Bone and Soft Tissue Ablation

Ryan C.B. Foster, MD[1] Joseph M. Stavas, MD, MPH, FSIR, FACR[2]

[1] Department of Radiology, Hospital for Special Surgery, New York, New York
[2] Department of Radiology, the University of North Carolina, Chapel Hill, North Carolina

Address for correspondence Joseph M. Stavas, MD, MPH, FSIR, FACR, Department of Radiology, University of North Carolina, CB 7510, Chapel Hill, NC 27599 (e-mail: jstavas@med.unc.edu).

Semin Intervent Radiol 2014;31:167–179

Abstract

Bone and soft tissue tumor ablation has reached widespread acceptance in the locoregional treatment of various benign and malignant musculoskeletal (MSK) lesions. Many principles of ablation learned elsewhere in the body are easily adapted to the MSK system, particularly the various technical aspects of probe/antenna design, tumoricidal effects, selection of image guidance, and methods to reduce complications. Despite the common use of thermal and chemical ablation procedures in bone and soft tissues, there are few large clinical series that show longitudinal benefit and cost-effectiveness compared with conventional methods, namely, surgery, external beam radiation, and chemotherapy. Percutaneous radiofrequency ablation of osteoid osteomas has been evaluated the most and is considered a first-line treatment choice for many lesions. Palliation of painful metastatic bone disease with thermal ablation is considered safe and has been shown to reduce pain and analgesic use while improving quality of life for cancer patients. Procedure-related complications are rare and are typically easily managed. Similar to all interventional procedures, bone and soft tissue lesions require an integrated approach to disease management to determine the optimum type of and timing for ablation techniques within the context of the patient care plan.

Keywords

- ► radiofrequency ablation
- ► interventional radiology
- ► cryoablation
- ► microwave ablation
- ► bone and soft tissue
- ► tumors

Objectives: Upon completion of this article, the reader will be able to identify the basis for treating bone and soft tissue tumors with various thermal and chemical ablation methods. In addition, the reader should be able to explain the expected outcomes and how to minimize procedure-related complications.

Accreditation: This activity has been planned and implemented in accordance with the Essential Areas and Policies of the Accreditation Council for Continuing Medical Education (ACCME) through the joint providership of Tufts University School of Medicine (TUSM) and Thieme Medical Publishers, New York. TUSM is accredited by the ACCME to provide continuing medical education for physicians.

Credit: Tufts University School of Medicine designates this journal-based CME activity for a maximum of ***1 AMA PRA Category 1 Credit***™. Physicians should claim only the credit commensurate with the extent of their participation in the activity.

Bone and soft tissue tumors present unique treatment challenges with a multitude of treatment options including external beam radiation, surgery, minimally invasive ablations, hormonal therapy, and chemotherapy. The technological advances achieved over the past few decades have allowed significant evolution of ablation procedures guided by modern imaging methods. Early ablations were conducted on abdominal visceral organs, and subsequently much has been learned about its clinical uses and complications. This knowledge served as the forerunner to skeletal and soft tissue ablation. Initial reports utilizing thermal ablation used to treat tumors of the musculoskeletal system date back to 1992 with the description by Rosenthal et al ablating osteoid osteomas (OOs).[1] Since then, there has been widespread use of thermal and chemical ablation in the treatment of musculoskeletal tumors. Not only has radiofrequency ablation (RFA) replaced surgical resection for osteoid osteoma because of proven curative rates, shorter convalescence, and

Issue Theme Tumor Ablation; Guest Editor, Charles T. Burke, MD, FSIR

DOI http://dx.doi.org/10.1055/s-0034-1373791. **ISSN** 0739-9529.

decreased morbidity[2] but new techniques including cryoablation, cementoplasty, microwave, laser, focused ultrasound, and electroporation have also been developed. Given the success of these minimally invasive therapies, many orthopedic surgeons, oncologic physicians, and interventional radiologists worldwide consider ablation techniques for a variety of bone and soft tissue tumors for cure and palliation. This article of *Seminars in Interventional Radiology* explores the most recent clinical indications and outcomes for bone and soft tissue ablation, as well as an update to the previous review by Kurup and Callstrom.[3]

Primary Bone Tumor Ablations

Osteoid Osteomas

These small benign bone tumors were originally described by Jaffe in 1935.[4] OOs are a relatively common bone lesion accounting for approximately 10% of all benign bone tumors.[5] They tend to occur in children and young adults with a male preponderance. Classically, these lesions are associated with intermittent pain that is worse at night and relieved with nonsteroidal anti-inflammatory drugs. OOs are most often cortically based, diaphyseal or metaphyseal, and most frequently found in the femur or tibia. They are composed of an osteoid nidus with a peripheral ring of highly vascularized fibrous connective tissue.[5] They can be associated with scoliosis, bowing deformities, and cartilage injury depending on their location. As a result, either for pain relief or to prevent long-term sequelae, patients seek expedient definitive therapy.

Curative treatment of these tumors, which are often less than 1 cm in size, is achieved by nidus elimination. OOs are highly innervated and very painful during ablation and therefore usually require general anesthesia. Lesion access is obtained by drill or large-bore needle using computed tomography (CT) fluoroscopy; a single tined RFA probe with a 5 to 10 mm tip is inserted so that the tip lies within the epicenter of the osteoma (►**Fig. 1**). The electrode is then heated to 90°C for 4 to 6 minutes and allowed to cool. After complete tumor coverage, the electrode is removed.

Clinical studies have reported high rates of success in patients with OOs treated with RFA. Rosenthal et al reported on 263 patients with OOs treated with RFA for which 2-year follow-up data were available for 126 patients.[6] Of these, 117 (89%) reported complete symptom relief. Rimondi et al reported on 557 nonspinal OOs treated with RFA and reported a primary success rate of 96% (533 cases) and a secondary success rate of 99.6% (555 cases) following reablation.[7] Gebauer et al performed ablations on 59 OOs with complete pain relief in 51 patients (89.2%) following a single ablation and 56 patients (97.9%) following a second ablation.[8] In the same study, a meta-analysis was performed that included 1,356 patients and 20 clinical studies, reporting an overall primary success rate of 92%.

There is no difference in the recurrence rate of surgically resected OOs versus ablated OOs, and the complication rates are lower with ablations.[2] Rosenthal and others' combined study group of 125 patients yielded a recurrence rate of 9% in the surgical group and 12% in the ablated group, the difference of which was not statistically significant.[2] A systematic review of the literature in 2013 by Lanza et al demonstrated the average rate of recurrence following ablation among 27 articles and 1,772 patients was 4.9%.[9] The meta-analysis of OO ablations of Gebauer et al in 1,187 patients across 13 studies reported a collective complication rate of 2.9% (ranging from 1 to 8%).[8]

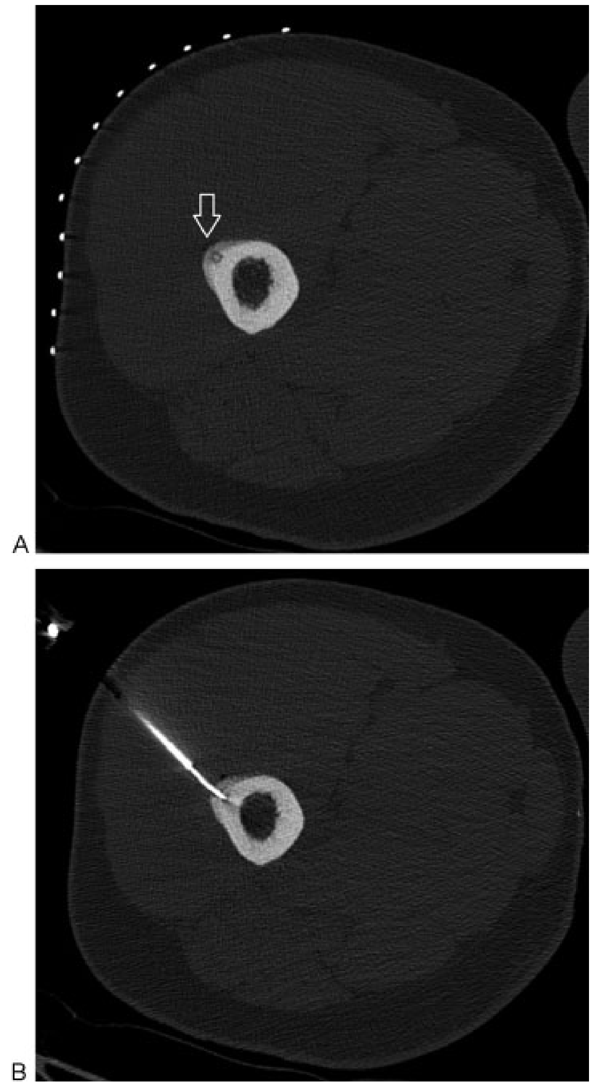


Figure 1 A 44-year-old man with recent onset radiating hip to mid-thigh pain. (**A**) Axial CT with cortical thickening and lucent lesion with central sclerotic nidus consistent with osteoid osteoma (arrow). Overlying skin grid used during lesion targeting for safe access window. (**B**) Initial biopsy needle for tissue sample was inserted, and the RFA probe tip was advanced into the central portion of the lesion. CT, computed tomography; RFA, radiofrequency ablation.

Laser-induced thermotherapy (LITT) has also been used successfully to eliminate OOs. LITT uses optical fibers that deliver infrared light into tissue causing irreversible cellular destruction from thermal injury. Most current systems consist of a Nd:YAG laser with a wavelength of 1,064 nm or diode lasers with wavelengths of 980 or 805 nm. During ablation, the applicators are actively cooled to prevent charring of the target. A spherical ablation volume in bone of 2.0 cm in diameter can be achieved by light energy of 2.0 W when delivered by closely grouped fibers.[10] Larger volumes can be ablated by spreading apart the optical fibers before insertion. Ablation time varies in the literature from 6 to 10 minutes and is determined by nidus size.

LITT is magnetic resonance imaging (MRI) and CT compatible, a major advantage of the system. MRI guidance permits additional accurate mapping during treatment while eliminating radiation exposure in young OO patient populations. Unfortunately, bone biopsy devices are noncompatible with MRI laser sets; therefore, biopsies are not possible to perform during the procedure. Fortunately, the diagnosis is often obvious on imaging before the ablation, but if necessary CT can be used to initially guide a biopsy followed by radiofrequency or laser ablation. Other benefits of laser ablation include a more predictable volume of energy deposition to target tissues and introduction via an 18-gauge spinal needle, reducing the needle size required for RFA.

Laser photocoagulation was first reported in 1997 by Gangi et al with a cohort of 15 patients in which CT guidance was used.[11] Since that time, there have been numerous reports demonstrating high technical and primary success rates with few complications.[12–15] The largest study published by Gangi et al in 2007 ($N = 114$) yielded a primary success rate of 93% (106 patients), recurrence in 5% (6 cases), and only one minor postprocedural complication of temporary reflex sympathetic dystrophy.[13] The first successful laser ablation of an OO with an open system 0.23T MRI was reported in 2003 by Sequeiros et al, a technique that continued to evolve with high-field 1.0 T MRI to guide laser ablation with continuous thermal monitoring (MR thermography).[16,17] A recent study in Germany by Maurer et al outlined a cost comparison of CT-guided RFA versus MR-guided laser ablation, and showed that MR-guided laser ablation was less expensive by 20%.[18] Their price extrapolations with identical assumptions showed CT-guided LITT had the lowest cost, being 44.5% less than CT-guided RFA and 31% less than MR-guided laser.

Chondroblastoma

Another benign primary bone tumor considered for ablation in the past 15 years is chondroblastoma (CB). Originally described by Jaffe and Lichtenstein in 1942, these rare tumors of children/young adults are located in the epiphyses/apophyses, are often painful, and can limit range of motion.[19] CBs have typically been treated with operative curettage; however, complications such as limb shortening and premature osteoarthritis were frequent given their proximity to the growth plate and cartilage. The rarity of this tumor prevents large-scale studies, but since 2001 case reports have been published describing successful RFA for tumor elimination.[20–25] RFA offers several advantages, similar to OOs, including a shorter postoperative hospital stay (most studies report a single day or overnight stay). Recurrence rates following surgery range from 10 to 35%, whereas with RFA treatment there have been no reported recurrences.[26–29] This suggests that RF ablation is a safe and effective alternative to surgery for smaller CBs when proximity to cartilage and growth plates and weight-bearing surface location are taken into account.

CBs are often painful and ablation requires general anesthesia. Probe size is chosen based on tumor volume and may require electrode repositioning and serial ablations to ensure complete tumor coverage. Single-tined probes have been postulated to have fewer complications than multi-tined probes.[21,24] Given the predictable and uniform ablation field produced, bipolar probes may be a valuable asset in the treatment of CBs in close proximity to cartilage or a physis.[30] An important consideration relating to epiphyseal location is to ensure the subchondral bone plate is excluded from the ablation zone to avoid chondrolysis, osteonecrosis, and/or articular surface collapse.[24] Thus far, Rybak et al has reported the largest number of CB ablations ($N = 17$) with one adverse outcome of delayed articular surface collapse (thought to be secondary to residual viable tumor).[21]

Other Primary Bone Lesions

The use of ablation in the treatment of other benign bone tumors has been expanded beyond OOs and CBs in the past 10 years. Corby et al reported on their experience in ablating two solitary eosinophilic granulomas of bone.[31] CT-fluoroscopy–guided treatment and a multi-tined probe were used due to larger lesion size, and no complications were experienced. Critics raised concern for treating such large lesions involving the weight-bearing axis because of pathologic fracture risk.[32] There have also been at least four case reports of RFA and cryoablation of sacrococcygeal chordomas.[33–36] Other slow growing but locally aggressive malignancies can be difficult to completely resect and have high recurrence rates and may be amendable to local ablation (►**Fig. 2**).

Metastatic Bone and Soft Tissue Ablations

Metastases are the most common bone lesions, with up to 85% of patients who die from breast, prostate, or lung cancer having pathologic evidence of osseous spread of disease.[37] Complications related to bone metastases include pathologic fracture, intractable pain, neurovascular impingement, and decreased mobility, all of which can contribute to a diminished quality of life. Conventional therapies for pain management include systemic treatments (e.g., chemotherapy, hormones, radiopharmaceuticals, bisphosphonates, and analgesics) and local treatments (external beam radiation therapy and surgery). Despite a vast array of available options, pain related to bone and soft tissue metastatic deposits is often inadequately treated and many times described as “the worst” pain cancer patients experience.

External beam radiation therapy or surgery for oligometastatic disease and systemic chemotherapy for widely disseminated metastatic disease are the most often used initial treatments for cure and palliation. External beam radiation therapy remains the most accepted first-line therapy for metastatic osseous disease, although lack of tumor sensitivity, risk of damage to regional organs, or the inability to reirradiate the same area may preclude its use. Radiation achieves relief in approximately 60% of patients but is often

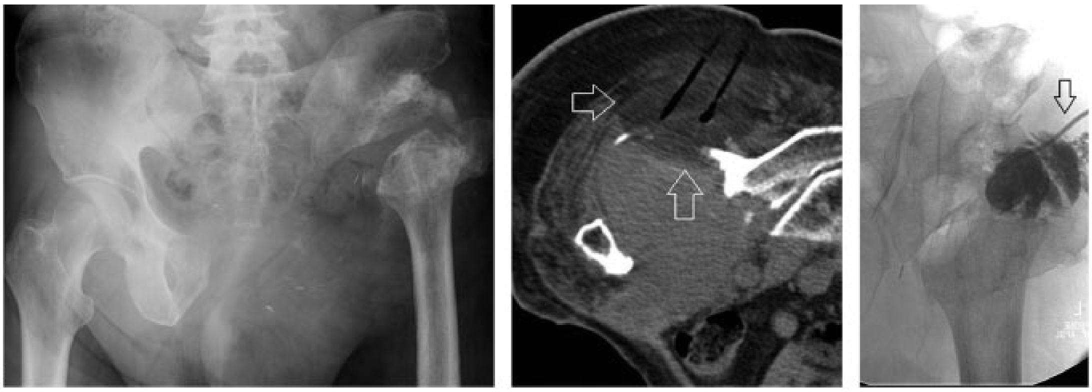


Figure 2 (**A**) A 60-year-old man with previous hemipelvectomy for large chondrosarcoma. Biopsy-proven recurrence near pseudoarticulation with large mucoid component. (**B**) Prone CT post-cryoablation depicts ice zone (arrows) after probe removal. Four probes were placed due to the large tumor size. (**C**) Two weeks later, the patient developed staphylococcal abscess at the treatment site requiring catheter drainage for an extended period. Contrast sinogram via pigtail catheter (arrow) shows residual cavity. CT, computed tomography.

temporary.[38] Surgical fixation is reserved for patients with recent or impending pathologic fractures, although many patients are nonoperative candidates. With improved overall patient survival among many cancer subsets, there has been an increased interest in alternative locoregional therapies including RFA, cryoablation, high-intensity focused ultrasound, laser ablation, and cementoplasty for pain management and tumor reduction.

Soft tissue metastases can also be a source of severe pain, ulceration, and mass effect. Many tumors are radiosensitive, but their location renders external beam therapy harmful to adjacent bowel or other viscera. In these instances, ablation techniques may be employed. Certain soft tissue lesions of the skin or other superficial locations may be amenable to percutaneous ablation if skin temperature modulation is possible to prevent ulceration (►**Fig. 3**).

Early reports indicate that percutaneous ablative treatments may improve overall survival and life years gained, and may be cost-effective.[39] Discussion before ablative therapy with the patient, family, and other caregivers is paramount to establish treatment expectations, particularly if hospice care is involved and non-resuscitation status is in place. A pretreatment pain assessment utilizing the Brief Pain Inventory Short Form (BPI) or Memorial Pain Assessment Card (MPAC) is necessary for quantitative posttreatment evaluation. A physical exam with imaging correlation is crucial to determine the source(s) of pain and the safest approach for ablation.

Based on imaging findings, relative contraindications to ablation include tumors that are less than 1 cm away from the spinal cord, major motor nerves, and arteries supplying the central nervous system, bladder, or bowel.[40] Osteolytic and mixed osteolytic/osteoblastic bone metastatic deposits are most amenable to ablation. Purely, osteoblastic lesions can be difficult to access due to their high density and are associated with poor deposition of RFA energy.[41]

Most procedures are performed on an outpatient basis with sedation or regional anesthesia. General anesthesia and monitoring may be necessary for patients with elevated baseline pain or on large doses of analgesics. With respect to primary imaging guidance, CT is mainly used for osseous and deeper soft tissue lesions, while ultrasound can be used to guide superficial treatments. MRI has limited use due to probe incompatibility.

The goal of probe/antenna placement is to destroy sensory afferent nerves in the region of the lytic bone cortex, periosteum, and contiguous soft tissue tumor. Insertion of probes within or adjacent to the area of bone destruction, rather than in the bone itself, often provides the most effective treatment and may reduce tumor stimulation factors and osteoclast activity (►**Fig. 3**).

Figure 3 A 55-year-old man with local colorectal bone metastasis, who failed external beam radiation therapy for pain control. He was receiving 15 mg/hour hydromorphone basal rate patient-controlled analgesia pump with breakthrough oral oxycodone. The patient was lethargic with severe pain (10/10). Two microwave antennae were placed adjacent to a destructive ilium soft tissue mass, and ablation was performed at 65 W for 10 minutes. After treatment, the patient's pain and medication requirements lessened with an improved quality of life during hospice.

Table 1 Results of published series of metastatic bone treatment using RFA and cryoablation with analgesic and pain reduction endpoints

Study	Publication year	Number of patients	Ablation method(s)	Analgesic reduction	Pain reduction, 0–10 (initial/postablation)	Complications
Callstrom et al[84]	2002	12	RFA	8/10 reduction	8/3.1	None
Goetz et al[80]	2004	43	RFA	Decreased at 6 and 12 wk	7.9/1.4	3—skin burn, incontinence, and fracture
Callstrom, et al[46]	2006	14	Cryoablation	8/8	6.7/1.4	None
Thanos et al[81]	2008	30	RFA	27/30	6.8/4.7 (mean pain)	None
Dupuy et al[42]	2010	55	RFA	Not reported	Reduction ($p < 0.001$) at 3 mo	5 total, possible or probable
Thacker et al[78]	2011	58	Cryoablation (36) RFA (22)	Decrease with both cryoablation > RFA	6.5/3.5 cryoablation 6/5 RFA (24 h posttreatment)	None
Callstrom et al[82]	2013	61	Cryoablation	Not reported	7.1/5.1	1—osteomyelitis

Abbreviation: RFA, radiofrequency ablation.

The two main types of ablative techniques are RFA and cryoablation, which although both being thermal tools have some differences. The use of these modalities for painful bone and soft tissue metastasis has shown to be effective in reducing pain and analgesic use (►**Table 1**). The American College of Radiology Imaging Network study by Dupuy et al using RFA showed continued pain improvement up to 3 months following ablation, and < 10% minor complication rate.[42] One of the primary goals of ablation is to incorporate all interfaces between the tumor and adjacent normal bone in the ablation field.[43] Depending on the size of the tumor, a single-tined electrode (ranging from 14 to 17 gauges) or a multi-tined electrode may be selected. Multiple electrodes with overlapping ablation fields may also be used for larger lesions to ensure appropriate coverage. RFA is performed at 90 to 100°C for 5 to 10 minutes. Following cooling of the probe for 5 minutes, it may be repositioned and subsequent ablation performed if necessary. Bipolar devices theoretically have greater predictability and precision and have recently been used to treat osseous spinal metastatic disease in both animal and human models with success and few complications.[44,45]

Cryoablation has been shown to be effective and safe in the treatment of bone metastases.[46] A distinct advantage of this method versus RFA is the ability to monitor the developing ice ball by intermittent CT or MRI. This allows for increased precision of tumor coverage and ensures proper exclusion of critical structures from ablation. The probes are larger than those used in RFA (ranging from 11 to 17 gauges), and multiple probes can be used synergistically to increase the size of the ice ball. Multiple probes must be placed approximately 1 cm from the tumor margins and 2 cm from each other. The ablation involves a 10-minute freeze, 5-minute thaw, and then a second 10-minute freeze, but there are numerous reported variations on freeze–thaw–freeze cycles that depend on tumor type and size. In relation to RFA, there is less procedural pain and reports also suggest slightly longer term pain relief.

Bone Augmentation: Cementoplasty

Cementoplasty, also called osteoplasty, involves the percutaneous injection of polymethylmethacrylate (PMMA) cement into bone. PMMA stabilizes microfractures and is often used in the treatment of osteoporotic or tumor-related spinal compression fractures (i.e., vertebroplasty). Cementoplasty can be used alone or in conjunction with RFA (►**Fig. 4**). Some authors suggest there may be a synergistic effect when using these techniques together, given the thermal effects of RFA and the tumoricidal effects of PMMA.[47] In the event that RFA will be followed by cementoplasty, it is important to obtain access with larger gauge needles to allow for the injection of the cement. As well, the use of fluoroscopy or CT fluoroscopy during cement injection will provide feedback to better direct the cement instillation.

There are many successful reports in the literature using this technique to treat pain referable to an underlying metastatic deposit.[47–49] Anselmetti et al treated extraspinal metastases with cement alone in 43 patients and with combination RFA and cementoplasty in 7 patients.[48] His group found a statistically significant reduction in mean pain scale from 9.1 to 2.1, which was associated with a decreased need for postprocedural analgesia medications. Interestingly, there was no statistical difference ($p = 0.83$) between the two groups with respect to pain reduction, although a study with larger sample sizes would be needed to draw a firm conclusion regarding the possibility of synergy with cementoplasty and RFA. Munk et al reported on 25 RFA procedures followed by cementoplasties in 19 patients with painful neoplastic lesions of bone; these authors reported a 100% technical success rate and significant reduction in pain.[47] Seven minor complications occurred including limited

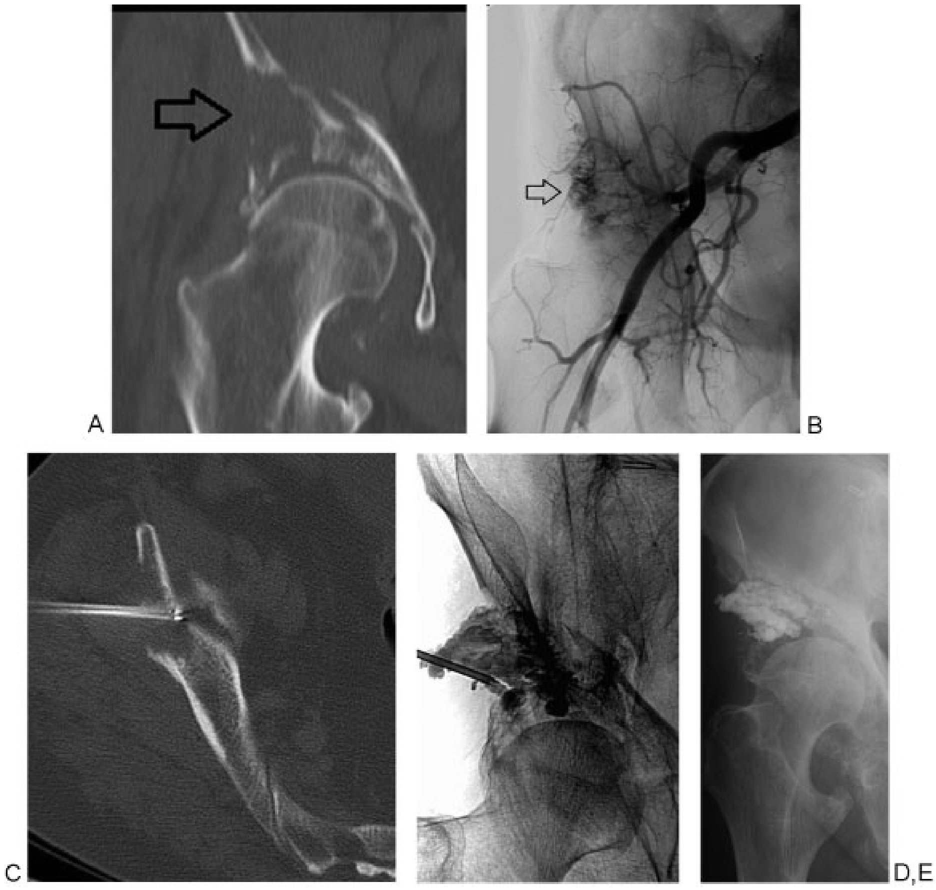


Figure 4 Multimodality treatment in 65-year-old nonambulatory man with metastatic renal cell cancer and severe right hip pain. (**A**) Coronal reconstruction CT scan demonstrates an acetabular osteolytic lesion and intra-articular fracture (arrow). (**B**) Preembolization angiogram demonstrating a hypervascular lesion (arrow) treated with particle embolization. (**C**) The patient suffered recurrent pain, and subsequent bone RFA was performed along the superior aspect of the lesion. (**D**) Cementoplasty augmentation after RFA was performed in to stabilize the joint. (**E**) Six-month posttreatment plain film; the patient's pain resolved and he was able to walk. CT, computed tomography; RFA, radiofrequency ablation.

cement extravasations and transient thermal nerve injury. Lane et al performed 53 combined RFA and cementoplasty procedures on painful bone metastasis with similar results of considerable pain reduction and decreased patient need for analgesia, with minimal complications.[49]

Soft Tissue Ablations

Desmoid tumors are the most frequently reported soft tissue lesions treated by thermal ablation, and have formed the foundation for other tissue tumor management protocols. Desmoid tumors represent highly differentiated monoclonal type fibroblasts with profuse collagen activity, which grow along fascial planes, causing local infiltration and compression of adjacent structures. They may have superficial (fascial) or deep (musculoaponeurotic) locations and varying degrees of biologic behavior.[50] The incidence of desmoids in the general population is two to four cases per million per year, which corresponds to approximately 900 new cases per year in the United States.[51,52] Those associated with Gardner syndrome and familial adenomatous polyposis may have an incidence up to 16%.[51–53]

Desmoids are commonly categorized into two types, those of abdominal and extra-abdominal location. Multiple treatment methods have been used, including surgical resection, external radiation, and chemotherapy. These lesions are aggressive, and recurrence is common; repeated surgeries are necessary in certain populations for local tumor control. Treatment strategies for symptomatic desmoids are ongoing, with surgery as a first-line therapy and adjunctive radiation treatment if necessary for positive margins.[50,54] For recalcitrant lesions where functional sparing surgery and radiation are not options, thermal ablation has provided local control in certain cases.[55] The oftentimes superficial location, avascular/hypovascular nature, and patient/physician frustration with conventional therapies allow desmoids to serve as a good model for percutaneous ablation therapies (►**Fig. 5**). If local control fails with percutaneous ablation methods, nothing has been lost, as other treatment options can still be pursued.

Other benign soft tissue tumors and lesion such as fibromas, neurofibromas (with or without neurofibromatosis type 1 [NF-1] or 2), keloid scars, and vascular malformations may show promise of symptom improvement with percutaneous ablation techniques. NF-1 is reported to have an 8 to 13%

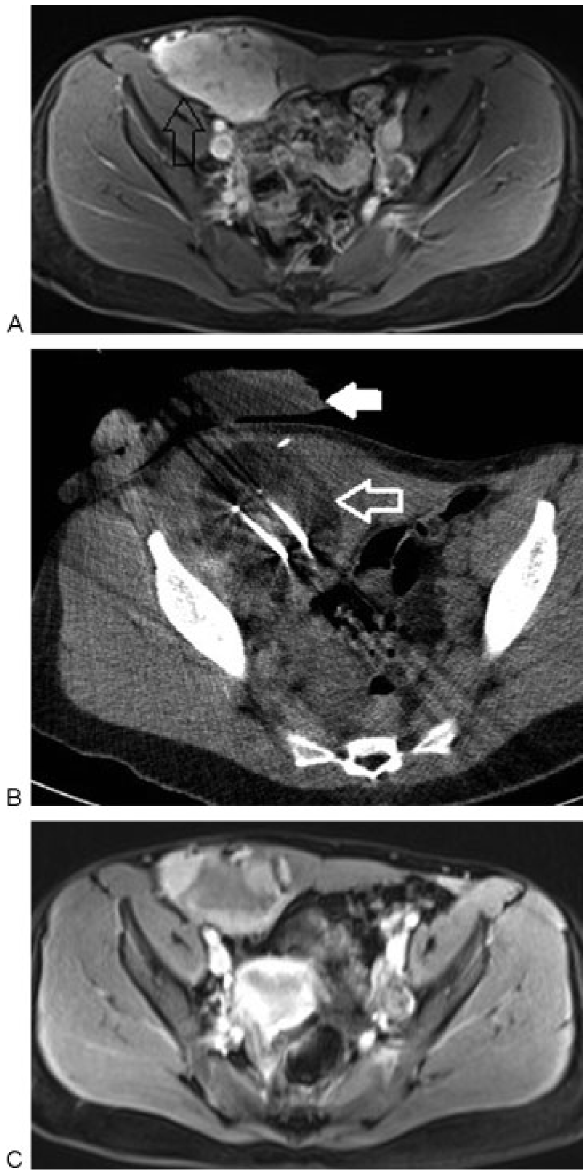


Figure 5 A 24-year-old woman professional dancer with recurring abdominal wall desmoid since the age of 12, now causing pain and inability to perform. She underwent multiple surgeries and chemotherapy. (**A**) Pretreatment MRI with large right rectus desmoid (arrow) with adjacent small bowel. (**B**) Cryoablation probes and ice ball formation (open arrow) with hydrodissection interface medially to protect bladder and bowel. Overlying gloves with warmed saline were placed for thermal skin insulation (solid arrow). (**C**) Six-month post-treatment scan demonstrating decreased tumor size and firmness, which allowed the patient to resume her dancing career. MRI, magnetic resonance imaging.

increased lifetime risk of malignant degeneration within peripheral nerve sheath tumors, and treatment with thermal ablation offers a nonsurgical option.[56,57] Neurofibromas associated with persistent pain, nerve deficits, altered texture, or those that have enlarged on serial exams should have a low threshold for biopsy and treatment (►**Fig. 6**). Surveillance with contrast MRI and positron emission tomography/CT allows for early management of suspicious lesions, especially in the more common NF-1 type.

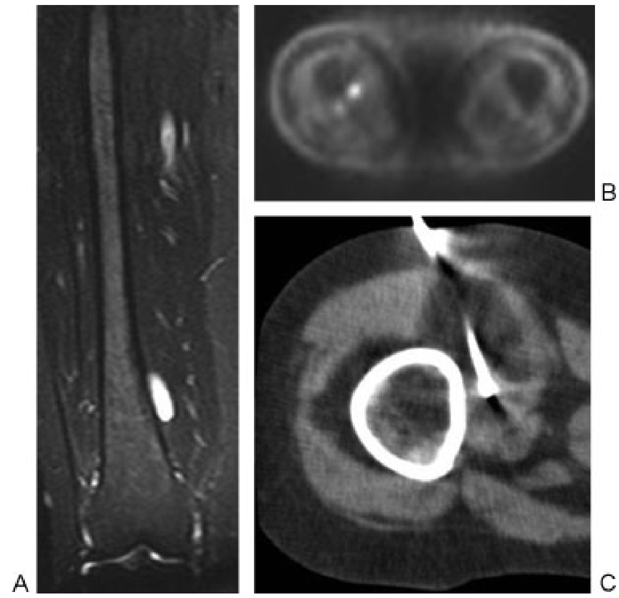


Figure 6 A 45-year-old with neurofibromatosis type 1 and new painful medial thigh neurofibroma (NF). (**A**) Coronal contrast-enhanced MRI shows NF enhancement. (**B**) PET/CT reveals FDG avid uptake in the lesion. (**C**) Biopsy results were benign, but the patient opted cryoablation for symptomatic control. CT scan performed during the procedure with ice ball formation at NF site. The patient's pain resolved posttreatment, and has now been symptom free for 3 years. CT, computed tomography; FDG, fluorodeoxyglucose; PET, positron emission tomography.

Keloids, always occurring at the site of prior skin injury, are defined as fibroproliferative tumors within the dermis that produce excess collagen. These tumors progress, sometimes exuberantly, but have no malignant potential. Numerous treatments have been attempted that include surgical excision and grafting, radiotherapy, laser and intralesional injections, and cryosurgery, all attempting to minimize additional skin surface injury. The recent use of intralesional cryoablation is promising and may offer an additional option for this challenging problem.

Cornelis et al recently reported on cryoablation treatment of symptomatic venous malformations.[58] Though a small series with short follow-up, there was symptomatic improvement at 6 months. This may prove beneficial for certain vascular malformations recalcitrant to standard conservative, operative, medication, or sclerotherapy treatments.

Chemical Ablation of Benign Bone Tumors

Wide excision curettage with methacrylate or bone allograft packing provides effective healing for most symptomatic benign bone lesions such as aneurysmal and unicameral bone cysts (ABC and UBC).[59] On occasion, there is tumor regrowth that necessitates further surgery, for instance, with ABCs located near a growth plate (where recurrence rates may be as high as 71%).[60] The use of adjunctive percutaneous chemical sclerosant therapy during surgical treatment of UBCs, ABCs, and other lesions has long been used by orthopedic surgeons. Primary percutaneous scleroablation of ABCs has been recently described by Shiels and Mayerson as a minimally invasive option.[61] In their series of 20 patients younger than 19 years treated with a doxycycline and 25% albumin regimen, 15 were nonsurgical primary treatments. These investigators demonstrated a 5% recurrence rate over a 24-month period, with the number of treatments ranging from 2 to 14 sessions.[61]

Special considerations for percutaneous chemical bone tumor ablation include (1) adequate tumor tissue diagnosis (either by open orthopedic or needle biopsy); (2) use of large gauge or cutting needles for cortical penetration into the lesion; (3) pediatric and adult general anesthesia; (4) precise total compartment treatment avoiding overfilling and control of venous outflow to reduce local and distant sclerosant complications; (5) postprocedural management of immobilization, pain, and other complications; and (6) follow-up to assess healing response and realization for repeated treatments.

Usually, the bone lesions are superficial with a thinned cortex and 14- to 25-gauge needles are adequate for lesion access (►**Fig. 7**). Foamed solutions offer improved ultrasound visualization to ensure the entire lesion is bathed with solution to limit the opportunity of recurrence. Lesions that fail surgical and intralesional injections may have another underlying pathology, such as a coexisting giant cell tumor.

Chemical Ablation of Soft Tissue Tumors

Percutaneous chemical ablation has also been used in the treatment of certain symptomatic fibrous soft tissue tumors, most commonly aggressive fibromatosis, desmoid tumors, and neurofibromas. As noted previously, primary management is surgical resection and chemotherapy, but high recurrence rates (up to 25–70%) make less invasive treatment methods a key second-line therapy. Since desmoid tumor treatment is extremely difficult, multidisciplinary management is necessary to provide effective therapies that include thermal ablation (previously described) and chemical injection.

There are no large series in the literature that detail the effectiveness and safety of intralesional soft tissue injections for symptom relief or tumor dissolution. Numerous chemical solutions have been described for intralesional injections including 50% acetic acid, dehydrated ethanol, steroids, and chemotherapy agents. Staged treatment is necessary because of lesion firmness and the small quantity of sclerosant that can be injected. Ultrasound-guided monitoring (►**Fig. 8**) is the favored imaging modality, and small gauge, side hole needles such as the Whitaker (Becton Dickinson, Franklin Lakes, NJ) or Sprotte (B. Braun Medical, Bethlehem, PA) offer better dispersion into the lesion.

Additional Ablation Techniques

Various other techniques have been used for ablation of MSK tumors including microwave, focused ultrasound, laser, and electroporation, for which only limited data exist.

Microwave ablation uses a 14.5-gauge antenna to deliver electromagnetic microwaves resulting in heating of tissue. This technique may be faster than RFA, as it can reach higher temperatures due to less influence from tissue impedance and vascular cooling effects. Early reports demonstrating palliative treatment of pain in osseous metastatic disease have been promising.[62,63]

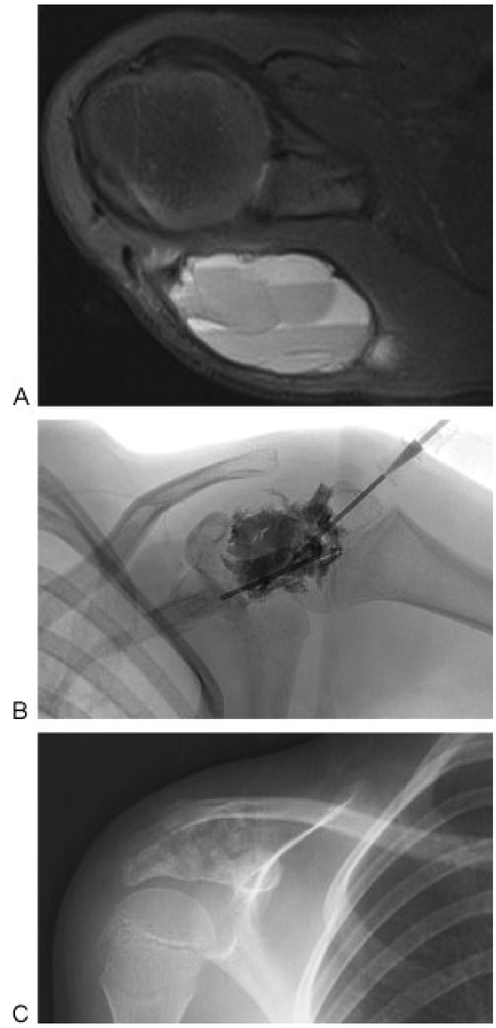


Figure 7 A 7-year-old patient with enlarging painful posterior right shoulder mass. (**A**) Axial MRI with multiple fluid-fluid levels and cortical thinning. On biopsy, this was proven to be an aneurysmal bone cyst (ABC). (**B**) The patient was placed prone under general anesthesia and bloody contents were aspirated from the ABC. Contrast injection showed absent vessel outflow and cyst communication. Foamed concentrated doxycycline was injected with double 18-gauge needles to allow the sclerosant to egress to prevent lesion overfilling. (**C**) Expected bony sclerosis posttreatment. MRI, magnetic resonance imaging.

Focused ultrasound is a noninvasive technique where sound waves are directed into and concentrated within an area of tissue, leading to local heating and thereby cellular destruction. Guidance may be performed with real-time ultrasound or MRI, the latter of which offers additional advantages of improved resolution allowing precise treatment mapping and intraprocedural thermal mapping with MR thermometry. This is useful in treating painful bone metastases due to destruction of periosteal innervation.[64] Reports in the published literature demonstrate significant and reproducible pain reduction.[65–68]

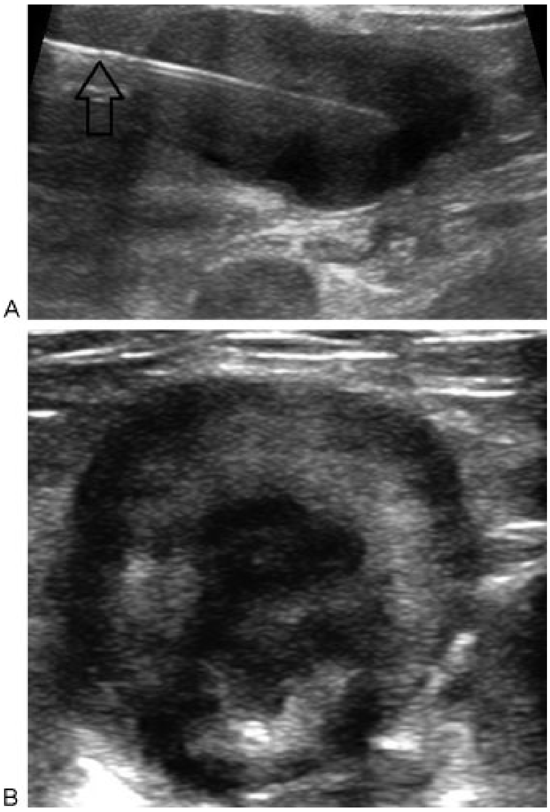


Figure 8 Painful quadriceps desmoid tumor limiting function. (**A**) A Whitaker needle (arrow) was placed into the tumor for slow intralesional injection of 2 mL of 50% acetic acid. Real-time ultrasound was used to observe for peritumoral extravasation. (**B**) Two-month follow-up ultrasound demonstrating hollowed hypoechoic central necrosis. The patient's pain reduced from 9/10 to 3/10.

Laser-induced thermotherapy, a modality described earlier for treatment of OO, has also seen limited use in the treatment of metastatic disease. Given the relatively small ablation zone afforded by a single standard applicator, larger lesions require multiple laser fibers for adequate treatment. Groenemeyer et al reported using a Nd:YAG laser with a wavelength of 1,064 nm under CT guidance to treat three patients with spinal metastases.[69] Delivering 4 to 10 W of laser energy for a total of 1,400 to 2,600 J of energy over 60 to 90 minutes yielded a 30 to 45% pain reduction without complications. Ahrar and Stafford recently described both preclinical studies where they successfully ablated lumbar vertebral tumors in four canine subjects as well as briefly outlining an open clinical trial in which, at the time of publishing, seven patients had been "successfully treated, with no adverse events."[70] Tumor types, laser parameters, and outcome measures were not provided.

Electroporation involves delivering short, intense electrical pulses via electrodes to a body of tissue which leads to reversible cell membrane permeability and can ultimately impair vital cell functions leading to cell lysis and death.[71] This technique is being studied with concurrent cytotoxic drug delivery, known as electrochemotherapy (ECT), as a method to increase tumor cell absorption of the chemotherapeutic agent. ECT is known to be effective in treating skin and subcutaneous lesions,[72,73] and recently studies have been published demonstrating tumor response in animal models with bone metastases.[74] A single case report exists in the literature describing curative treatment of a digital chondrosarcoma by two courses of ECT (yielding 90% tumor cell necrosis), followed by marginal resection allowing the finger to be spared.[75] It is clear that more primary research is needed before this technique can be considered among the treatment options for osseous malignancies.

Complications of Soft Tissue and Bone Ablation

Preprocedure consultation with patients and family members must include the risks and benefits of the ablation and related complications, and weighed against other forms of treatment. Conservative management that delays treatment may be an option in certain situations, if acceptable to the patient and family (►**Fig. 9**).

Precautionary measures such as correction of coagulation factors or low platelets ($< 50,000/dL$) and administration of prophylactic antibiotics will lower certain procedural risks. Assessment of renal function is necessary if intravenous

Figure 9 A 13-year-old boy with knee pain. (**A**) Radiography demonstrated a vague lucent area near growth plate. (**B**) Coronal MRI showing osteoid osteoma lesion and adjacent edema. (**C**) Due to risk of early growth plate closure with surgical and RFA treatment, he was treated conservatively. Follow-up plane film at the age of 16 years at the time of closure. (**D**) CT-guided RFA ablation at sclerotic OO zone. CT, computed tomography; MRI, magnetic resonance imaging; RFA, radiofrequency ablation.

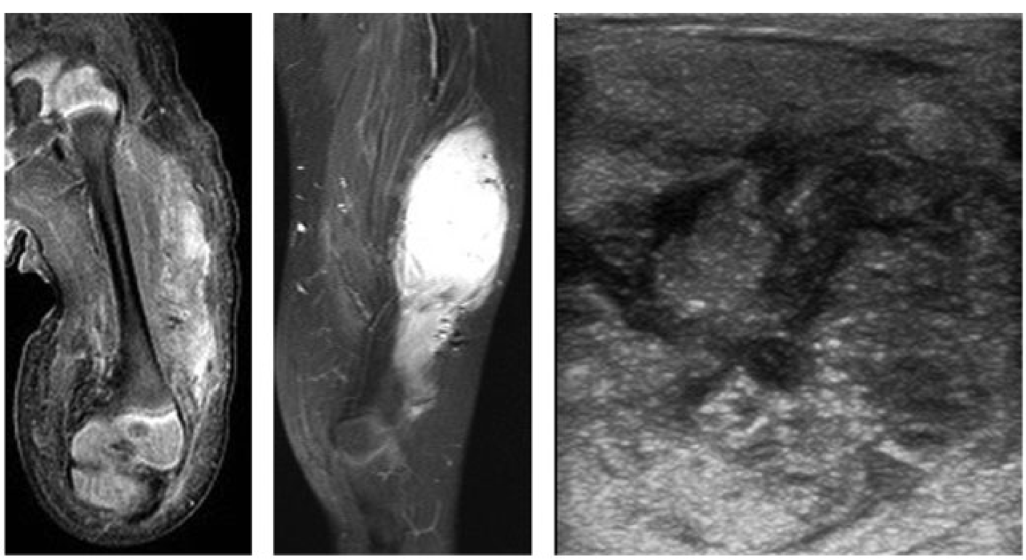
Figure 10 Large soft tissue skin ulceration following thermal ablation of a painful ischial fibrous tumor. The skin ulceration was due to insufficient dermal temperature protection. A second small ulcer is noted more medially. The wound eventually healed follow eschar formation and surgical debridement.

contrast agents are given for CT or MRI. Fracture risk and prevention must be assessed in weight-bearing bone treatments (OOs and metastatic disease), and the need for bed rest or ambulation assist measures must be determined. Finally, patient expectations must be addressed to better understand the limitations of minimally invasive pain reduction methods, tumor management, and the possibility of recurrence.

In seven separate bone metastasis ablation series conducted for pain reduction, the reported combined complication rate was less than 3.3% (9 total complications out of 273 ablations) and possibly lower (►**Table 1**). Included in the bone ablation series were hypervascular metastases from renal and thyroid tumors that potentially would have increased bleeding risks. Littrup et al treated 251 oligometastatic tumors at numerous sites with cryoablation, and reported a major (> grade 3) complication rate of 2.3%.[76] Their series included 34 bone and 76 superficial soft tissue tumors. In a study of complete bone tumor remission by McMenomy et al, two major events occurred in 40 procedures (5%).[77] The low complication rates are likely due to the superficial nature of many ablation sites, the relative avascular or hypovascular nature of many soft tissue tumors, the use of visceral and nerve displacement methods, and tract cauterization with RFA and microwave techniques. In addition, many tumor sites have decreased or altered vascular perfusion from prior surgical resection, chemotherapy exposure, and radiotherapy.

Most immediate and delayed complications of bone and soft tissue ablations are similar to those encountered with thermal and chemical ablations performed elsewhere in the body. Immediate complications are related to bleeding, pain or neuritis, vessel damage, pneumothorax, and injury to muscle, skin, or viscera from device placement and thermal ablation effects. Delayed problems occur due to vascular compromise, abscess or seroma formation, and adjacent deep or superficial tissue burns. Complications are limited by awareness of device heat specifications, extent of treatment zones, and proximity of nearby structures. Intermittent CT scanning at lower milliamperes during cryoablation will reveal "ice ball" growth and its proximity to other structures.

Preprocedure planning and intraprocedural real-time imaging allow safe device placement. The literature supports less procedural/immediate postprocedural pain resulting from cryotherapy versus heat-based modalities, particularly along neurovascular bundles.[78] Electrosensory monitoring



A B,C

Figure 11 A 1-month-old baby with thigh mass. (**A**) MRI with diffuse vastus lateralis tissue thickening. A biopsy was performed, and the diagnosis of diffuse infantile fibromatosis was made. No therapy was undertaken, and the lesion became more discreet over time. (**B**) MRI at age 7 demonstrating a symptomatic enlargement of the mass. At this point, the family opted for intralesional injection treatment. (**C**) Ultrasound image during 50% acetic acid injection with immediate posttreatment fluid leakage around mass. Abdominal pain and nausea 3 days later required hospitalization for acute kidney injury from tumor lysis or acetic acid–induced crystal/cast nephropathy. Subsequent repeat biopsy showed a fibrosarcoma with tumor dedifferentiation. MRI, magnetic resonance imaging.

may be useful for lesions in proximity to neurovascular structures and thermocouple placement for viscera to determine adjacent sensory innervation or temperature, respectively.

Certain technical maneuvers before, during, and after treatment may lessen intraoperative complications. Superficial lesion treatment may cause collateral injury to subdermal and dermal layers (►**Fig. 10**). Fluid injection (hydrodissection) with sterile water or lidocaine in the subcutaneous soft tissues forms an insulation buffer between the lesion and skin or viscera to prevent injury. Placement of cooled or warmed/tepid sterile water–soaked gauze or water-filled sterile gloves on the overlying skin surface counteracts the damaging effects of conducted temperatures; bladder and adjacent bowel can be protected with warmed water instilled via a Foley catheter. In a similar manner, sterile water infusion into a joint space or cerebral spinal fluid may reduce collateral heat effects on chondral surfaces, growth plates, spinal nerves, or adjacent neurovascular structures. The injection of carbon dioxide along nearby viscera and nerves has also been described.[79,83] Treatment to hypervascular bone and soft tissue masses can increase bleeding risks. Posttreatment tract cauterization with radiofrequency probes or microwave antennae will reduce this risk, similar to liver and renal tumor ablations. Current cryoablation probes are unable to perform tract cautery, but advances in technology may offer this feature in the future. Pretreatment intra-arterial embolization may also reduce bleeding but requires a second procedure. Interventions in or near the chest may cause pneumothorax and require aspiration or chest tube placement. Posttreatment abscess formation may require catheter drainage and/or antibiotics, and neuritis effect may be reduced with oral steroids, regional pain treatment, or physical and/or occupational therapy. Tumor lysis (►**Fig. 11**) and postembolization syndromes may require intravenous hydration and hospital admission for symptom control.

Conclusion

Image-guided ablation for bone and soft tissue tumors offers minimally invasive treatments that are safe and effective in many situations. Appropriate patient selection and multidisciplinary team consultation are keys to success. Preablation imaging is necessary to identify anatomical landmarks, technical approaches, and optimal ablation technique. Precautionary measures such as hydrodissection temperature control can minimize potential injury to nontarget tissues.

Overall, these minimally invasive techniques represent a burgeoning field of interventional and MSK radiology. Recent literature demonstrates an increased utilization of current ablative techniques used in the treatment of osseous and soft tissue metastases and other bony lesions. New and expanding indications may include the treatment of CB and palliation of unresectable chordomas. Finally, novel and alternative complimentary technologies, including MR compatible laser devices, versatile open intraoperative MRI systems, noninvasive-focused ultrasound, and electroporation will allow expanded applications of ablation treatments.

References

1 Rosenthal DI, Alexander A, Rosenberg AE, Springfield D. Ablation of osteoid osteomas with a percutaneously placed electrode: a new procedure. Radiology 1992;183(1):29–33

2 Rosenthal DI, Hornicek FJ, Wolfe MW, Jennings LC, Gebhardt MC, Mankin HJ. Percutaneous radiofrequency coagulation of osteoid osteoma compared with operative treatment. J Bone Joint Surg Am 1998;80(6):815–821

3 Kurup AN, Callstrom MR. Image-guided percutaneous ablation of bone and soft tissue tumors. Semin Intervent Radiol 2010;27(3):276–284

4 Jaffe HL. Osteoid osteoma: a benign osteoblastic tumor composed of osteoid and atypical bone. Arch Surg 1935;31:708–728

5 Greenspan A. Benign bone-forming lesions: osteoma, osteoid osteoma, and osteoblastoma. Clinical, imaging, pathologic, and differential considerations. Skeletal Radiol 1993;22(7):485–500

6 Rosenthal DI, Hornicek FJ, Torriani M, Gebhardt MC, Mankin HJ. Osteoid osteoma: percutaneous treatment with radiofrequency energy. Radiology 2003;229(1):171–175

7 Rimondi E, Mavrogenis AF, Rossi G, et al. Radiofrequency ablation for non-spinal osteoid osteomas in 557 patients. Eur Radiol 2012;22(1):181–188

8 Gebauer B, Collettini F, Bruger C, et al. Radiofrequency ablation of osteoid osteomas: analgesia and patient satisfaction in long-term follow-up. Rofo 2013;184(10):959–966

9 Lanza E, Thouvenin Y, Viala P, et al. Osteoid osteoma treated by percutaneous thermal ablation: when do we fail? A systematic review and guidelines for future reporting. Cardiovasc Intervent Radiol 2013

10 Gangi A, Buy X. Percutaneous bone tumor management. Semin Intervent Radiol 2010;27(2):124–136

11 Gangi A, Dietemann JL, Gasser B, et al. Interstitial laser photocoagulation of osteoid osteomas with use of CT guidance. Radiology 1997;203(3):843–848

12 Witt JD, Hall-Craggs MA, Ripley P, Cobb JP, Bown SG. Interstitial laser photocoagulation for the treatment of osteoid osteoma. J Bone Joint Surg Br 2000;82(8):1125–1128

13 Gangi A, Alizadeh H, Wong L, Buy X, Dietemann JL, Roy C. Osteoid osteoma: percutaneous laser ablation and follow-up in 114 patients. Radiology 2007;242(1):293–301

14 Moser T, Giacomelli MC, Clavert JM, Buy X, Dietemann JL, Gangi A. Image-guided laser ablation of osteoid osteoma in pediatric patients. J Pediatr Orthop 2008;28(2):265–270

15 Etienne A, Waynberger É, Druon J. Interstitial laser photocoagulation for the treatment of osteoid osteoma: retrospective study on 35 cases. Diagn Interv Imaging 2013;94(3):300–310

16 Sequeiros RB, Hyvönen P, Sequeiros AB, et al. MR imaging-guided laser ablation of osteoid osteomas with use of optical instrument guidance at 0.23 T. Eur Radiol 2003;13(10):2309–2314

17 Streitparth F, Gebauer B, Melcher I, et al. MR-guided laser ablation of osteoid osteoma in an open high-field system (1.0 T). Cardiovasc Intervent Radiol 2009;32(2):320–325

18 Maurer MH, Gebauer B, Wieners G, et al. Treatment of osteoid osteoma using CT-guided radiofrequency ablation versus MR-guided laser ablation: a cost comparison. Eur J Radiol 2012;81(11):e1002–e1006

19 Jaffe HL, Lichtenstein L. Benign chondroblastoma of bone: a reinterpretation of the so-called calcifying or chondromatous giant cell tumor. Am J Pathol 1942;18(6):969–991

20 Rajalakshmi P, Srivastava DN, Rastogi S, Julka PK, Bhatnagar S, Gamanagatti S. Bipolar radiofrequency ablation of tibial chondroblastomas: a report of three cases. World J Radiol 2012;4(7):335–340

21 Rybak LD, Rosenthal DI, Wittig JC. Chondroblastoma: radiofrequency ablation—alternative to surgical resection in selected cases. Radiology 2009;251(2):599–604

22 Christie-Large M, Evans N, Davies AM, James SL. Radiofrequency ablation of chondroblastoma: procedure technique, clinical and MR imaging follow up of four cases. Skeletal Radiol 2008;37(11): 1011–1017
23 Petsas T, Megas P, Papathanassiou Z. Radiofrequency ablation of two femoral head chondroblastomas. Eur J Radiol 2007;63(1): 63–67
24 Tins B, Cassar-Pullicino V, McCall I, Cool P, Williams D, Mangham D. Radiofrequency ablation of chondroblastoma using a multi-tined expandable electrode system: initial results. Eur Radiol 2006; 16(4):804–810
25 Erickson JK, Rosenthal DI, Zaleske DJ, Gebhardt MC, Cates JM. Primary treatment of chondroblastoma with percutaneous radiofrequency heat ablation: report of three cases. Radiology 2001; 221(2):463–468
26 Atalar H, Basarir K, Yildiz Y, Erekul S, Saglik Y. Management of chondroblastoma: retrospective review of 28 patients. J Orthop Sci 2007;12(4):334–340
27 Ramappa AJ, Lee FY, Tang P, Carlson JR, Gebhardt MC, Mankin HJ. Chondroblastoma of bone. J Bone Joint Surg Am 2000;82-A(8): 1140–1145
28 Lin PP, Thenappan A, Deavers MT, Lewis VO, Yasko AW. Treatment and prognosis of chondroblastoma. Clin Orthop Relat Res 2005; 438(438):103–109
29 Suneja R, Grimer RJ, Belthur M, et al. Chondroblastoma of bone: long-term results and functional outcome after intralesional curettage. J Bone Joint Surg Br 2005;87(7):974–978
30 Burdío F, Güemes A, Burdío JM, et al. Large hepatic ablation with bipolar saline-enhanced radiofrequency: an experimental study in in vivo porcine liver with a novel approach. J Surg Res 2003;110(1): 193–201
31 Corby RR, Stacy GS, Peabody TD, Dixon LB. Radiofrequency ablation of solitary eosinophilic granuloma of bone. AJR Am J Roentgenol 2008;190(6):1492–1494
32 Munk PL, Malfair D, Rashid F, Torreggiani WC. Radiofrequency ablation of solitary eosinophilic granuloma of bone. AJR Am J Roentgenol 2008;191(6):W320, author reply W321
33 Teichgräber V, Aubé C, Schmidt D, et al. Percutaneous MR-guided radiofrequency ablation of recurrent sacrococcygeal chordomas. AJR Am J Roentgenol 2006;187(2):571–574
34 Anis N, Chawki N, Antoine K. Use of radio-frequency ablation for the palliative treatment of sacral chordoma. AJNR Am J Neuroradiol 2004;25(9):1589–1591
35 Neeman Z, Patti JW, Wood BJ. Percutaneous radiofrequency ablation of chordoma. AJR Am J Roentgenol 2002;179(5):1330–1332
36 Kurup AN, Woodrum DA, Morris JM, et al. Cryoablation of recurrent sacrococcygeal tumors. J Vasc Interv Radiol 2012;23(8): 1070–1075
37 Nielsen OS, Munro AJ, Tannock IF. Bone metastases: pathophysiology and management policy. J Clin Oncol 1991;9(3):509–524
38 Wu JS, Wong R, Johnston M, Bezjak A, Whelan T; Cancer Care Ontario Practice Guidelines Initiative Supportive Care Group. Meta-analysis of dose-fractionation radiotherapy trials for the palliation of painful bone metastases. Int J Radiat Oncol Biol Phys 2003;55(3):594–605
39 Bang HJ, Littrup PJ, Currier BP, et al. Percutaneous cryoablation of metastatic lesions from non-small-cell lung carcinoma: initial survival, local control, and cost observations. J Vasc Interv Radiol 2012;23(6):761–769
40 Nazario J, Hernandez J, Tam AL. Thermal ablation of painful bone metastases. Tech Vasc Interv Radiol 2011;14(3):150–159
41 Dupuy DE, Hong R, Oliver B, Goldberg SN. Radiofrequency ablation of spinal tumors: temperature distribution in the spinal canal. AJR Am J Roentgenol 2000;175(5):1263–1266
42 Dupuy DE, Liu D, Hartfeil D, et al. Percutaneous radiofrequency ablation of painful osseous metastases: a multicenter American College of Radiology Imaging Network trial. Cancer 2010;116(4): 989–997
43 Callstrom MR, Charboneau JW, Goetz MP, et al. Image-guided ablation of painful metastatic bone tumors: a new and effective approach to a difficult problem. Skeletal Radiol 2006;35(1):1–15
44 Gazis AN, Beuing O, Franke J, Jöllenbeck B, Skalej M. Bipolar radiofrequency ablation of spinal tumors: predictability, safety, and outcome. Spine J 2014;14(4):604–608
45 Pezeshki PS, Woo J, Akens MK, et al. Evaluation of a bipolar-cooled radiofrequency device for ablation of bone metastases: preclinical assessment in porcine vertebrae. Spine J 2014;14(2):361–370
46 Callstrom MR, Atwell TD, Charboneau JW, et al. Painful metastases involving bone: percutaneous image-guided cryoablation—prospective trial interim analysis. Radiology 2006;241(2):572–580
47 Munk PL, Rashid F, Heran MK, et al. Combined cementoplasty and radiofrequency ablation in the treatment of painful neoplastic lesions of bone. J Vasc Interv Radiol 2009;20(7):903–911
48 Anselmetti GC, Manca A, Ortega C, Grignani G, Debernardi F, Regge D. Treatment of extraspinal painful bone metastases with percutaneous cementoplasty: a prospective study of 50 patients. Cardiovasc Intervent Radiol 2008;31(6):1165–1173
49 Lane MD, Le HB, Lee S, et al. Combination radiofrequency ablation and cementoplasty for palliative treatment of painful neoplastic bone metastasis: experience with 53 treated lesions in 36 patients. Skeletal Radiol 2011;40(1):25–32
50 Walczak BE, Rose PS. Desmoid: the role of local therapy in an era of systemic options. Curr Treat Options Oncol 2013;14(3):465–473
51 Molloy AP, Hutchinson B, O'Toole GC. Extra-abdominal desmoid tumours: a review of the literature. Sarcoma 2012;2012:578052
52 Escobar C, Munker R, Thomas JO, Li BD, Burton GV. Update on desmoid tumors. Ann Oncol 2012;23(3):562–569
53 Okuno S. The enigma of desmoid tumors. Curr Treat Options Oncol 2006;7(6):438–443
54 Bonvalot S, Desai A, Coppola S, et al. The treatment of desmoid tumors: a stepwise clinical approach. Ann Oncol 2012;23 (Suppl 10):x158–x166
55 Kujak JL, Liu PT, Johnson GB, Callstrom MR. Early experience with percutaneous cryoablation of extra-abdominal desmoid tumors. Skeletal Radiol 2010;39(2):175–182
56 Kolberg M, Høland M, Agesen TH, et al. Survival meta-analyses for >1800 malignant peripheral nerve sheath tumor patients with and without neurofibromatosis type 1. Neuro-oncol 2013;15(2):135–147
57 McCaughan JA, Holloway SM, Davidson R, Lam WW. Further evidence of the increased risk for malignant peripheral nerve sheath tumour from a Scottish cohort of patients with neurofibromatosis type 1. J Med Genet 2007;44(7):463–466
58 Cornelis F, Havez M, Labrèze C, et al. Percutaneous cryoablation of symptomatic localized venous malformations: preliminary short-term results. J Vasc Interv Radiol 2013;24(6):823–827
59 Freiberg AA, Loder RT, Heidelberger KP, Hensinger RN. Aneurysmal bone cysts in young children. J Pediatr Orthop 1994;14(1): 86–91
60 Dormans JP, Hanna BG, Johnston DR, Khurana JS. Surgical treatment and recurrence rate of aneurysmal bone cysts in children. Clin Orthop Relat Res 2004;(421):205–211
61 Shiels WE II, Mayerson JL. Percutaneous doxycycline treatment of aneurysmal bone cysts with low recurrence rate: a preliminary report. Clin Orthop Relat Res 2013;471(8):2675–2683
62 Carrafiello G, Laganà D, Pellegrino C, et al. Percutaneous imaging-guided ablation therapies in the treatment of symptomatic bone metastases: preliminary experience. Radiol Med (Torino) 2009; 114(4):608–625
63 Grieco CA, Simon CJ, Mayo-Smith WW, Dipetrillo TA, Ready NE, Dupuy DE. Image-guided percutaneous thermal ablation for the palliative treatment of chest wall masses. Am J Clin Oncol 2007; 30(4):361–367
64 Catane R, Beck A, Inbar Y, et al. MR-guided focused ultrasound surgery (MRgFUS) for the palliation of pain in patients with bone metastases—preliminary clinical experience. Ann Oncol 2007; 18(1):163–167

65 Liberman B, Gianfelice D, Inbar Y, et al. Pain palliation in patients with bone metastases using MR-guided focused ultrasound surgery: a multicenter study. Ann Surg Oncol 2009;16(1):140–146
66 Li C, Zhang W, Fan W, Huang J, Zhang F, Wu P. Noninvasive treatment of malignant bone tumors using high-intensity focused ultrasound. Cancer 2010;116(16):3934–3942
67 Chen W, Zhu H, Zhang L, et al. Primary bone malignancy: effective treatment with high-intensity focused ultrasound ablation. Radiology 2010;255(3):967–978
68 Napoli A, Anzidei M, Marincola BC, et al. MR imaging-guided focused ultrasound for treatment of bone metastasis. Radiographics 2013;33(6):1555–1568
69 Groenemeyer DH, Schirp S, Gevargez A. Image-guided percutaneous thermal ablation of bone tumors. Acad Radiol 2002;9(4): 467–477
70 Ahrar K, Stafford RJ. Magnetic resonance imaging-guided laser ablation of bone tumors. Tech Vasc Interv Radiol 2011;14(3): 177–182
71 Fini M, Tschon M, Ronchetti M, et al. Ablation of bone cells by electroporation. J Bone Joint Surg Br 2010;92(11):1614–1620
72 Marty M, Sersa G, Garbay JR, et al. Electrochemotherapy—an easy, highly effective and safe treatment of cutaneous and subcutaneous metastases: Results of ESOPE (European Standard Operating Procedures of Electrochemotherapy) study. Eur J Cancer, Suppl 2006; 4(11):3–13
73 Mir LM, Gehl J, Sersa G, et al. Standard operating procedures of the electrochemotherapy: instructions for the use of bleomycin or cisplatin administered either systemically or locally and electric pulses delivered by the Cliniporator™ by means of invasive or non-invasive electrodes. Eur J Cancer, Suppl 2006;4(11):14–25
74 Fini M, Salamanna F, Parrilli A, et al. Electrochemotherapy is effective in the treatment of rat bone metastases. Clin Exp Metastasis 2013;30(8):1033–1045
75 Shimizu T, Nikaido T, Gomyo H, et al. Electrochemotherapy for digital chondrosarcoma. J Orthop Sci 2003;8(2):248–251
76 Littrup PJ, Bang HJ, Currier BP, et al. Soft-tissue cryoablation in diffuse locations: feasibility and intermediate term outcomes. J Vasc Interv Radiol 2013;24(12):1817–1825
77 McMenomy BP, Kurup AN, Johnson GB, et al. Percutaneous cryoablation of musculoskeletal oligometastatic disease for complete remission. J Vasc Interv Radiol 2013;24(2):207–213
78 Thacker PG, Callstrom MR, Curry TB, et al. Palliation of painful metastatic disease involving bone with imaging-guided treatment: comparison of patients' immediate response to radiofrequency ablation and cryoablation. AJR Am J Roentgenol 2011; 197(2):510–515
79 Buy X, Tok CH, Szwarc D, Bierry G, Gangi A. Thermal protection during percutaneous thermal ablation procedures: interest of carbon dioxide dissection and temperature monitoring. Cardiovasc Intervent Radiol 2009;32(3):529–534
80 Goetz MP, Callstrom MR, Charboneau JW, et al. Percutaneous image-guided radiofrequency ablation of painful metastases involving bone: a multicenter study. J Clin Oncol 2004;22(2): 300–306
81 Thanos L, Mylona S, Galani P, et al. Radiofrequency ablation of osseous metastases for the palliation of pain. Skeletal Radiol 2008; 37(3):189–194
82 Callstrom MR, Dupuy DE, Solomon SB, et al. Percutaneous image-guided cryoablation of painful metastases involving bone: multicenter trial. Cancer 2013;119(5):1033–1041
83 Tsoumakidou G, Buy X, Garnon J, Enescu J, Gangi A. Percutaneous thermal ablation: how to protect the surrounding organs. Tech Vasc Interv Radiol 2011;14(3):170–176
84 Callstrom MR, Charboneau JW, Goetz MP, et al. Painful metastases involving bone: feasibility of percutaneous CT- and US-guided radio-frequency ablation. Radiology 2002;224(1):87–97