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Percutaneous Cryoablation in Bone Tumors: Current Applications, Technical Considerations, Clinical Outcomes, and Future Perspectives

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Abstract

Image-guided percutaneous cryoablation has emerged as an increasingly important minimally invasive treatment option in musculoskeletal oncology. Its applications range from the definitive treatment of selected benign bone tumors to local tumor control and pain palliation in patients with malignant primary bone lesions and skeletal metastases. Compared with heat-based ablation techniques, cryoablation offers several potential advantages, including visualization of the ice ball during treatment, the ability to create large and irregular ablation zones, and reduced procedural pain.

This review aims to provide a comprehensive overview of the principles, technical considerations, clinical applications, efficacy, and complications of percutaneous cryoablation in the management of bone tumors, emphasizing its current role and future perspectives in musculoskeletal interventional oncology.

Relevant publications addressing the use of image-guided cryoablation in benign and malignant bone tumors were reviewed, including clinical studies, prospective trials, retrospective series, systematic reviews, and international recommendations. Particular attention was given to treatment indications, procedural techniques, local tumor control, pain reduction, and complication prevention. Cryoablation has demonstrated favorable clinical outcomes in selected benign bone tumors, particularly osteoid osteoma, and in patients with painful skeletal metastases. Its role in locally aggressive benign tumors, oligometastatic disease, and selected recurrent malignant bone tumors is expanding. The ability to monitor the ice ball in real time facilitates treatment planning and protection of adjacent critical structures. However, pathological fractures, neural injuries, and incomplete tumor coverage remain important considerations.

Percutaneous cryoablation represents a valuable addition to multidisciplinary bone tumor management. Appropriate patient selection, accurate imaging guidance, adequate ablation margins, and systematic protection of adjacent structures are essential for achieving optimal outcomes. Further prospective comparative studies are required to establish its long-term oncological efficacy and define its role relative to surgery and other ablative techniques.

Categories: Radiology, Oncology, Orthopedics
Keywords: bone metastases, bone tumors, cryoablation, interventional radiology, musculoskeletal oncology, osteoid osteoma, percutaneous ablation

Introduction And Background

Bone tumors encompass a heterogeneous group of lesions with different biological behaviors, clinical presentations, and therapeutic requirements. These lesions include benign tumors, locally aggressive neoplasms, primary malignant bone tumors, and secondary metastatic deposits. Conventional treatment strategies primarily involve surgical resection, curettage, radiotherapy, systemic anticancer therapies, and supportive interventions. Although these approaches remain essential, they may be associated with considerable morbidity, prolonged recovery, and limitations in patients with advanced malignancies or significant comorbidities. Consequently, minimally invasive image-guided interventions have gained increasing attention as complementary therapeutic approaches in musculoskeletal oncology [1-3].

Percutaneous thermal ablation techniques, including radiofrequency ablation (RFA), microwave ablation (MWA), laser ablation, and cryoablation, provide an alternative approach to the local treatment of selected bone lesions. Among these modalities, cryoablation has attracted particular interest because of its ability to produce controlled tissue destruction while allowing direct visualization of the developing ice ball during the procedure. This characteristic is especially advantageous when treating large lesions, irregularly shaped tumors, and lesions located near sensitive anatomical structures. Furthermore, the relative analgesic effect of freezing may reduce procedural discomfort compared with heat-based ablation techniques [2,4,5].

The clinical applications of cryoablation have expanded considerably over the last decade. Initially used

primarily for the treatment of selected benign bone lesions and painful skeletal metastases, the technique is increasingly considered for oligometastatic disease, locally recurrent tumors, and selected patients with primary malignant bone lesions who are unsuitable for conventional surgery [4,6]. Nevertheless, the available evidence remains heterogeneous, and the optimal indications depend on tumor biology, lesion size, anatomical location, skeletal stability, and therapeutic objectives. This review discusses the current evidence and technical principles underlying percutaneous cryoablation in bone tumors, with particular emphasis on clinical applications, safety, and future developments [3,5,6].

Cryoablation destroys pathological tissue through the application of extremely low temperatures using specialized percutaneous cryoprobes. Modern systems generally utilize argon gas expansion to generate rapid cooling through the Joule-Thomson effect. Depending on the device and probe configuration, temperatures substantially below −100°C can be achieved near the active probe tip. The resulting freezing process induces cellular injury through multiple interconnected mechanisms, including intracellular and extracellular ice crystal formation, osmotic disturbances, membrane disruption, and microvascular damage [4,7,8].

During the initial freezing phase, extracellular ice formation increases the extracellular solute concentration, producing osmotic dehydration and cellular shrinkage. With more rapid cooling, intracellular ice crystals may also develop, directly damaging cellular membranes and intracellular organelles. During subsequent thawing, osmotic changes and recrystallization contribute to additional cellular destruction. Repeated freeze-thaw cycles enhance tissue necrosis by increasing the extent of irreversible cellular injury. These mechanisms are particularly important in neoplastic tissue, where complete tumor destruction requires adequate freezing throughout the intended treatment volume [7-9].

Another important mechanism involves microvascular injury. Freezing damages endothelial cells and produces intravascular ice formation, platelet aggregation, and microthrombus development. These changes compromise local tissue perfusion and result in secondary ischemic necrosis. The combination of direct cellular destruction and vascular injury contributes to the effectiveness of cryoablation. Temperatures below approximately −40°C are generally associated with reliable tissue destruction, whereas the peripheral region of the ice ball may experience less complete cellular injury. Therefore, the visible ice ball should not be interpreted as a uniformly lethal treatment zone [4,7,9].

An important characteristic distinguishing cryoablation from heat-based techniques is the possibility of monitoring the ablation zone through computed tomography (CT) or magnetic resonance imaging (MRI). The ice ball appears as a well-defined structure during CT-guided procedures, although its visible boundary does not precisely correspond to the lethal isotherm. This distinction is clinically relevant because the central region reaches lower temperatures than the peripheral margin. Consequently, an adequate safety margin beyond the tumor boundary is necessary to ensure complete treatment, particularly when pursuing curative local control [4,5,8].

Review

Technical considerations

Preprocedural Evaluation and Patient Selection

Appropriate patient selection is fundamental to the success of percutaneous cryoablation. Treatment planning should begin with a comprehensive assessment of the patient's clinical condition, tumor histology, previous treatments, lesion dimensions, anatomical relationships, and therapeutic objectives. Cryoablation may be considered for a broad spectrum of benign and malignant lesions, including osteoid osteoma, osteoblastoma, selected locally aggressive benign bone tumors, painful osseous metastases, and oligometastatic bone disease [1,3]. In addition, it has an expanding role in the management of selected soft-tissue tumors, particularly desmoid-type fibromatosis, as well as locally recurrent or unresectable bone and soft-tissue tumors. Depending on the clinical context, the primary treatment objectives may include complete local tumor eradication, durable local disease control, pain palliation, reduction of tumor burden, and preservation of adjacent anatomical structures and functional integrity. Cryoablation may be particularly advantageous in patients who are poor surgical candidates, those with recurrent disease following previous surgery or radiotherapy, and patients in whom conventional surgical resection would result in substantial functional impairment or morbidity. It may also serve as an adjunct to surgery in selected cases, particularly for locally aggressive bone tumors [3-5]. A multidisciplinary team involving musculoskeletal radiologists, interventional radiologists, orthopedic oncologists, medical oncologists, and radiation oncologists should determine whether cryoablation is appropriate as a definitive treatment, an adjunct to surgery, or a palliative intervention. The final decision should take into account tumor size, number, biological behavior, accessibility, proximity to critical neurovascular structures, risk of pathological fracture, and the feasibility of achieving an adequate ablation margin while preserving surrounding healthy tissues [1,2,4].

Preprocedural imaging plays a central role in defining the treatment strategy. Thin-section CT is particularly useful for evaluating cortical integrity, identifying the precise location of the lesion, and planning probe

trajectories [1,4]. It allows detailed assessment of cortical thinning, erosion, destruction, and potential cortical breakthrough, which may influence the feasibility and safety of the procedure. Furthermore, multiplanar reconstructions help delineate the relationship between the lesion and adjacent anatomical structures, including neurovascular bundles, joints, and surrounding soft tissues. This information is essential for selecting the optimal access route, determining the appropriate probe number and orientation, and minimizing the risk of cortical injury, pathological fracture, and inadvertent damage to adjacent structures [4,7,8]. MRI provides superior soft-tissue contrast and is valuable for assessing marrow involvement, extraosseous tumor extension, neural relationships, and adjacent joint structures. In patients with metastatic disease, whole-body staging using appropriate imaging techniques is necessary to determine whether the treatment objective is local palliation or comprehensive management of oligometastatic disease [4,5,10].

Biopsy should be considered before ablation when the diagnosis is uncertain or when histological confirmation would influence treatment selection, and in case of suspicion of lesional vascular nature [10]. In suspected primary malignant bone tumors, the diagnostic workup and biopsy trajectory should be coordinated with the orthopedic oncology team before any definitive local intervention. Ablation without an established diagnosis may compromise subsequent oncological management and should generally be avoided. Similarly, patients with unstable pathological fractures or significant structural compromise may require surgical stabilization rather than isolated cryoablation [1,2,10].

Imaging Guidance and Probe Placement

CT guidance is the most commonly used imaging modality for percutaneous bone lesion cryoablation because it provides excellent spatial resolution and facilitates accurate probe positioning. MRI guidance is another option, particularly in specialized centers, offering improved soft-tissue visualization and the potential for monitoring treatment-related changes [4,11,12]. The choice of imaging modality depends on lesion location, available equipment, operator experience, and the proximity of vulnerable anatomical structures. For lesions involving bone structure, CT is the primary imaging modality, whereas for soft tissue adjacent to vascular and neural structures, MRI is the preferred modality [4,5,11].

Cryoprobes are typically introduced through bone access trocars under image guidance. Multiple probes can be deployed simultaneously to create overlapping ice balls and achieve coverage of large or irregularly shaped lesions [11]. Probe number, spacing, orientation, and activation sequence should be determined according to tumor geometry and the expected ablation volume. Particular attention should be paid to probe trajectories when several applicators are used, as inadvertent damage to an adjacent probe may result in potentially serious complications [4,11]. Particular attention should be paid to probe trajectories when multiple applicators are used, as inadvertent probe-to-probe contact may cause applicator damage and compromise procedural safety. Other potential complications include injury to adjacent neurovascular structures, unintended soft-tissue damage, hemorrhage, hematoma formation, cortical bone fracture, and unintended extension of the ice ball into surrounding tissues [11-13].

For curative treatment, the ice ball should extend approximately 5-8 mm beyond the tumor margin, taking into account the lower cytotoxic effect at its periphery. At least two freeze-thaw cycles are generally recommended to enhance cellular destruction. A commonly described protocol involves an initial freezing period, passive thawing, and a second freezing period. However, the exact duration and sequence should be adapted to the specific cryoablation system, tumor characteristics, and clinical indication rather than applied as a universal protocol [4,8,11].

Protection of Adjacent Structures

One of the most important aspects of bone cryoablation is the protection of adjacent tissues. Peripheral nerves, spinal cord, skin, cartilage, major blood vessels, and hollow organs may be vulnerable to unintended freezing. Although cryoablation allows visualization of the ice ball, the visible treatment boundary does not eliminate the risk of thermal injury. Therefore, careful procedural planning and active tissue protection are essential, especially for lesions located in the spine, pelvis, and periarticular regions [4,12,13].

Several protective techniques are available [13]. Hydrodissection involves the injection of fluid, usually saline or dextrose solution, into the space between the target lesion and adjacent vulnerable structures. This technique physically separates the tissues and provides an additional protective layer. It is particularly useful for displacing and protecting adjacent nerves, blood vessels, bowel loops, ureters, and other critical structures during ablation. For example, hydrodissection may be performed to separate an abdominal or pelvic lesion from adjacent bowel loops or to displace peripheral nerves away from the anticipated ice-ball margin. Pneumodissection, using air or carbon dioxide, may also be employed when appropriate, particularly to create separation between the target lesion and adjacent structures such as the bowel or other soft tissues [11,12]. These techniques help increase the safety margin during ablation and reduce the risk of unintended thermal injury to surrounding tissues. The choice of protective technique depends on lesion location, the anatomical structures at risk, and the feasibility of creating and maintaining adequate tissue separation throughout the procedure [12-15]. In selected cases, temperature monitoring with thermocouples or fiber-

optic sensors can provide additional information about the thermal environment near critical structures [4,12,14].

Neural protection is particularly important during spinal and pelvic procedures. Nerve injury may result from exposure to excessively low temperatures, and the risk depends on both the minimum temperature and duration of exposure. Techniques such as epidural or foraminal monitoring, hydrodissection, active warming, and electrophysiological monitoring may be considered according to lesion location [13-16]. Continuous neurological assessment is also important when the procedure is performed under conscious sedation. The selection of protective techniques should be individualized to ensure adequate tumor treatment without compromising neurological function [4,12,13].

Clinical applications in benign bone tumors

Osteoid Osteoma

Osteoid osteoma is one of the most established indications for minimally invasive percutaneous ablation. It is a benign osteogenic tumor that typically affects young patients and is characterized by a small vascular nidus surrounded by reactive sclerosis. Patients frequently present with localized pain, which may worsen at night and respond to nonsteroidal anti-inflammatory drugs. Although RFA is widely accepted as a standard minimally invasive treatment, cryoablation has emerged as a promising alternative [15-17].

The advantages of cryoablation in osteoid osteoma include visualization of the ice ball, the potential for precise treatment near vulnerable structures without the heat sink limitations, and reduced immediate postprocedural pain [15,16]. An additional technical advantage is the possibility of positioning the cryoprobe adjacent to the nidus without necessarily penetrating the lesion, particularly when the cortical anatomy permits an extraosseous approach. This may reduce the need for extensive bone drilling and simplify the procedure in selected patients [15,16,18].

Clinical studies have demonstrated encouraging outcomes. Santiago and colleagues reported substantial pain reduction following CT-guided cryoablation in adults with osteoid osteoma, with high technical success and a low recurrence rate. A subsequent study published in Radiology evaluated 50 patients and demonstrated an overall clinical success rate of approximately 96%. More recently, a 2024 study involving 25 patients reported complete clinical response and no recurrence during one-year follow-up. These findings support the feasibility and effectiveness of cryoablation as an alternative to RFA in appropriately selected patients [15,18,19].

Despite these encouraging findings, cryoablation has not completely replaced RFA in the management of osteoid osteoma. The comparative evidence remains limited, and differences in procedural duration, cost, availability, and operator experience must be considered. Nevertheless, cryoablation may be particularly attractive for lesions located near neurovascular structures or articular surfaces, where the ability to visualize the treatment zone may offer an important procedural advantage [16,17,19].

Other Benign and Locally Aggressive Bone Tumors

Beyond osteoid osteoma, cryoablation has been investigated for selected benign and locally aggressive bone tumors, including aneurysmal bone cysts, osteoblastomas, chondroblastomas, and eosinophilic granulomas (Figure *1*).

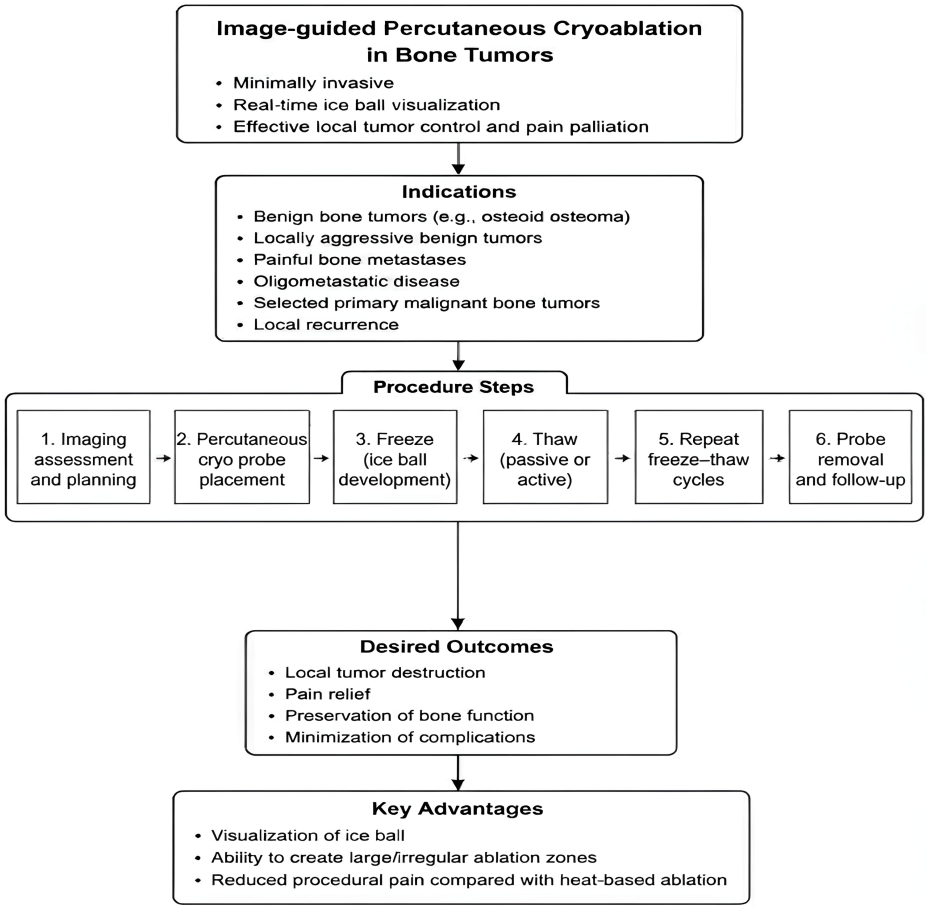


FIGURE 1: Overview of percutaneous cryoablation in bone tumors

Image-guided percutaneous cryoablation is a minimally invasive treatment for bone tumors that allows real-time visualization of the ice ball. Indications include benign and locally aggressive bone tumors, painful bone metastases, oligometastatic disease, selected primary malignant bone tumors, and local recurrence.

The procedure progresses from imaging and planning to probe placement, freezing, thawing, repeated freeze-thaw cycles, and probe removal and follow-up. Desired outcomes are local tumor destruction, pain relief, preservation of bone function, and fewer complications. Listed advantages include ice ball visualization, creation of large or irregular ablation zones, and less procedural pain than heat-based ablation.

Note: ChatGPT Free (5.6, OpenAI, San Francisco, California, United States) was used in the creation of this figure. Claude (Anthropic, San Francisco, California, United States), and Gemini Pro (version 1.5, Google, Mountain View, California, United States) were used to refine the figure.

These lesions may produce substantial pain, cortical destruction, and functional impairment. Conventional management often involves curettage, bone grafting, embolization, or surgical reconstruction. In selected patients, image-guided ablation may provide local tumor control while avoiding more extensive surgical procedures [2,4,20].

Aneurysmal bone cysts are particularly challenging because of their vascularity, expansile behavior, and potential for recurrence. Cryoablation may be considered in selected cases, sometimes in combination with embolization or cementoplasty. However, the evidence supporting this approach is predominantly based on small clinical series and case reports. Therefore, treatment should be individualized according to lesion size, anatomical location, structural integrity, and the risk of recurrence [4,20,21]. The combination of precise visual control and the ability to cover large volumes of tissue with multiple cryoprobes and the ability to cause less pain than heat-based methods with overlapping ice balls ‘shaped’ to the morphology of the lesion make cryoablation stand out in the treatment of very large lesions (> 4 cm) with complex morphology and tumors close to organs at risk [4].

Osteoblastomas and other locally aggressive benign lesions may also be considered for image-guided ablation in carefully selected patients. Nevertheless, their larger dimensions and proximity to neural structures may limit the feasibility of complete treatment. In these cases, cryoablation should be viewed as a complementary option rather than a universal replacement for surgical management. Long-term clinical

and imaging surveillance is particularly important because incomplete treatment may result in local progression [4,20,22].

Cryoablation in malignant bone tumors

Primary Malignant Bone Tumors

The role of cryoablation in primary malignant bone tumors remains less established than its application in benign lesions and metastatic disease. Surgery remains the principal treatment for most primary bone sarcomas, often combined with chemotherapy or radiotherapy according to histological subtype and disease stage. Nevertheless, percutaneous cryoablation may be considered in highly selected patients who are unsuitable for surgery or who refuse more invasive treatment [1,4,6].

Potential applications include small-volume lesions, selected local recurrences, and tumors in anatomically challenging locations. The ability to create large, geometrically controlled ablation zones may be beneficial when treating irregular tumor configurations. However, the presence of extensive soft-tissue involvement, aggressive tumor biology, and the possibility of microscopic extension beyond the imaging-defined margin represent important limitations. In such cases, achieving an adequate oncological margin through percutaneous treatment may be difficult [4,6,22].

The available clinical evidence is insufficient to establish cryoablation as an equivalent alternative to wide surgical excision in primary malignant bone tumors (Table *1*).

Tumor category	Clinical indication	Main therapeutic objective	Evidence
Osteoid osteoma	Benign symptomatic lesion	Definitive local treatment	Established
Osteoblastoma	Selected lesions	Local tumor control	Limited
Aneurysmal bone cyst	Selected recurrent lesions	Local control	Limited
Bone metastases	Painful metastatic lesions	Pain palliation and local control	Prospective clinical studies
Oligometastatic disease	Limited skeletal metastases	Local disease control	Emerging
Primary malignant bone tumors	Selected inoperable lesions	Local tumor control/palliation	Limited

TABLE 1: Clinical applications of cryoablation in bone tumors

Consequently, its use should remain restricted to carefully selected patients after multidisciplinary assessment. Prospective studies with longer follow-up are necessary to clarify local recurrence rates, disease-free survival, and the optimal integration of cryoablation with systemic and radiation-based treatments [1,4,6].

Bone Metastases

Bone metastases represent one of the most important clinical indications for percutaneous cryoablation. Skeletal involvement is common in patients with advanced malignancies, particularly breast, prostate, lung, renal, and thyroid cancers. Metastatic lesions may cause severe pain, pathological fractures, spinal instability, and neurological compromise, substantially reducing quality of life. Although radiotherapy and systemic treatments remain fundamental components of management, some patients experience persistent symptoms or develop local progression despite conventional therapy [2,3,23].

Cryoablation offers a minimally invasive approach for treating painful metastatic lesions, particularly when conventional analgesic management or radiotherapy has provided insufficient relief. Its analgesic effect may become evident within the first few days following treatment. In addition to direct tumor destruction, the reduction of tumor-related inflammation and involvement of periosteal pain fibers may contribute to symptom improvement. These characteristics make cryoablation an attractive option for patients with limited treatment alternatives [3,23,24].

One of the most important studies evaluating this application was the multicenter trial published by Callstrom and colleagues in 2013. The study included 61 patients with one or two painful bone metastases who had failed or declined conventional treatments. The results demonstrated clinically meaningful pain reduction and improvements in quality-of-life measures following percutaneous image-guided cryoablation. These findings provided important clinical evidence supporting the use of cryoablation for palliation of painful skeletal metastases [23].

Further evidence was provided by the MOTION multicenter prospective study, which evaluated cryoablation in patients with painful bone metastases who were not candidates for standard therapies or had experienced inadequate symptom control. The study demonstrated sustained improvements in pain-related outcomes during follow-up. Importantly, the results support cryoablation as a potential treatment option for patients with persistent metastatic bone pain, although the single-arm design limits direct comparisons with radiotherapy and other ablative modalities [24,25].

Oligometastatic Bone Disease

The development of modern systemic therapies and advanced imaging techniques has increased interest in local treatment strategies for oligometastatic disease. In this setting, a limited number of metastatic lesions may be treated with curative or long-term disease-control intent in carefully selected patients. Cryoablation may offer an effective local treatment option for small-volume skeletal metastases, particularly when complete tumor coverage can be achieved without compromising adjacent structures [4,6,22].

The potential benefits of cryoablation in oligometastatic disease include reduced treatment-related morbidity, preservation of surrounding tissues, and the possibility of combining local ablation with systemic therapies. Selected patients with isolated or limited bone metastases may benefit from local control, especially when the primary malignancy is otherwise controlled. However, the evidence supporting a survival advantage remains limited, and local treatment should be integrated into a comprehensive oncological strategy [6,22,24].

Spinal Metastases

Spinal metastases require particular attention because of their potential to cause vertebral collapse, spinal instability, and epidural spinal cord compression. Cryoablation may provide local tumor control and pain relief in selected patients, but the proximity of the spinal cord and nerve roots necessitates careful procedural planning. In cases involving significant vertebral destruction, cryoablation alone may not provide adequate mechanical stabilization [4,12,13].

Combination procedures involving cryoablation, vertebroplasty, kyphoplasty, sacroplasty, cementoplasty, or percutaneous screw fixation may be considered according to the degree of vertebral instability [14]. Cement augmentation can improve structural support and reduce mechanical pain, whereas ablation targets viable tumor tissue. The sequence of these interventions should be individualized, particularly in patients with extensive lytic lesions or epidural disease. Importantly, patients with established spinal cord compression or unstable pathological fractures generally require urgent evaluation for surgical or radiation-based management rather than isolated percutaneous ablation [4,12,13].

Clinical outcomes and treatment efficacy

The clinical effectiveness of cryoablation depends on the indication, tumor histology, lesion size, anatomical location, and adequacy of the ablation margin. In benign tumors, treatment success is generally assessed through symptom resolution and absence of local recurrence [18,19]. The clinical effectiveness of cryoablation depends on the indication, tumor histology, lesion size, anatomical location, and adequacy of the ablation margin. In benign tumors, treatment success is generally assessed through symptom resolution and the absence of local recurrence. Clinical and radiological follow-up are essential for monitoring treatment response and detecting residual or recurrent disease [4]. Although no universally standardized follow-up protocol has been established, MRI evaluation within three to six months after treatment is a reasonable approach for lesions treated with curative intent or for local tumor control. Subsequent imaging at 12 months and periodic assessments thereafter may be considered according to tumor biology, treatment response, and the risk of recurrence. MRI is particularly useful for evaluating residual viable tumor and local recurrence, whereas CT can demonstrate structural changes, cortical integrity, and progressive osseous remineralization [26]. In patients treated primarily for pain palliation, clinical assessment, including pain scores and analgesic requirements, should remain the principal measure of therapeutic response, with additional imaging performed when symptoms persist, recur, or complications are suspected. Follow-up duration should be individualized according to tumor type, treatment intent, and clinical response [4,23,26]. In malignant lesions, additional endpoints include local tumor control, pain reduction, analgesic consumption, quality of life, and the incidence of skeletal-related events. These different objectives should be clearly distinguished when interpreting published outcomes [4,15,23].

In osteoid osteoma, available clinical studies suggest high technical and clinical success rates, with substantial pain reduction following treatment. The ability to monitor the ice ball may be particularly beneficial in anatomically challenging lesions. However, the relatively small number of patients included in most studies and the limited duration of follow-up restrict the strength of conclusions regarding long-term comparative effectiveness [15,18,19].

In metastatic bone disease, prospective multicenter studies have demonstrated meaningful improvements in pain and quality of life. Nevertheless, the degree of benefit may vary according to tumor characteristics,

previous radiotherapy, baseline pain severity, and the presence of structural instability. Cryoablation should therefore be considered as part of an individualized treatment strategy rather than a universal intervention for all symptomatic bone metastases [23-25].

Radiological evaluation after treatment is also important, particularly when cryoablation is performed with curative intent. MRI may help identify residual enhancing tumor tissue, while CT is useful for evaluating cortical integrity and subsequent osseous remodeling. Clinical follow-up should include pain assessment, functional evaluation, and documentation of analgesic requirements. The timing and choice of follow-up imaging should be determined according to the tumor type and therapeutic objective [4,10,22].

Complications and limitations

Although cryoablation is generally considered a safe minimally invasive procedure, complications may occur. The most clinically important adverse events include pathological fractures, peripheral nerve injuries, skin damage, infection, bleeding, and injury to adjacent organs. Their occurrence is influenced by lesion size, anatomical location, the number of probes used, and the patient's overall clinical condition. Appropriate preprocedural planning and protective measures are essential to minimize these risks [4,12,13].

Pathological fracture is particularly relevant when treating weight-bearing bones with extensive cortical destruction or large lytic lesions. Tumor destruction may further compromise structural integrity, increasing the risk of fracture following treatment. Therefore, patients with substantial cortical involvement should undergo careful orthopedic assessment, and cryoablation may need to be combined with cementoplasty, bone augmentation, or surgical fixation. Ablation without adequate structural support may be inappropriate in patients with significant mechanical instability [4,13,23].

Neural injury is another important concern, especially in lesions adjacent to the spinal canal, neural foramina, or major peripheral nerves. Freezing can cause temporary or permanent neurological deficits depending on the extent and duration of exposure. Protective measures, including hydrodissection, thermosensors, electrophysiological monitoring, and careful monitoring of the ice-ball boundary, should be employed whenever indicated. Patients should be informed about the possibility of transient sensory or motor dysfunction before treatment [4,12,14].

Other limitations include procedural duration, equipment costs, the need for specialized expertise, and restricted availability in some institutions. Furthermore, the evidence base remains heterogeneous, with many studies consisting of retrospective series or small prospective cohorts. Although the clinical results are encouraging, larger randomized and comparative studies are required to establish the relative effectiveness of cryoablation against RFA, MWA, radiotherapy, and surgery across different bone tumor subtypes [4,5,24,25].

Comparison with other ablation techniques

RFA is a widely established technique for the treatment of selected benign bone tumors and painful skeletal metastases. It produces tissue destruction through high-frequency alternating electrical current and subsequent thermal coagulation. Its advantages include extensive clinical experience, established treatment protocols, and relatively short procedural times. However, the inability to directly visualize the ablation zone and the potential influence of tissue impedance and heat-sink effects may limit its application in certain anatomical settings [2,4,16].

MWA uses electromagnetic energy to produce rapid tissue heating and may achieve larger ablation volumes within shorter treatment periods. It is less affected by tissue impedance than RFA and can be useful in selected sclerotic or larger lesions. Nevertheless, the absence of direct visualization of the ablation zone remains a limitation when treating tumors close to critical structures. Cryoablation may therefore be preferable when precise monitoring of the treatment boundary is particularly important [4,5,10].

Compared with heat-based ablation techniques, cryoablation offers the advantage of visible ice-ball formation, reduced immediate procedural pain, and the ability to configure multiple overlapping treatment zones (Figure *2*).

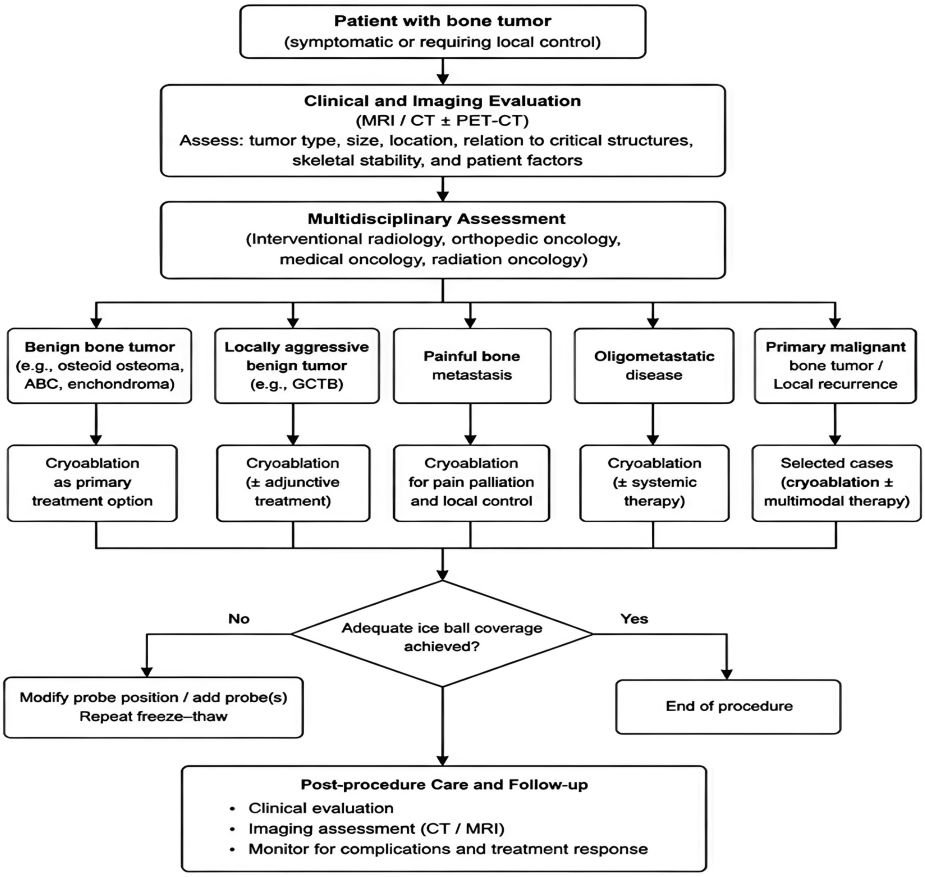


FIGURE 2: Suggested clinical pathway for patient selection and management in bone tumor cryoablation

Flowchart for cryoablation of bone tumors: Clinical and imaging evaluation and multidisciplinary assessment guide treatment selection. Cryoablation may be a primary option for benign tumors, used with or without adjunctive treatment for locally aggressive benign tumors, used for pain relief and local control of painful bone metastases, or combined with systemic therapy for oligometastatic disease. Selected primary malignant tumors or local recurrences may receive cryoablation with or without multimodal therapy.

After treatment, assess ice ball coverage. If inadequate, reposition or add probes and repeat the freeze-thaw cycle; if adequate, end the procedure. Follow-up includes clinical evaluation, CT or MRI, and monitoring for complications and treatment response.

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These characteristics may be particularly beneficial for large, irregularly shaped tumors and lesions located near vulnerable structures. However, cryoablation often requires longer treatment times because of the necessary freezing and thawing cycles (Table 2).

Characteristic	Cryoablation	Radiofrequency ablation	Microwave ablation
Mechanism	Freeze-induced cellular injury	Thermal coagulation	Dielectric heating
Treatment monitoring	Visible ice ball	Indirect	Indirect
Treatment margin assessment	Relatively favorable	Limited	Limited
Pain during treatment	Generally lower	Heat-related discomfort possible	Heat-related discomfort possible
Heat-sink effect	Not a major limitation	Can be relevant	Less pronounced
Multiple probes	Yes	Yes	Yes
Main limitation	Cost and procedural duration	Limited visualization	Limited visualization
Important complications	Neural injury, fracture, skin injury	Thermal injury, fracture	Thermal injury, fracture

TABLE 2: Comparison of percutaneous thermal ablation techniques in bone tumors

The optimal modality should therefore be selected according to the lesion characteristics, therapeutic objective, and available expertise rather than assuming that one technique is universally superior [4,5,8].

Future perspectives

The future of percutaneous cryoablation in musculoskeletal oncology will likely involve improvements in imaging guidance, probe technology, treatment monitoring, and patient selection. Advances in CT-based navigation and image fusion may facilitate more accurate probe positioning and improve treatment coverage in anatomically complex lesions. MRI-based approaches may provide additional information about treatment-related tissue changes and the relationship between the ablation zone and adjacent soft tissues [4,5,11].

Another promising area is the potential immunological effect of cryoablation. Tumor destruction may release intracellular antigens and damage-associated molecular patterns, potentially stimulating an antitumor immune response. This phenomenon has generated interest in combining cryoablation with immune checkpoint inhibitors and other systemic therapies. However, the clinical relevance of these mechanisms in bone tumors remains incompletely understood, and further translational and prospective clinical studies are required [7,9,25].

Future research should also focus on identifying patients most likely to benefit from cryoablation, defining standardized treatment protocols, and establishing reliable imaging biomarkers of treatment response. Prospective comparative studies should evaluate local tumor control, pain reduction, functional outcomes, complications, and cost-effectiveness. Such investigations will be essential for defining the optimal position of cryoablation within contemporary musculoskeletal oncology practice [4,5,24].

Conclusions

Percutaneous cryoablation has become an important minimally invasive treatment option in the management of selected benign and malignant bone tumors. Its principal advantages include direct visualization of the ice ball, the ability to treat large and irregular lesions, reduced procedural discomfort, and the potential for precise protection of adjacent anatomical structures. Clinical evidence supports its application in osteoid osteoma and painful skeletal metastases, while its use in other benign and malignant bone tumors continues to expand. Despite encouraging outcomes, cryoablation should not be considered a universal replacement for surgery, radiotherapy, or other ablative techniques. Appropriate patient selection, multidisciplinary assessment, adequate treatment margins, protection of vulnerable structures, and consideration of skeletal stability remain essential. Further high-quality prospective studies are needed to clarify its long-term oncological effectiveness and establish standardized indications. Overall, cryoablation represents a valuable and evolving component of contemporary image-guided musculoskeletal oncology.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Emrah Karatay, Cagri Saylan, Emre Karacay, Hasan Sermet, Zafer Unsal Coskun

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Drafting of the manuscript: Emrah Karatay, Cagri Saylan, Emre Karacay, Hasan Sermet, Zafer Unsal Coskun

Critical review of the manuscript for important intellectual content: Emrah Karatay, Cagri Saylan, Emre Karacay, Hasan Sermet, Zafer Unsal Coskun

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Disclosures

AI use statement: The authors used ChatGPT Free (5.6, OpenAI, San Francisco, California, United States), Claude (Anthropic, San Francisco, California, United States), and Gemini Pro (version 1.5, Google, Mountain View, California, United States) as follows: language polishing, literature comparison, structure or formatting, extensive copy editing or writing support, creation of figures in the article. This is a review article; no human data or images were used during the preparation of the manuscript. The authors confirm that they have reviewed and verified all AI-assisted content and take full responsibility for the work.
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