Technical and Practical Considerations for Device Selection in Locoregional Ablative Therapy

Sean P. Zivin, MD¹ Ron C. Gaba, MD¹

¹Division of Interventional Radiology, Department of Radiology, University of Illinois Hospital and Health Sciences System, Chicago, Illinois

Address for correspondence Ron C. Gaba, MD, Division of Interventional Radiology, Department of Radiology, University of Illinois Hospital and Health Sciences System, 1740 West Taylor Street, MC 931, Chicago, IL 60612 (e-mail: rgaba@uic.edu).

Semin Intervent Radiol 2014;31:212–224

Abstract

Keywords

- percutaneous ablation
- radiofrequency
- microwave
- cryoablation
- percutaneous ethanol injection
- interventional radiology

Percutaneous ablation therapy is an essential component of contemporary interventional oncologic therapy of primary and secondary malignancies. The growing armamentarium of available ablation technologies calls for thorough understanding of the different ablation modalities to optimize device selection in individual clinical settings. The goal of the current article is to provide direction on ablative device selection by reviewing device mechanisms of action, advantages and disadvantages, and practical considerations in real-life case scenarios.

Percutaneous image-guided ablation is increasingly being used as definitive treatment of primary and metastatic focal malignancies, local therapy for tumors in poor operative candidates, and for pain palliation. Advances in tissue ablation technologies with development of new modalities have made device selection an increasingly complex endeavor. As the arsenal of ablation devices continues to evolve, each is slowly finding its optimal niche; however, the clinical benefits and limitations of each tool are still not conclusively delineated, with significant overlap in effective and safe applicability. In many scenarios, the choice of ablation modality is dependent on the available equipment, operator expertise, and institutional preference. However, a firm understanding of the physical, chemical, and biological mechanisms underlying induction of tissue necrosis, the real-world benefits and shortcomings of each technology, and the performance profile for each ablation technique in specific organ systems is critical in choosing the most favorable device for each individual clinical situation. This article aims to provide practical guidance on ablative device selection by

briefly reviewing the mechanism of action of currently available thermal and nonthermal ablation technologies, highlighting the clinical and technical advantages or disadvantages of each modality, and utilizing a case-based format to illustrate selection considerations and practical application of ablation equipment in assorted clinical cases.

Ablation Modalities and Mechanisms of Action

Thermal Ablation

Hyperthermic or heat-based ablation techniques cause cellular death by coagulative necrosis, leading to denaturation of intracellular enzymes and protein complexes, and leading to structural damage and apoptosis. Irreversible cellular injury typically occurs when cells are heated to greater than 60°C, and ensues more rapidly as temperature rises.¹ Examples of commonly utilized hyperthermic ablation modalities include radiofrequency ablation (RFA) and microwave ablation (MWA). Other hyperthermic modalities, including high-

Table 1 Positive and negative attributes of major ablation modalities

Thermal Ablation			
	Modality	Advantages and benefits	Disadvantages and limitations
Hyper-thermic	Radiofrequency ablation (RFA)	<ul style="list-style-type: none"> • Long track record and robust clinical experience supporting efficacy and safety • Numerous commercial devices 	<ul style="list-style-type: none"> • Requires grounding pads • Susceptible to heat sink effect • Limited single probe ablation volumes • Potentially lengthier procedures (multiple electrodes used sequentially rather than simultaneously)
	Microwave ablation (MWA)	<ul style="list-style-type: none"> • Less susceptible to heat sink effect • High temperatures (greater than 100-150°C) • Fast ablation (simultaneous use of multiple antennas possible) • Large ablation volumes • Not restricted by high impedance (penetrates aerated lung, bone, and charred or vaporized tissue) • No grounding pads 	<ul style="list-style-type: none"> • Short track record and less clinical experience • Some devices susceptible to oblong ablation zones and shaft heating • Fast ablation may limit intra-procedural monitoring and adjustment
Hypo-thermic	Cryoablation	<ul style="list-style-type: none"> • Reduced pain (tissue cooling provides anesthetic effect) • Tissue preservation • Enhanced visualization (ice ball) • Simultaneous use of multiple probes possible 	<ul style="list-style-type: none"> • Susceptible to cold sink effect • Increased bleeding risk (lack of cautery effect) • Lengthier procedures (due to multiple freeze-thaw cycles) • Dependent on multi-probe positioning • Potential for cryoshock or organ fracture
Non-thermal Ablation			
	Irreversible electroporation (IRE)	<ul style="list-style-type: none"> • Non-thermal mechanism • Avoids heat-sink effect • Avoids damage to extracellular matrix (potentially fewer complications to adjacent structures) • Fast ablation (treatment on the order of seconds) • Uniform destruction 	<ul style="list-style-type: none"> • General anesthesia and paralytic induction required • Potential to stimulate cardiac arrhythmias or muscle contraction • Fast ablation may limit intra-procedural monitoring and adjustment • Increased bleeding risk (lack of cautery effect) • New device (least studied, to date)
	Chemical ablation	<ul style="list-style-type: none"> • Non-thermal mechanism • Simple • Inexpensive • Long track record and robust experience 	<ul style="list-style-type: none"> • Potential for non-uniform agent distribution (difficult to control liquid dispersal) • Not applicable for larger tumors • Requires multiple treatment sessions

intensity focused ultrasound and laser interstitial thermal ablation, will not be discussed or included in the case presentation herein due to less extensive clinical use, although both have been previously described in detail.²

RFA operates within the radiofrequency range of electrical current (3 kHz–300 GHz), causing heat-based thermal cytotoxicity in close proximity to the needle electrode, with tapering conduction of heat further away from the probe.² Surrounding tissues cause electrical impedance, with frictional agitation and heat generation (the Joule effect) ultimately leading to thermal damage.³ The electrical circuit is completed through the body with the exit of the current through dispersing electrodes affixed to the thigh or back (grounding pads). The most common RFA design is monopolar, with single or multitined (arrays of 4–12 tines) electrode designs emanating from a single electrode sheath distributing energy spatially, and with a central zone of high temperatures (greater than 60 to ~100°C) and a peripheral zone of decreased tissue heating.²

MWA utilizes electromagnetic energy—with either 915 MHz or 2.54 GHz devices currently commercially available—applied to tissue through a microwave antenna.² Microwave energy agitates water molecules in surrounding tissue (“dielectric hysteresis,” or rotating dipoles), producing friction and heat, elevating local temperatures to 60 to 150°C, and ultimately inducing cellular death via coagulation necrosis.⁴ Microwave energy can penetrate tissues

with low electrical conductivity (high impedance), such as lung and bone, and through charred or desiccated tissues that tend to accumulate around hyperthermic ablation applicators.

Hypothermic ablation utilizes freezing temperatures to cause cellular death by mechanical, osmotic, and coagulative mechanisms.² The sole hypothermic ablation technique is cryoablation, in which a cryoprobe tip forms an ice ball with alternating freeze and thaw cycles, resulting in a lethal isotherm of –20 to –40°C located several millimeters inside of the ice ball boundary. The mechanism for freezing is the Joule–Thomson effect, where temperature changes of a gas (commonly argon or helium) results from expansion and compression of the gas within a small chamber inside the distal end of the cryoprobe, creating the necessary heat sink and source for freezing and thawing.⁵ Argon provides a heat sink of approximately 9 kJ, and can create temperatures as low as –140°C. Performing rapid cooling typically causes intracellular ice crystals leading to cellular mechanical rupture. Performing slow cooling with alternating freeze and thaw cycles causes extracellular ice to form, changing osmolality, and ultimately leading to irreversible osmotic damage. Prolonged cooling for greater than 5 minutes leads to ice crystal formation within microvessels and finally leads to coagulation. However, being a hypothermic process, there is a lack of a cautery effect upon the vessels.

Figure 1 RFA in a 53-year-old woman with hepatitis C viral cirrhosis and HCC, performed as bridge to liver transplantation. Contrast-enhanced MR imaging scan (A) reveals a 2.5 cm solitary right lobe HCC (arrowhead). The hypoechoic mass (arrowheads) was localized with ultrasound (B), and percutaneous RFA performed using StarBurst XLi device (AngioDynamics; Latham, NY) with expected increased lesion echogenicity (arrowheads) on the postablation ultrasound (C). A 6-month follow-up MR imaging scan shows no enhancement of tumor (black arrowhead), indicating complete response to therapy; nodular peripheral high-signal material (white arrowheads) represents blood product also seen on precontrast scan. HCC, hepatocellular carcinoma; MR, magnetic resonance; RFA, radiofrequency ablation.

Nonthermal Ablation

The foremost nonthermal ablation techniques are chemical ablation and irreversible electroporation (IRE). While each method has very different mechanisms of action, the commonality between both is that temperature change is not the primary process of cellular injury.

Chemical ablation involves intratumoral administration of chemically destructive substances, most commonly ethanol or acetic acid.² The chemical causes coagulative and ischemic tissue necrosis. When the chemical diffuses into neoplastic cells, cytoplasmic dehydration and protein denaturation occurs, leading to coagulative necrosis.³ As the chemical enters the local circulation, thrombosis and necrosis of the vascular endothelium and platelet aggregation also occurs, leading to concurrent ischemic necrosis.³

IRE involves application of a strong electrical field that causes irreversible damage to cell membranes and induction of apoptosis.⁶ By generating several rapid and short (microsecond to millisecond long) electric field pulses through the electrodes, pores form within the cell membrane lipid bilayer, leading to increased permeability and the inability to maintain cellular homeostasis.⁶ An electrical field strength of greater than 500 to 600 V/cm is needed to achieve irreversible pore formation of the cell membranes, and the electrical field strength diminishes with increasing distance from the electrode(s). For most applications, multiple electrodes are required, spaced 1 to 3 cm apart to provide sufficient electric field strengths. By utilizing a nonthermal mechanism and primarily effecting cellular membranes, IRE has demonstrated a relative advantage of sparing nearby ductal and visceral structures that have a higher connective tissue content.⁷

Ablation Modality Benefits and Shortcomings

Positive and negative attributes of major ablation modalities are presented in ► **Table 1**. In addition to hands on experience gained in day-to-day interventional practice, a working knowledge of each of these technique properties provides a foundation for effective clinical device selection.

Case-Based Device Selection

The following cases illustrate clinical applications of various ablation techniques, with particular attention to the thought process underlying device selection. Because operator experience and preference play a major role in modality choice, it warrants mention that none of the selections made in each case are categorically correct or incorrect; rather, there may be significant variations in approach between operators and institutions, even among the particular example cases presented here.

Case 1: RFA for Solitary Hepatocellular Carcinoma

RFA of a small (≤ 3 cm) focal hepatocellular carcinoma (HCC) (► **Fig. 1**) in a cirrhotic patient is a good therapeutic choice for several reasons. First, this therapy aligns with current

treatment guidelines as put forth by the American Association for the Study of Liver Diseases and the Barcelona Clinic Liver Cancer staging system.⁸ Second, RFA is to date the most studied percutaneous ablation technique for treatment of

Figure 2 MWA in a 59-year-old man with hepatitis C viral cirrhosis and HCC abutting portal vessel. Axial contrast-enhanced MR imaging scan (A) demonstrates a 1.1 cm solitary left lobe HCC (arrow) located immediately adjacent to the lateral segment portal vein branch (arrowheads). The hypoechoic tumor (arrows) was identified on ultrasound (B), and MWA performed using 17-gauge antenna (NeuWave Medical, Madison, WI); note the adjacent portal vein branch (arrowheads). A 30-month follow-up contrast-enhanced CT scan (C) shows no lesion enhancement (arrow), indicating a complete response to therapy, and maintained patency of the adjacent portal vessel (arrowheads). CT, computed tomography; HCC, hepatocellular carcinoma; MR, magnetic resonance; MWA, microwave ablation.

primary liver tumors, and has established efficacy and safety. Small tumors measuring ≤ 3 cm can be completely ablated using one electrode in a single treatment session with a high complete ablation rate approximating 80 to 90%,⁹ and 5-year survival outcomes range from 60 to 70%^{10,11}—similar to surgical resection—while complication rates are generally low ($< 5\%$).⁹ Third, hyperthermic ablation techniques, including RFA, provide efficient therapy for tumors within a cirrhotic liver due to an “oven effect,” as the scarred liver and tumor pseudocapsule act as thermal insulators during ablation, resulting in higher peak temperatures and prolonged duration of cytotoxic heating. Fourth, as illustrated by the mass in the current case, lesions that are most amenable to RFA are intraparenchymal and far from major vessels; this decreases the risk for damage to vascular

structures and convective heat loss (heat sink effect) while enhancing procedure safety by reducing bleeding risk and tract seeding incidence as compared with ablation of a subcapsular lesion.¹²

From a technical standpoint, performance of ablation with ultrasound-guided probe insertion is favorable in the current case due to excellent sonographic lesion visualization and the capability for real-time electrode puncture, confirmation of fine tip position, and ablation monitoring. Computed tomography (CT) guidance is useful for challenging locations such as liver dome lesions or for ultrasound occult lesions. Ablation is routinely performed with settings and duration as per manufacturer protocol, and is followed by tract ablation both to secure hemostasis and avoid tract seeding.

Figure 3 Percutaneous ethanol ablation in a 60-year-old man with HCC. Contrast-enhanced CT scan (A) demonstrates a 1.0 cm solitary HCC (arrowhead) in the left hepatic lobe, segment 2. The hypoechoic tumor (arrowhead) was identified on ultrasound (B); because the tumor was located near the diaphragm (arrows) and other critical structures (heart, asterisk), ethanol ablation was performed. Sequential ultrasound images ([C] and [D]) demonstrate 20-gauge needle (arrowheads) advanced into nodule, with injection of hyperechoic ethanol (arrowheads). An 8-month follow-up MRI scan (E) reveals no lesion enhancement (arrowhead), signifying a complete response to therapy. CT, computed tomography; HCC, hepatocellular carcinoma; MRI, magnetic resonance imaging.

Case 2: MWA for Solitary HCC near Large Blood Vessel

As in Case 1, thermal ablation of the small single HCC in the cirrhotic patient in Case 2 is a good therapeutic option, for all of the reasons previously discussed. However, location of the tumor immediately adjacent to a large vessel prompted selection of MWA rather than RFA in the described clinical scenario, with the rationale of avoiding incomplete ablation related to convective heat loss (heat sink effect) (►Fig. 2). The heat sink effect refers to convective heat dissipation from tissue mediated by high blood flow within large blood vessels in close proximity to ablation sites, precluding adequate radiofrequency energy deposition¹³; in general, such

effects should be a consideration when a tumor abuts a vessel ≥ 3 mm in size.¹⁴ Compared with RFA, MWA is relatively less susceptible to convective heat loss because of the larger zone of active heating and less dependence on thermal conduction,¹⁵ and is thus more capable of obtaining higher intratumoral temperatures throughout a lesion despite abutting a vessel. For this reason, MWA may be a better choice than RFA in the current clinical case, and would be expected to yield similar clinical outcomes in terms of technical success and therapeutic response. As a final note, the technical elements involved with MWA parallel those used for RFA.

Figure 4 Combined TACE and RFA in a 71-year-old man with HCC. Contrast-enhanced CT (A) demonstrates a 4.0 cm solitary mass (arrowheads) in the right hepatic lobe, segment 7. Fluoroscopic spot images ([B] and [C]) from conventional TACE demonstrate segmental treatment of the tumor (arrowheads) with excellent uptake of high-attenuation chemotherapy–lipiodol emulsion. Percutaneous ultrasound-guided RFA performed immediately thereafter (D), and a 5-year follow-up MRI (E), exhibits no lesion enhancement (arrowheads), representing complete response to therapy. CT, computed tomography; HCC, hepatocellular carcinoma; MRI, magnetic resonance imaging; RFA, radiofrequency ablation; TACE, transarterial chemoembolization.

Case 3: Ethanol Ablation for Solitary HCC near Critical Structures

Similar to Cases 1 and 2, the small isolated HCC presented in the current case may be effectively treated with percutaneous ablation (► **Fig. 3**). In this case, however, lesion location near the diaphragm and heart rendered thermal ablation less desirable due to small but nonzero risk of injury to these critical structures. Percutaneous ethanol injection was therefore selected due to its nonthermal nature, which reduces the risk of damage to surrounding tissues; this approach may also be utilized for central lesions near major vascular channels, those near bile ducts or other vital structures (such as the gallbladder), and for superficial (subcapsular) lesions. Ethanol ablation, similar to RFA, has the advantage of long-term data and record of use. Chemical ablation has been in use for more than 20 years, and is associated with excellent therapeutic efficacy, with high technical success and necrosis rates ranging between 90 and 100% for lesions ≤ 2 cm.^{16–18} While intratumoral injection of a liquid has the disadvantage of nonuniform diffusion, particularly in larger tumor volumes, the surrounding fibrosis of the cirrhotic liver as well as the pseudocapsule of HCC may promote some retention of the injected ethanol within the lesion. This difference in firmness between relatively soft tumors and relatively firm cirrhotic liver explains in part why results for chemical ablation are so

much more favorable for primary liver tumors in cirrhotic livers than metastatic disease in noncirrhotic livers. Another drawback of ethanol ablation is its limited applicability to small tumors (≤ 2 cm), and requirement for multiple sessions to obtain complete ablation of larger lesions (for which thermal ablation is more effective).

From a technical perspective, ethanol may be injected via an end-hole needle or a multi-side-hole needle, which has the theoretical benefit of more homogeneous agent infusion. A small—20 or 22-gauge needle may be employed, which limits the risk for hemorrhagic complications. The necessary volume of ethanol is calculated by estimating volume of a sphere, according to the formula $V = (4/3) \times \pi \times (r + 0.5)^3$, where V is the ethanol volume in milliliters and r is the tumor radius in centimeters (0.5 cm is added to ensure a tumor free margin).

Case 4: Combined RFA and Chemoembolization for Intermediate Size Solitary HCC

Combination therapy is an evolving option for HCC, particularly for lesions larger than 3 cm diameter (► **Fig. 4**). The combination of transarterial chemoembolization (TACE) with hyperthermic percutaneous ablation allows for complementary outcomes, as heat sink effects are diminished by embolization of both intratumoral blood vessels as well as

Figure 5 Renal tumor cryoablation in an 82-year-old woman. Contrast-enhanced CT (A) reveals a 2.7 cm solitary left renal mass (arrowheads) compatible with RCC. CT images during image-guided cryoablation demonstrate 17-gauge cryoprobes (IceRod; Galil Medical, Arden Hills, MN) (arrowheads) introduced into the tumor (B) with subsequent ice ball formation (arrowheads). A 15-month follow-up MRI scan (D) shows marked size reduction of the tumor (arrowheads), which exhibits nonenhancement indicative of complete necrosis. CT, computed tomography; MRI, magnetic resonance imaging; RCC, renal cell carcinoma.

vasculature adjacent to cancers, allowing for higher ablation temperatures.¹⁹ From a clinical standpoint, there is growing evidence that combination therapy improves therapeutic outcomes—including response rates, local tumor recurrence rates, and patient survival—for HCCs larger than 3 cm.^{20,21} To this end, Morimoto et al demonstrated reduced 3-year tumor progression rates (6 vs. 39%) and enhanced 3-year survival (93 vs. 80%) in a randomized trial of 37 patients with 3 to 5 cm solitary HCCs undergoing combination TACE and RFA versus RFA alone.²⁰ Similarly, Peng et al demonstrated superiority of TACE-RFA compared with RFA alone in improving survival for patients with HCC less than 7 cm; the 1-, 3-, and 4-year survival for TACE-RFA compared with RFA alone were 93, 67, and 62% versus 85, 59, and 45%, respectively.²¹ MWA has also been shown to be effective for combination therapy with TACE.^{22–24}

Despite mounting support, combination therapy may still be underutilized,²⁵ but should be applied for intermediate to

large-sized tumors in technically amenable locations. In the current case scenario, RFA was used because of operator preference; however, MWA would have been a good option as well.

From a technical viewpoint, the order of therapeutic intervention—TACE followed by ablation or ablation followed by TACE—is a matter of debate. The former has the benefit of post-TACE reduction in tumor vascularity, dampening of heat sink effects, and larger ablation volumes,¹⁹ while the latter has the potential advantage of postablation hyperemia and bolstering of TACE chemotherapy deposition.²⁶ The optimal timing of therapies, which may range from single setting to 2 to 3 weeks separation, is currently unknown.

Case 5: Cryoablation for Renal Cell Carcinoma

Percutaneous ablation is currently utilized in the treatment of renal tumors in patients who are poor operative candidates or in whom a minimally invasive, nephron-sparing approach is

Figure 6 Lung tumor cryoablation in a 64-year-old man, nonoperative candidate. PET-CT scan (A) displays a 3.5 cm ^{18}F -FDG avid recurrent mesothelioma (arrowhead) following surgical resection. Intraprocedural CT images ([B] and [C]) demonstrate percutaneous cryoablation performed from a posterior approach, with a reduction in tumor attenuation (arrowheads) following ablation. A 1-month follow-up PET-CT (D) demonstrates no further ^{18}F -FDG avidity, signifying tumor necrosis (Case courtesy Rajesh P. Shah, MD). ^{18}F -FDG, ^{18}F -fluorodeoxyglucose; CT, computed tomography; PET, positron emission tomography.

desirable.²⁷ Both RFA and cryoablation have been utilized with clinical success; primary ablation success rates range from 79 to 97%,²⁸ and 5-year disease-free survival rates approximate 87 to 97%.²⁹ Based on small (≤ 4 cm) tumor size, posterior and peripheral location, and distance from other abdominal structures, the renal cell carcinoma (RCC) in the current clinical case was ideally positioned for successful ablation (**►Fig. 5**). While both RFA and cryoablation may be appropriate modality selections in this case, cryoablation was utilized based on operator preference; notably, these technologies have not been compared in a randomized trial, and based on current evidence either can be employed without clinical disparity. Tumor characteristics that may favor use of cryoablation rather than RFA include a more central location near the collecting system, as cryoablation is less damaging to fibrous structures (such as the walls of the renal collecting system). In contrast, more peripheral or exophytic tumors might favor use of hyperthermic techniques, such as RFA or MWA, which have the advantage of cautery hemostasis and single probe ablative capacity. It warrants mention that adjunctive maneuvers, such as hydrodissection,³⁰ interposition of balloon catheters³¹ aimed at displacing adjacent structures, or fluid irrigation of urinary collecting systems³² intended to prevent urothelial thermal injuries, while not employed in the current case, may be used to increase the safety of kidney thermal ablation.

Case 6: Cryoablation for Recurrent Mesothelioma of the Lung

Percutaneous ablation provides effective therapy for primary and secondary pulmonary tumors in patients with contraindications to surgical resection, such as severe medical comorbidity or inadequate pulmonary reserve.³³ The majority of reports published to date pertain to use of RFA,³³ but more recent reports have supported safety and efficacy of pulmonary cryoablation.³⁴ This technique is associated with 1-year progression free rates approximating 80%, but the incidence of pneumothorax, pleural effusion, and hemoptysis is nontrivial.³⁵ In the current clinical case, cryoablation was a reasonable treatment choice for several reasons (**►Fig. 6**). First, cryoablation may be particularly well suited for lung ablation, as it is not affected by the high electrical resistance of aerated lung, which limits modalities such as RFA that are dependent on electrical current conduction.³⁶ Second, cryoablation has the advantage of monitoring the ablation zone relatively real time with a sharply demarcated hypoattenuating zone on CT, as ice has a slightly lower attenuation than water and soft tissue. Third, cryoablation is less painful than hyperthermic techniques due to cooling-based anesthetic effect on nervous tissue,⁴ which is beneficial in the current case of a tumor situated near the pleural lining where many nerve endings are present. One disadvantage of cryoablation is the requirement for multiple probes in lesions that could otherwise not be treated with a single RFA electrode or microwave antenna; a typical approach employs the “2 to 1 rule,” in which probes are placed within 1 cm of the tumor margin and no more than 2 cm apart from one another.³⁷

Case 7: MWA and Cryoablation for Squamous Cell Carcinoma Pulmonary Metastases

This case highlights the benefits of both hyperthermic and hypothermic ablation in the treatment of lung tumors (**►Fig. 7**). Different modalities were selected for the treatment of each lesion to optimize therapeutic efficacy and safety for each tumor. MWA was selected for the peripheral

Figure 7 MWA and cryoablation in a 59-year-old smoker with metastatic anal squamous cell carcinoma in the lung. The patient refused systemic chemotherapy. PET-CT images ([A] and [B]) reveal ¹⁸F-FDG-avid pulmonary nodules (arrowheads). CT images (C) during percutaneous ablative therapy shows microwave antenna (arrow) within a peripheral 1.0 cm nodule and cryoprobe (arrowhead) within a central 2.5 cm nodule. A 3-month follow-up PET-CT images ([D] and [E]) demonstrates complete response to therapy, with no further ¹⁸F-FDG uptake at either site (arrowheads) (Case courtesy Rajesh P. Shah, MD). ¹⁸F-FDG, ¹⁸F-fluorodeoxyglucose; CT, computed tomography; MWA, microwave ablation; PET, positron emission tomography.

Figure 8 RFA in a 41-year-old woman with symptomatic osteoid osteoma. Coronal reconstructed CT image (A) shows an osteoid osteoma nidus (arrowhead) within the proximal right femur. CT scan (B) obtained during percutaneous RFA demonstrates probe (arrowheads) (StarBurst Talon Semi-Flex device; AngioDynamics; Latham, NY) with tip positioned in osteoid osteoma nidus. The patients' symptoms rapidly disappeared following treatment. CT, computed tomography; RFA, radiofrequency ablation.

lesion; this technique is advantageous in the lung, with possible benefits including higher intratumoral temperatures due to relative insensitivity to tissues with high impedance (such as lung) and the potential for larger ablation volumes without the need for grounding pads. Moreover, MWA for pulmonary lesions has been performed with 75 to 95% initial technical success and provides 1-year survival rates ranging from 80 to 90%.^{38,39} Cryoablation was utilized for the more central lesion because of its potentially lower complication profile following ablation near adjacent critical structures. Cryoablation preserves collagenous architecture of ablated tissue, causes less scarring, and is thus considered safer to perform near major vasculature.⁴⁰ In this case, avoidance of thermal injury to nearby mediastinal constituents—namely the heart—was of utmost concern.

Case 8: RFA for Osteoid Osteoma

RFA is a safe and effective treatment option for the osteoid osteoma nidus (►Fig. 8).⁴¹ Treatment of the central nidus is the key to therapeutic success, and RFA achieves a focus of high temperatures around the probe positioned directly within the nidus. While RFA has the longest track record, MWA⁴² and cryoablation⁴³ have also been shown to be safe and effective for treatment of symptomatic osteoid osteomas in preliminary investigations, and either could have been used in this case as well. From a technical standpoint, the percutaneous penetration and ablation of the osteoid osteoma nidus is often extremely painful, and thus the intervention is frequently performed using general anesthesia or utilizing nerve blocks. With CT guidance, the lesion is accessed with a bone trocar, with image-guided drilling sometimes required to gain access through dense

Figure 9 Cryoablation in a 14-year-old boy with recurrent chondroblastoma, which had previously undergone resection twice with curettage and bone grafting. Axial MR imaging scan (A) exhibits recurrent enhancing tumor (arrowhead) along the posterior margin of humeral head. (B) CT image during percutaneous cryoablation demonstrates cryoprobe (arrow) (IceSeed; Galil Medical, Arden Hills, MN) within the lesion; the ice ball rim is clearly visualized in adjacent musculature (arrowheads). A 2-year follow-up MR imaging scan (C) reveals no further abnormal enhancement, compatible with complete ablation. CT, computed tomography; MR, magnetic resonance.

cortical bone. This is followed by coaxial insertion of the RFA electrode. The majority of patients report resolution of pain symptoms after 2 to 5 days, with a very high technical success rate and an overall clinical success rate varying from 76 to almost 100%.⁴⁴

Case 9: Cryoablation for Chondroblastoma

Recurrent primary osseous lesions and metastatic disease to bone can be a cause of significant pain and morbidity. In this case of recurrent chondroblastoma after two surgical procedures, the patient was a candidate for palliative ablation to reduce the local tumor burden while also limiting pain and risk of complication (→Fig. 9). Much of the literature on clinical outcomes concerns open surgery and adjunctive cryoablation following curettage, which has demonstrated high 2-year disease-free survival rates.^{45,46} From the perspective of a percutaneous ablation procedure, treatment of bone and soft tissue tumors with ablative techniques requires careful consideration of the perilesional anatomy, and cryoablation was selected in this case given the desire to preserve adjacent normal structures. In the current clinical scenario, the critical structures to preserve were the shoulder joint capsule and intra-articular ligamentous and tendinous structures, as well as the axillary nerve, all of which could be susceptible to burn injury with hyperthermic ablation modalities. In addition, with many nerve endings located in the periosteum, cryoablation may afford decreased pain in the immediate posttreatment period due to the relative anesthetic effect of hypothermic ablation. Lastly, the formation of ice during cryoablation has been shown to more deeply penetrate into bone, which is critical in situations such as the current case to encompass the full extent of intramedullary tumor.⁴⁷

Case 10: IRE for RCC

At present, IRE is an actively developing technology without long-term data, and is currently utilized as a therapy for tumors in which other ablative techniques are contraindicated (→Fig. 10). As a nonthermal modality, IRE does not disrupt extracellular matrix but rather maintains the structural integrity of vascular and ductal structures.^{48–51} This modality is thus suitable for ablation of tumors located near important adjacent structures, such as major blood vessels, bile ducts, and the renal collecting system, among others. Proposed applications of IRE include ablation of hepatic,⁵² renal,⁷ prostatic,⁵³ and pancreatic⁵⁴ tumors. Its use in the treatment of pancreatic malignancies⁵⁴ may be particularly beneficial given the complicated glandular and ductal microstructure of the pancreas as well as apposition to multiple critical abdominal structures, including bowel and vasculature. IRE was selected as the ablation modality of choice in the current case due to the tumor location near adjacent colon. While thermal ablation with adjunctive hydrodissection or balloon catheter interposition may have been used in lieu of IRE, the benefit of this technology in preserving not only nearby large intestine but also renal collecting system structures—which have been shown to be unaffected by IRE in animal studies⁵⁵—prompted its use.

Figure 10 IRE in a 79-year-old woman with right-sided RCC in close proximity to bowel. Contrast-enhanced CT scan (A) demonstrates a 2.0 cm solitary renal mass (arrowhead) in the anterior right kidney with closely apposed ascending colon (arrows). Intraprocedural CT image (B) displays percutaneous IRE performed from a posterolateral approach, with two probes (arrowheads) (NanoKnife; AngioDynamics; Latham, NY) spanning the renal tumor. A 1-month follow-up CT scan (C) demonstrates no enhancement of the mass (arrowhead), signifying complete tumor necrosis; adjacent colon (arrows) is unaffected (Case courtesy Jordan C. Tasse, MD). CT, computed tomography; IRE, irreversible electroporation; RCC, renal cell carcinoma.

The technical parameters of IRE are still being optimized, including the best voltage gradient, and the duration, number, and frequency of the pulses applied. For most applications, multiple electrodes are required, which are spaced 1 to 3 cm apart.³ IRE can potentially deliver a full treatment to a targeted area in a matter of seconds. Given the use of high-voltage electrical pulses, there are two technical limitations of IRE compared with other ablative technologies: the requirement for general anesthesia with a muscle relaxant, and the need for electrocardiographic synchronization with the refractory period of the cardiac rhythm.⁷

Conclusion

Locoregional percutaneous ablation has become an accepted treatment modality for focal primary and secondary malignancies in a wide range of organs. The benefits of minimally invasive, image-guided ablation techniques include reduced morbidity and cost, and the ability to treat patients who are not surgical candidates. However, limitations in ablation efficacy do exist, and mandate a fundamental understanding of the different ablative technologies, their mechanisms of action, differing advantages and disadvantages, and performance in different scenarios. Awareness of such factors is necessary to optimize individualized ablation strategies for lesions of varying sizes, multiplicity, and organ system location to improve outcomes while reducing complications.

Conflict of Interest
None.

References

- Goldberg SN, Gazelle GS, Halpern EF, Rittman WJ, Mueller PR, Rosenthal DI. Radiofrequency tissue ablation: importance of local temperature along the electrode tip exposure in determining lesion shape and size. *Acad Radiol* 1996;3(3):212-218
- Saldanha DF, Khiatani VL, Carrillo TC, et al. Current tumor ablation technologies: basic science and device review. *Semin Intervent Radiol* 2010;27(3):247-254
- Ahmed M, Brace CL, Lee FT Jr, Goldberg SN. Principles of and advances in percutaneous ablation. *Radiology* 2011;258(2):351-369
- Lubner MG, Brace CL, Hinshaw JL, Lee FT Jr. Microwave tumor ablation: mechanism of action, clinical results, and devices. *J Vasc Interv Radiol* 2010;21(8, Suppl):S192-S203
- Erinjeri JP, Clark TW. Cryoablation: mechanism of action and devices. *J Vasc Interv Radiol* 2010;21(8, Suppl):S187-S191
- Al-Sakere B, André F, Bernat C, et al. Tumor ablation with irreversible electroporation. *PLoS ONE* 2007;2(11):e1135
- Pech M, Janitzky A, Wendler JJ, et al. Irreversible electroporation of renal cell carcinoma: a first-in-man phase I clinical study. *Cardiovasc Intervent Radiol* 2011;34(1):132-138
- Bruix J, Sherman M; American Association for the Study of Liver Diseases. Management of hepatocellular carcinoma: an update. *Hepatology* 2011;53(3):1020-1022
- McWilliams JP, Yamamoto S, Raman SS, et al. Percutaneous ablation of hepatocellular carcinoma: current status. *J Vasc Interv Radiol* 2010;21(8, Suppl):S204-S213
- Chen MS, Li JQ, Zheng Y, et al. A prospective randomized trial comparing percutaneous local ablative therapy and partial hepatectomy for small hepatocellular carcinoma. *Ann Surg* 2006;243(3):321-328
- Huang J, Yan L, Cheng Z, et al. A randomized trial comparing radiofrequency ablation and surgical resection for HCC conforming to the Milan criteria. *Ann Surg* 2010;252(6):903-912
- Jaskolka JD, Asch MR, Kachura JR, et al. Needle tract seeding after radiofrequency ablation of hepatic tumors. *J Vasc Interv Radiol* 2005;16(4):485-491
- McGhana JP, Dodd GD III. Radiofrequency ablation of the liver: current status. *AJR Am J Roentgenol* 2001;176(1):3-16
- Lu DS, Yu NC, Raman SS, et al. Radiofrequency ablation of hepatocellular carcinoma: treatment success as defined by histologic examination of the explanted liver. *Radiology* 2005;234(3):954-960
- Wright AS, Sampson LA, Warner TF, Mahvi DM, Lee FT Jr. Radiofrequency versus microwave ablation in a hepatic porcine model. *Radiology* 2005;236(1):132-139
- Livraghi T, Bolondi L, Lazzaroni S, et al. Percutaneous ethanol injection in the treatment of hepatocellular carcinoma in cirrhosis. A study on 207 patients. *Cancer* 1992;69(4):925-929
- Ishii H, Okada S, Nose H, et al. Local recurrence of hepatocellular carcinoma after percutaneous ethanol injection. *Cancer* 1996;77(9):1792-1796
- Okada S. Local ablation therapy for hepatocellular carcinoma. *Semin Liver Dis* 1999;19(3):323-328
- Mostafa EM, Ganguli S, Faintuch S, Mertyna P, Goldberg SN. Optimal strategies for combining transcatheter arterial chemoembolization and radiofrequency ablation in rabbit VX2 hepatic tumors. *J Vasc Interv Radiol* 2008;19(12):1740-1748
- Morimoto M, Numata K, Kondou M, Nozaki A, Morita S, Tanaka K. Midterm outcomes in patients with intermediate-sized hepatocellular carcinoma: a randomized controlled trial for determining the efficacy of radiofrequency ablation combined with transcatheter arterial chemoembolization. *Cancer* 2010;116(23):5452-5460
- Peng ZW, Zhang YJ, Chen MS, et al. Radiofrequency ablation with or without transcatheter arterial chemoembolization in the treatment of hepatocellular carcinoma: a prospective randomized trial. *J Clin Oncol* 2013;31(4):426-432
- Seki T, Tamai T, Nakagawa T, et al. Combination therapy with transcatheter arterial chemoembolization and percutaneous microwave coagulation therapy for hepatocellular carcinoma. *Cancer* 2000;89(6):1245-1251
- Yang WZ, Jiang N, Huang N, Huang JY, Zheng QB, Shen Q. Combined therapy with transcatheter arterial chemoembolization and percutaneous microwave coagulation for small hepatocellular carcinoma. *World J Gastroenterol* 2009;15(6):748-752
- Xu LF, Sun HL, Chen YT, et al. Large primary hepatocellular carcinoma: transarterial chemoembolization monotherapy versus combined transarterial chemoembolization-percutaneous microwave coagulation therapy. *J Gastroenterol Hepatol* 2013;28(3):456-463
- Gaba RC. Chemoembolization practice patterns and technical methods among interventional radiologists: results of an online survey. *AJR Am J Roentgenol* 2012;198(3):692-699
- Carmi L, Georgiades C. Combination percutaneous and intraarterial therapy for the treatment of hepatocellular carcinoma: a review. *Semin Intervent Radiol* 2010;27(3):296-301
- Clark TW, Millward SF, Gervais DA, et al; Technology Assessment Committee of the Society of Interventional Radiology. Reporting standards for percutaneous thermal ablation of renal cell carcinoma. *J Vasc Interv Radiol* 2009;20(7, Suppl):S409-S416
- Thumar AB, Trabulsi EJ, Lallas CD, Brown DB. Thermal ablation of renal cell carcinoma: triage, treatment, and follow-up. *J Vasc Interv Radiol* 2010;21(8, Suppl):S233-S241

- 29 Gervais DA. Cryoablation versus radiofrequency ablation for renal tumor ablation: time to reassess? *J Vasc Interv Radiol* 2013;24(8):1135–1138
- 30 Gervais DA, Arellano RS, McGovern FJ, McDougal WS, Mueller PR. Radiofrequency ablation of renal cell carcinoma: part 2, Lessons learned with ablation of 100 tumors. *AJR Am J Roentgenol* 2005;185(1):72–80
- 31 Kam AW, Littrup PJ, Walther MM, Hvizda J, Wood BJ. Thermal protection during percutaneous thermal ablation of renal cell carcinoma. *J Vasc Interv Radiol* 2004;15(7):753–758
- 32 Cantwell CP, Wah TM, Gervais DA, et al. Protecting the ureter during radiofrequency ablation of renal cell cancer: a pilot study of retrograde pyeloperfusion with cooled dextrose 5% in water. *J Vasc Interv Radiol* 2008;19(7):1034–1040
- 33 Pua BB, Thornton RH, Solomon SB. Ablation of pulmonary malignancy: current status. *J Vasc Interv Radiol* 2010;21(8, Suppl):S223–S232
- 34 Yashiro H, Nakatsuka S, Inoue M, et al. Factors affecting local progression after percutaneous cryoablation of lung tumors. *J Vasc Interv Radiol* 2013;24(6):813–821
- 35 Inoue M, Nakatsuka S, Yashiro H, et al. Percutaneous cryoablation of lung tumors: feasibility and safety. *J Vasc Interv Radiol* 2012;23(3):295–302, quiz 305
- 36 Ahrar K, Littrup PJ. Is cryotherapy the optimal technology for ablation of lung tumors? *J Vasc Interv Radiol* 2012;23(3):303–305
- 37 Wang H, Littrup PJ, Duan Y, Zhang Y, Feng H, Nie Z. Thoracic masses treated with percutaneous cryotherapy: initial experience with more than 200 procedures. *Radiology* 2005;235(1):289–298
- 38 Wolf FJ, Grand DJ, Machan JT, Dipetrillo TA, Mayo-Smith WW, Dupuy DE. Microwave ablation of lung malignancies: effectiveness, CT findings, and safety in 50 patients. *Radiology* 2008;247(3):871–879
- 39 Vogl TJ, Naguib NN, Gruber-Rouh T, Koitka K, Lehnert T, Nour-Eldin NE. Microwave ablation therapy: clinical utility in treatment of pulmonary metastases. *Radiology* 2011;261(2):643–651
- 40 Khairy P, Chauvet P, Lehmann J, et al. Lower incidence of thrombus formation with cryoenergy versus radiofrequency catheter ablation. *Circulation* 2003;107(15):2045–2050
- 41 Earhart J, Wellman D, Donaldson J, Chesterton J, King E, Janicki JA. Radiofrequency ablation in the treatment of osteoid osteoma: results and complications. *Pediatr Radiol* 2013;43(7):814–819
- 42 Kostrzewa M, Diezler P, Michaely H, et al. Microwave ablation of osteoid osteomas using dynamic MR imaging for early treatment assessment: preliminary experience. *J Vasc Interv Radiol* 2014;25(1):106–111
- 43 Liu DM, Kee ST, Loh CT, et al. Cryoablation of osteoid osteoma: two case reports. *J Vasc Interv Radiol* 2010;21(4):586–589
- 44 Donkol RH, Al-Nammi A, Moghazi K. Efficacy of percutaneous radiofrequency ablation of osteoid osteoma in children. *Pediatr Radiol* 2008;38(2):180–185
- 45 Veth R, Schreuder B, van Beem H, Pruszczynski M, de Rooy J. Cryosurgery in aggressive, benign, and low-grade malignant bone tumours. *Lancet Oncol* 2005;6(1):25–34
- 46 Souna BS, Belot N, Duval H, Langlais F, Thomazeau H. No recurrences in selected patients after curettage with cryotherapy for grade I chondrosarcomas. *Clin Orthop Relat Res* 2010;468(7):1956–1962
- 47 Callstrom MR, Kurup AN. Percutaneous ablation for bone and soft tissue metastases—why cryoablation? *Skeletal Radiol* 2009;38(9):835–839
- 48 Faroja M, Ahmed M, Appelbaum L, et al. Irreversible electroporation ablation: is all the damage nonthermal? *Radiology* 2013;266(2):462–470
- 49 Maor E, Ivorra A, Leor J, Rubinsky B. The effect of irreversible electroporation on blood vessels. *Technol Cancer Res Treat* 2007;6(4):307–312
- 50 Cannon R, Ellis S, Hayes D, Narayanan G, Martin RC II. Safety and early efficacy of irreversible electroporation for hepatic tumors in proximity to vital structures. *J Surg Oncol* 2013;107(5):544–549
- 51 Kingham TP, Karkar AM, D'Angelica MI, et al. Ablation of perivascular hepatic malignant tumors with irreversible electroporation. *J Am Coll Surg* 2012;215(3):379–387
- 52 Cheung W, Kavnoudias H, Roberts S, Szkandera B, Kemp W, Thomson KR. Irreversible electroporation for unresectable hepatocellular carcinoma: initial experience and review of safety and outcomes. *Technol Cancer Res Treat* 2013;12(3):233–241
- 53 Neal RE II, Millar JL, Kavnoudias H, et al. In vivo characterization and numerical simulation of prostate properties for non-thermal irreversible electroporation ablation. *Prostate* 2014;74(5):458–468
- 54 Narayanan G, Hosein PJ, Arora G, et al. Percutaneous irreversible electroporation for downstaging and control of unresectable pancreatic adenocarcinoma. *J Vasc Interv Radiol* 2012;23(12):1613–1621
- 55 Wendler JJ, Porsch M, Hühne S, et al. Short- and mid-term effects of irreversible electroporation on normal renal tissue: an animal model. *Cardiovasc Intervent Radiol* 2013;36(2):512–520