient experience and optimizes facility utilization by obviating the need to split multimodality procedures across days.

This article examines the utility of integrated CT–fluoroscopy equipment in the treatment of MSK malignancies as a means to expand the comprehensive IR approach. The primary minimally invasive treatment methods for MSK malignancies are reviewed, as are the potential treatment challenges by a single imaging modality. The basic conceptual design of the hybrid units is outlined and several case examples are presented that demonstrate the added benefit to address MSK treatment challenges. Lastly, ongoing controversies critique the equipment as a redundant or excessive imaging tool, along with rebuttals that advocate for the application in a patient-tailored approach.

MSK IR Treatment Techniques

Multiple minimally invasive procedures have been advanced for MSK malignancies to treat the high variability in disease presentation. Common interventional radiology techniques that are applied include embolization, percutaneous thermal ablation, vertebral augmentation, cementoplasty, and percutaneous screw fixation.⁶ Each technique provides either curative or palliative effects through unique methods. The approach is tailored to address the specific treatment challenges of the targeted lesion for maximal impact on patient survival, activities of daily living, and quality of life.

Embolization describes the endovascular occlusion of tumor arterial blood supply and relies on the preferential deposition of embolic agents to hypervascular tumors due to

increased arterial density in relation to the adjacent non-tumorous structures. Embolization is performed only under fluoroscopic guidance. This procedure may be applied as a presurgical adjunct or as an independent pain palliative measure.⁷ Presurgical embolization has been routinely utilized for hypervascular MSK tumors with the aim to reduce intraoperative bleeding and facilitate surgical exposure and tumor resection.^{8–10} Embolization in the non-preoperative setting is typically used as a pain palliative measure.^{11,12} Pain palliation from embolization occurs through impedance of locoregional osteolysis and reduction of tumor volume, which in combination results in downregulation of cytokine-mediated tumor-associated inflammation, decreases intraosseous pressure and periosteal stretching, and relieves tumoral compression on surrounding tissues and neurovascular structures.^{13,14} Embolization in 243 cancer patients with painful bone metastases achieved a significant clinical response in 97% of procedures with greater than 50% reduction in visual analog pain scale (VAS) and decreased analgesic use.¹⁵

Percutaneous thermal ablation describes the controlled delivery of energy through needle probes to a finite tissue volume to achieve irreversible tumor cellular death.¹⁶ The main thermal energy sources are radiofrequency, microwave, cryotherapy, and laser. Percutaneous thermal ablation of MSK malignancies is typically monitored by CT. Thermal ablation may provide an effective means for local control of both primary and metastatic MSK malignancies that measure less than 3 cm in diameter.^{17,18} In addition, thermal ablation has demonstrated pain palliative effects regardless of tumor size through similar mechanisms listed earlier for embolization.^{19–21} In a multicenter clinical trial for painful bone metastases, percutaneous cryoablation was found to achieve significant pain relief in 75% of patients, with overall mean worst pain score decreasing from 7.1/10 to 5.1/10 at 1 week, and to 1.4/10 at 6 months.²²

Vertebral augmentation and cementoplasty describe pain palliative methods to reinforce structurally weakened or fractured bones by needle injection of bone cement, most commonly the polymer polymethyl methacrylate (PMMA). These techniques may be performed with either CT or fluoroscopic guidance with optimal imaging utilization depending on lesional characteristics. Vertebral augmentation encompasses the treatments of vertebroplasty and kyphoplasty, while cementoplasty replicates these stabilization treatments outside of the spine.^{23–28} A meta-analysis of clinical outcomes of both vertebroplasty and kyphoplasty for the treatment of mixed pathologic compression fractures reviewed 111 studies with 4,235 patients from 2000 to 2014 and showed that, in all studies, a mean VAS ≥ 7.0 was significantly reduced to <4.0 , with a corresponding reduction of analgesic use and improvement in pain-related disability scores.²⁹ Similar benefits are documented for cementoplasty in the long and flat bones. Cementoplasty in 105 patients treated for 140 painful bone lesions showed significantly reduced pain in 91% of cases with reduction of mean VAS from 8.7 to 1.9 at 9-month follow-up.³⁰

Percutaneous screw fixation describes the minimally invasive placement of metallic screws across pathologic lesions in weight-bearing osseous structures.^{31–33} Percutaneous screw fixation may be performed with either CT or fluoroscopic guidance. Optimal imaging utilization depends on lesional characteristics and screw trajectory. The goal of fixation is pain palliation through stabilization of a pathologic fracture or prevention of an impending fracture in locations that require more substantial structural support than provided by cementoplasty alone.^{31,34,35} For pelvic ring and proximal femur stabilization, percutaneous screw fixation performed by the interventional radiologist has demonstrated significant durable pain palliation with mean VAS score decrease from 8/10 to 2/10 in 33 painful fractures, and prevention of impending pathologic fracture in 43/45 patients with median follow-up of 75 days for iliac lesions and 205 days for femoral neck lesions.³³

Challenges to Single-Modality Treatment

Challenges to IR treatment of MSK malignancies are predicated on the high variability in tumor presentation. Deficiencies of single-modality treatment approaches can be exposed when evaluating the ramifications of aggressive tumor biology, tumor location near critical structures, large tumor size, and high tumor vascularity. Careful consideration of each factor independently, as well as in combination, can potentiate the selection of a multimodality treatment. A safer and more effective approach may exploit the expanded benefits of dual-imaging capabilities to negotiate these challenging variables.

Genetic mutational differences within the same tumor type, and even the same patient, may amplify proliferation, accentuate the pain mediator response, and fortify resistance to systemic and locoregional therapy. These factors have important implications for the application of single-modality treatment approaches. Aggressive tumor histology may require more powerful thermal ablation to achieve locoregional control.³⁶ Highly angiogenic tumors can undermine the effects of meticulous embolization through the brisk recruitment and hypertrophy of collateral arterial supply. Rapidly proliferative osteolytic malignancy may destabilize the consolidative effects of fixation hardware or PMMA cement. Reflection upon these tumor biology challenges can suggest that combination treatments might well have utility through synergistic effects. For example, local tumor control by embolization or ablation before consolidative stabilization techniques may be critical to ensure palliative durability.

Another important tumor characteristic that affects treatment approach is tumor location, particularly as it applies in relation to weight-bearing bone and adjacent structures. Tumor location in weight-bearing bone may require multimodality treatment, with initial technique applied for locoregional control and a subsequent technique applied to achieve consolidative stabilization. Furthermore, concern for damage to adjacent structures may block safe passage of treatment needles, may confine or even preclude safe embolization or ablation, or may temper consolidative

efforts to minimize risk associated with potential cement leakage. Adjacent structures that typically generate high procedural risk include critical motor and sensory nerves, spinal cord, end-organ vasculature, hollow organs, and joints. Several innovative techniques have been advanced to isolate tumor from adjacent structures or provide early warning of impending complications.^{37–41} The safest application of these techniques might benefit from guidance from either CT or fluoroscopy, and at times from both.

Large tumor size can amplify the challenges imposed by high-grade tumor biology and tumor location. For example, locoregional control by thermal ablation may be hindered in large tumors due to aggressive underlying tumor biology or curbed by a greater likelihood that the mass abuts a critical structure. Large lytic bone tumors with extensive cortical destruction present greater technical complexity for consolidative techniques. In these cases, creativity with PMMA cement injection and percutaneous screw placement may be required to achieve meaningful stabilization.^{42,43} To address the challenges of large tumor size, lateral thinking may take advantage of multiple imaging modalities to best isolate the lesion, provide more aggressive treatment through a combination of techniques, and monitor for potential complications.

Lastly, increased vascularity may pose treatment challenges for needle-directed therapies. Preventative embolization may be warranted to curtail bleeding risks before proceeding with advancement of ablation probes, cement needles, and screws. By necessity, the combination might require both fluoroscopy for embolization and CT equipment to advance treatment needles or monitor ablation. In addition, vascular lesions may adversely affect thermal ablation efficacy due to heat sink effects. These associations may suggest a greater synergistic role for concomitant embolization and thermal ablation in rapid sequence, similar to the presurgical embolization model.

The Integrated Design

Hybrid units are designed to expand treatment potential through the integration of flat panel fluoroscopy and a high-resolution multidetector CT within the same procedural suite (► **Fig. 1**). The design positions the two separate imaging modalities around a common procedural table. While only one imaging component is used at a time, the intent is easy and rapid selection of the safest and most useful imaging modality for each portion of a procedure.

Various hybrid room configurations are possible to meet the spatial dimensions of the procedural room as well as accommodate the facility-specific workflow. Most units are installed with components aligned in a linear orientation within the same procedure room. A convertible two-room configuration can be constructed that allows the option for single-modality use on two different patients after segregation by a retractable wall. Imaging components can also be oriented in an oblique or angulated configuration, in either the single or convertible two-room configuration. To switch between imaging modalities, various combinations

Fig. 1 Integrated CT-fluoroscopy equipment (hybrid unit). Note the floor tracks extending from the moveable CT to the procedure table, the ceiling tracks for the moveable suspended fluoroscopy c-arm, and rails for the moveable table.

of moveable CT gantry, fluoroscopy c-arm, and table have been devised. See ►**Fig. 1** for an example of an integrated CT-fluoroscopic room.

Although the components function independently, both imaging modalities are fully integrated with the procedural table and often have positional communication with each other. The control monitor and postprocessing equipment may be segregated by modality or combined into one system. All the independent functions of both the CT and fluoroscopy units are provided, often with varied imaging packages to meet heterogeneous utility requirements and budgets. Cone beam CT function is typically retained on the fluoroscopy unit. Advanced CT imaging capabilities and software may be added at the discretion and expense of the proceduralist. Navigation and needle guidance software is available for both modalities and typically functions independently, although information can be communicated from one system to the other.

Hybrid Unit Applications

Integrated CT-fluoroscopy equipment can prove particularly useful for the treatment of MSK malignancies that demonstrate multiple challenging characteristics. The applications may be broadly divided into two categories: (1) a combined treatment to consolidate what would normally require two separate treatments and (2) treatments not otherwise possible with a single imaging modality. Six cases are presented to illustrate procedural approaches for a variety of challenging MSK malignancies. The purposeful use of the hybrid unit was planned to provide a comprehensive treatment in one setting.

►**Fig. 2** depicts the treatment of painful metastatic renal cell carcinoma to the left fifth rib. Pain palliation was the primary objective, with locoregional control as a secondary intent. Challenging treatment factors included large tumor size (>3 cm) and high vascularity. An approach was planned with a combination of embolization followed immediately by cryoablation, to decrease bleeding risk of hemothorax and

Fig. 2 Metastatic renal cell carcinoma to the left fifth rib measured $5.7 \times 3.4 \times 3.4$ cm (a and b). Given the size and vascularity, embolization of fourth to fifth intercostal arteries was performed via radial access (c and d), followed immediately by CT-guided cryoablation (e) with protective carbon dioxide iatrogenic pneumothorax (f).

possibly synergistically potentiate local control. The use of a hybrid unit was offered to consolidate both treatments into a single combined procedure to streamline care and decrease postprocedural hospitalizations. The patient preferred the hybrid approach to decrease procedure-related anxiety from two separate interventions and also minimize time away from work.

►**Fig. 3** depicts the treatment of a patient with multifocal painful pathologic fractures of the left iliac bone from metastatic breast cancer. Challenging treatment factors included aggressive tumor biology and large extent of osseous destruction. Palliative stabilization was planned with percutaneous screw fixation across the two main fracture lines. The use of the hybrid unit was offered, as one fracture was best approached by fluoroscopy guidance to facilitate long oblique screw placement and liberal cement consolidation, while the other fracture was best approached by CT guidance to facilitate closed reduction of the major fracture fragment before precise screw placement through the thin flat bone. Again, the patient preferred the hybrid approach to decrease procedure-related anxiety, minimize time away from home, minimize family time away from work during recovery, and minimize hospitalization and anesthesia requirements from two separate procedures.

►**Fig. 4** depicts the treatment of a patient with metastatic lung cancer and a painful T6 paraspinal mass encroaching on the lateral aspect of the spinal cord. Challenging treatment factors were aggressive tumor biology, large tumor size, high vascularity, and adjacent structures including the spinal

Fig. 3 Two pathologic fractures of the iliac bone from metastatic breast adenocarcinoma (a) treated for pain palliation. Weight-bearing fracture (a—yellow arrows) treated by percutaneous screw fixation using fluoroscopic guidance to facilitate screw placement and cement injection via a posterior approach (b and c). Painful iliac crest fracture (a and d—red arrows) treated using CT guidance to facilitate fracture reduction (e) before percutaneous screw fixation (f).

cord, vertebral artery, lung, and pleura. Treatment was planned in cooperation with neurosurgery for the prevention of tumor compression of the spinal cord. The plan was presurgical embolization of the hypervascular mass before surgical laser ablation of the epidural component. At the time of embolization, cryoablation was planned to treat the paraspinal component for pain control. Rapid sequence of embolization followed by cryoablation was favored to reduce cryoablation bleeding risk and augment the cryoablation outcome through devascularization.

►**Fig. 5** depicts the treatment of a patient with recurrent retroperitoneal liposarcoma for local tumor control. Challenging treatment factors included aggressive tumor biology, large size, and proximity to multiple adjacent critical structures. Treatment was planned with cryoablation and embolization of the adjacent lumbar artery. To achieve margins of at least 5 mm, extensive adjunctive measures were required

to isolate the lesion. The use of a hybrid unit was required to perform the treatment in one procedural setting. Fluoroscopic guidance was first used to embolize the adjacent lumbar artery to decrease bleeding risk. Subsequently, a 0.035-inch wire was passed via a posterior percutaneous approach into a renal calyx and advanced into the ureter to provide a means to reference the ureter during subsequent hydrodissection of the tumor from the ureter and kidney. Carbon dioxide injection into the adjacent neuroforamen was performed to minimize risk of nerve damage from subsequent cryoablation. The use of the hybrid unit was planned to allow embolization and safe ablation to be performed in rapid sequence, as well as to facilitate the advancement of the ureteral guide wire before ablation.

►**Fig. 6** depicts the treatment of a patient with painful metastatic renal cell cancer to the acetabulum. Challenging treatment factors included aggressive tumor biology, large

Fig. 4 Metastatic lung adenocarcinoma of the sixth vertebra and paraspinal tissues measured $3.1 \times 3.6 \times 3.3$ cm (a and b) with epidural encroachment. Treatment performed for pain palliation and prevention of skeletal-related event from potential further extension into the spinal canal. Given size, vascularity, and proximity of intercostal artery (c), embolization was performed with particle and coil deployment (d), followed immediately by CT-guided cryoablation (e—yellow arrows delineate cryoablation margins) after protective insufflation of carbon dioxide (e—red arrows). Posttreatment imaging demonstrates marked reduction in viable tumor (f—postcontrast MRI; g—PET/CT).

Fig. 5 Recurrent retroperitoneal liposarcoma status postsurgical resection measured $3.1 \times 3.2 \times 4.4$ cm (a) treated for locoregional cure. Proximity to multiple critical structures requiring extensive isolation using both fluoroscopy and CT-guided techniques: coil embolization of the adjacent lumbar artery (b), fluoroscopic placement of a wire within the adjacent ureter (c—arrows), hydrodissection of ureter marked by this wire (d—arrow head), hydrodissection of kidney (d—arrow), and carbon dioxide insufflation at adjacent lumbar nerve root (e—arrows) before CT-guided cryoablation (f—arrows delineate ice ball margins).

Fig. 6 Metastatic renal cell carcinoma to the acetabulum measured $3.8 \times 5.5 \times 9.2$ cm (a and b—arrows) treated for pain palliation and prevention of skeletal-related event. Given size and vascularity, particle embolization (c) was followed immediately by CT-guided cryoablation (d and e, arrows delineate ice ball margins) and cementoplasty of superior and posterior aspects of acetabulum (f and g).

size, extensive lytic destruction of the bone including weight-bearing osseous component, and close proximity to the hip joint and femoral head. A rapid sequence of embolization followed by cryoablation was favored to improve complementary treatment effect, especially since the cryoablation margins were intentionally deviated around the hip joint and femoral head. After actively thawing the therapeutic ice ball, cementoplasty of the weight-bearing superior acetabulum was performed for added pain palliation and preventative consolidation.

—**Fig. 7** depicts the treatment of a patient with painful metastatic renal cell cancer to the left iliac bone. Challenging treatment factors included large size, aggressive tumor biology, lytic destruction of weight-bearing osseous component, and high vascularity. A rapid sequence of embolization followed by cryoablation was favored to improve complementary treatment effect for local tumor control. Stabilization was performed with percutaneous cemented screw fixation for pain palliation and to prevent pathologic fracture. The patient preferred the hybrid approach to decrease procedure-related anxiety, minimize hospitalization and anesthesia requirements from two separate procedures, and reduce recovery time with more timely return to normal routine.

Controversies

Several ongoing controversies exist as to the true utility of integrated CT-angiography units for the treatment of MSK malignancies. The hybrid unit can be regarded as a redun-

dant or excessive imaging tool, as flat panel detector fluoroscopy already possessed the potential for volumetric cone beam CT. Furthermore, all procedures could be split into two independent settings performed on different imaging equipment in separate rooms. In addition, the cost of the equipment is higher than single-modality equipment by approximately 50 to 100%. The single-room hybrid design does not translate to appreciable financial benefit as one of the components is often underutilized. Lastly, the ability to perform two sequential procedures in the same setting has not been proven to improve treatment outcome, decrease overall procedure time, or reduce procedural risk.

The rebuttals to these critiques are equally subjective. From the patient perspective, a consolidated single-treatment session provides intangible benefits by decreasing the procedure-related anxiety, anesthesia effects, and hospital encounters by half. From the physicians' perspective, hybrid image-guided procedures require no more, and typically substantially less, time and radiation compared with two separate procedures. Furthermore, the technical advantage of the hybrid design to enhance treatment approach and safety surpasses concerns of redundancy, as the proceduralist is often best served by having the opportunity to use either modality depending on the particular case requirements. From the hospital perspective, the overall time and room utilization is theoretically decreased if considering reasonable projections for a second treatment preprocedural care, anesthesia induction, transportation, room turnaround time, and stay in the recovery unit.

Fig. 7 Metastatic renal cell carcinoma to the left iliac bone measured $4.5 \times 2.6 \times 1.9$ cm (a) with surrounding bone edema on MRI (b and c) treated for pain palliation and prevention of impending pathologic fracture. Given size and vascularity, particle and coil embolization (d) was followed immediately by CT-guided cryoablation (e and f, arrows delineate ice ball margins) and stabilization with percutaneous screw fixation (g).

Conclusion

Integrated CT-fluoroscopy equipment expands the potential of the interventional radiologist to treat challenging MSK malignancies by facilitating the simultaneous application of multiple synergistic treatments and protective measures. The capability to apply both fluoroscopic and CT-guided techniques during the same treatment session enables a more comprehensive and patient-tailored approach. Furthermore, the patient's experience is enhanced by the potential consolidation of two hospital encounters into one.

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