RadioGraphics

Microwave Ablation: Principles and Applications[1]

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TEACHING POINTS
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Microwave ablation is the most recent development in the field of tumor ablation. The technique allows for flexible approaches to treatment, including percutaneous, laparoscopic, and open surgical access. With imaging guidance, the tumor is localized, and a thin (14.5-gauge) microwave antenna is placed directly into the tumor. A microwave generator emits an electromagnetic wave through the exposed, noninsulated portion of the antenna. Electromagnetic microwaves agitate water molecules in the surrounding tissue, producing friction and heat, thus inducing cellular death via coagulation necrosis. The main advantages of microwave technology, when compared with existing thermoablative technologies, include consistently higher intratumoral temperatures, larger tumor ablation volumes, faster ablation times, and an improved convection profile. Microwave ablation has promising potential in the treatment of primary and secondary liver disease, primary and secondary lung malignancies, renal and adrenal tumors, and bone metastases. The technology is still in its infancy, and future developments and clinical implementation will help improve the care of patients with cancer.

Abbreviations: H-E = hematoxylin-eosin, NADH = nicotinamide adenine dinucleotide, reduced, RF = radiofrequency

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Introduction

Tumor ablation is defined as the direct application of chemical or thermal therapies to a tumor to achieve eradication or substantial tumor destruction. The principle of tumor ablation has been known for more than 100 years (1). The advantages of imaging-guided ablative therapies compared with traditional cancer treatments include reduced morbidity and mortality, lower procedural cost, suitability for real-time imaging guidance, the ability to perform ablations in an outpatient setting, synergy with other cancer treatments, and repeatability (2,3). Many ablation modalities have been used, including cryoablation, ethanol ablation, laser ablation, and radiofrequency (RF) ablation. The most recent development has been the use of microwave energy in tumor ablation.

Microwave ablation refers to the use of all electromagnetic methods for inducing tumor destruction by using devices with frequencies of at least 900 MHz (4–6). Microwave ablation offers many of the benefits of RF ablation and has several other theoretical advantages that may increase its effectiveness in the treatment of tumors. The potential benefits of microwave technology include consistently higher intratumoral temperatures, larger tumor ablation volumes, faster ablation times, ability to use multiple applicators, improved convection profile, optimal heating of cystic masses, and less procedural pain (7–10). In addition, microwave ablation does not require the placement of grounding pads.

Teaching Point

In this article, the authors describe a recently developed percutaneous device for microwave ablation (8); outline the physics of microwaves; illustrate the histologic changes after microwave ablation in the lung and liver; and show clinical examples of its percutaneous use in the liver, lung, kidney, adrenal gland, and bone.

Physics of Microwaves

Microwave radiation refers to the region of the electromagnetic spectrum with frequencies from 900 to 2450 MHz. This type of radiation lies between infrared radiation and radio waves. Water molecules (H_2O) are polar; that is, the electric charges on the molecules are not symmetric. The alignment and the charges on the atoms are such that the hydrogen side of the molecule has a positive charge, and the oxygen side has a negative charge. Electromagnetic radiation has electric charge as well; the "wave" representation is actually the electric charge on the wave as it flips between positive and negative.

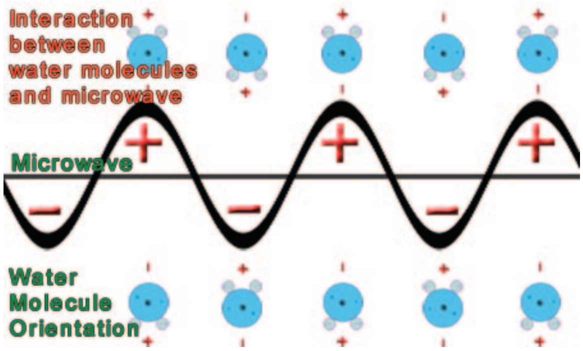


Figure 1. Schematic illustrates the interaction between water molecules and microwaves.

For a microwave oscillating at 9.2×10^8 Hz, the charge changes signs nearly 2 billion times a second (9.2×10^8 Hz). When an oscillating electric charge from radiation interacts with a water molecule, it causes the molecule to flip (Fig 1). Microwave radiation is specially tuned to the natural frequency of water molecules to maximize this interaction. As a result of the radiation hitting the molecules, the electrical charge on the water molecule flips back and forth 2–5 billion times a second depending on the frequency of the microwave energy. Temperature is a measure of how fast molecules move in a substance, and the vigorous movement of water molecules raises the temperature of water. Therefore, electromagnetic microwaves heat matter by agitating water molecules in the surrounding tissue, producing friction and heat, thus inducing cellular death via coagulation necrosis.

Teaching Point

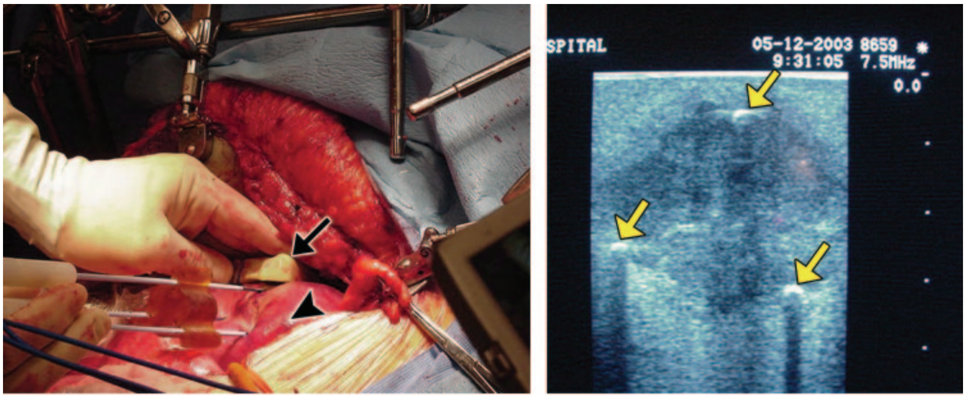
Microwave Ablation Technique

As with RF ablation, microwave ablation allows for flexible approaches to treatment, including percutaneous, laparoscopic, and open surgical access. Percutaneous microwave ablation is usually performed with the patient under conscious sedation (achieved with intravenous administration of midazolam and fentanyl, for example), although in certain situations when procedural pain is problematic, a general anesthetic may be required. Patients undergo monitoring with continuous pulse oximetry and electrocardiography and measurement of blood pressure every 5 minutes. Standard surgical preparation and draping are performed. Local anesthesia is achieved with injection of 1% lidocaine hydrochloride solution both intradermally and into deeper tissues.

With either computed tomographic (CT) or ultrasound (US) guidance, the tumor is localized,

a. b.

Figure 2. **(a)** Photographs show current microwave applicators available for percutaneous tumor ablation (Vivant Medical). **(b)** Photograph of the setup for a percutaneous microwave ablation procedure shows three single microwave applicators connected to three microwave generators.



a. b.

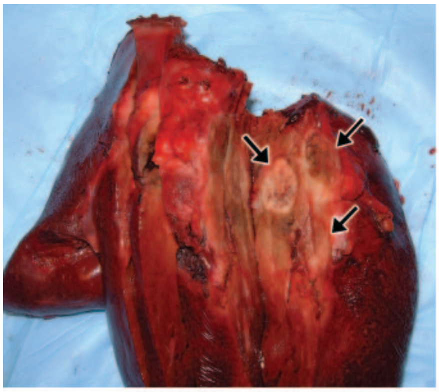
Figure 3. **(a)** Intraoperative photograph demonstrates the US probe (arrow) used to guide microwave ablation and three single microwave applicators in a triangular configuration with 2.5-cm spacing. Note exposed liver surface (arrowhead). **(b)** Transverse US scan shows the three microwave antennae in cross section (arrows) within the hypoechoic liver metastasis.

and the optimal approach is determined. A thin (14.5-gauge) microwave antenna is then placed directly into the tumor. When the antenna is attached to the microwave generator with a coaxial cable, an electromagnetic microwave is emitted from the exposed, noninsulated portion of the antenna. Each generator is capable of producing 60 W of power at a frequency of 915 MHz. Because of the inherent properties of the electromagnetic wave, the device does not need to be grounded, thus alleviating the problem of grounding pad burns. Intratumoral temperatures can be measured with a separately placed thermocouple. Several groups have successfully applied microwave ablation in the treatment of hepatic malignancies (4–6). To our knowledge, there is currently only one percutaneous microwave ablation system (Vivant Medical, Mountain View, Calif) available for use in humans in the United States (Fig 2).

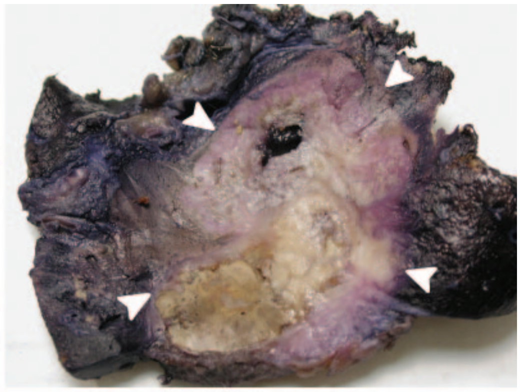
Experimental Studies

To evaluate the ablation zone and histologic features of microwave ablation with this device, experimental studies were performed in patients undergoing tumor resection; these studies were approved by our institutional review board. At our institution, we have completed pilot "ablate and resect" (intraoperative) trials in the liver and lung.

In the pilot liver study, patients with known hepatic masses underwent microwave tumor ablation before elective hepatic resection. We measured the size of the ablation zone and evaluated the histologic changes with standard hematoxylin-eosin (H-E) and nicotinamide adenine dinucleotide, reduced (NADH), vital histochemical staining. The hepatic lesions were targeted with real-time intraoperative US guidance (Fig 3),

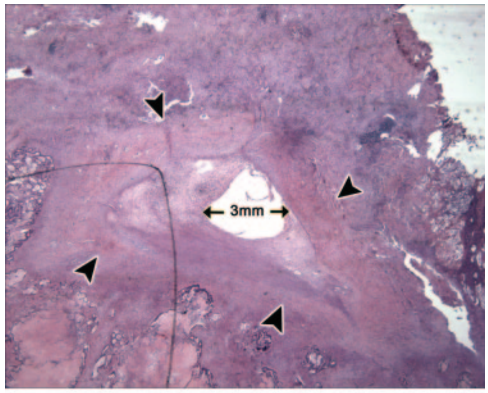


a.



b.

Figure 4. **(a)** Photograph of the gross resected liver specimen shows three discrete areas of thermocoagulation (arrows). **(b)** Photograph of the sectioned NADH-stained gross specimen shows an area of marked thermocoagulation (arrowheads) surrounding a 4-mm hepatic vein. **(c)** Photomicrograph (original magnification, ×40; H-E stain) of the hepatic section shows an area of thermocoagulation (arrowheads) surrounding a 3-mm artery (arrows).



c.

with three microwave antennae in a triangular configuration (Vivant Medical, Mountain View, Calif). The distance between antennae in this triangular system was set at 1.5–2.5 cm. Microwave ablation was performed at 45 W for 10 minutes. Hepatic resection was then completed in standard fashion.

Gross specimens were immediately sectioned and measured for tumor and ablation zone sizes. Volumes determined at gross examination were calculated on the assumption of an ellipsoid geometry ($1/6 \cdot \pi \cdot x \cdot y \cdot z$). The mean maximal tumor diameter was 4.5 cm (range, 2.0–5.7 cm), with an average tumor volume of 33.1 cm^3 (2.3–76.3 cm^3). The mean maximal ablation diameter was 5.5 cm (range, 5.0–6.5 cm), and the average ablation zone volume was 50.4 cm^3 (30.3–58.9 cm^3). Large blood vessels in the resection specimens did not create typical ablation zone distortion because of the minimal heat sink effect observed (Fig 4).

Teaching Point

H-E staining showed a marked thermal-like effect with maximal intensity closest to the antenna site (Fig 5a). NADH staining demonstrated the uniform absence of viable tumor in the ablation zone (Fig 5b). Sections from normal liver parenchyma showing the thermocoagulation effect after microwave ablation are provided for comparison (Fig 5c, 5d).

Teaching Point

Similarly, in the "ablate and resect" lung study, patients who were scheduled for elective lobar resections consented to microwave tumor ablation of their known lung cancer before resection. Again, the ablation zone size was measured and histologic examinations with H-E and

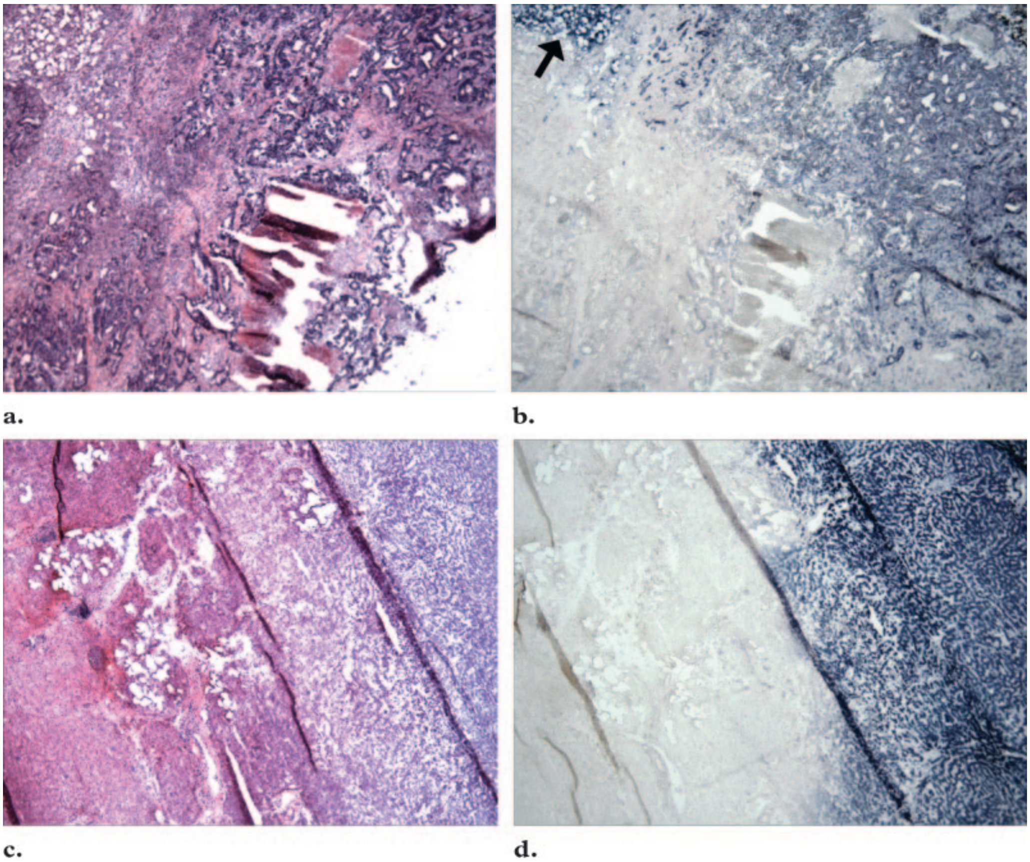


Figure 5. **(a, b)** Photomicrographs (original magnification, ×200) of the same sections of liver adenocarcinoma stained with H-E **(a)** and NADH vital histochemical **(b)** stains show complete microwave thermocoagulation of all areas except a small group of cells at the top left-hand corner (arrow in **b**). This effect is seen more clearly on the NADH-stained section. **(c, d)** Photomicrographs (original magnification, ×100) of sections from normal liver parenchyma, obtained for comparison after microwave ablation and stained with H-E **(c)** and NADH **(d)**, show complete thermocoagulation on the left half of the slide but viable tissue on the right. The dark-blue area (viable cells) on the right is more evident on the NADH-stained slide **(d)**.

NADH stains were performed. The mean maximal tumor diameter was 3.0 cm (range, 2.0–5.5 cm), with an average tumor volume of 7.1 cm^3 (1.6–17.3 cm^3). The mean maximal ablation diameter was 4.0 cm (range, 3.0–5.0 cm), and the average ablation zone volume was 23.4 cm^3 (9.8–35.4 cm^3). The size range was greater than in the liver study because a ring needle applicator was used in one patient. Sections of lung adenocarcinoma stained with H-E showed marked coagulation necrosis effect (Fig 6a). Again, this finding was more evident with NADH staining, which demonstrated the complete thermocoagulation and uniform absence of any viable tumor within the ablated tissue (Fig 6b). Sections from normal lung parenchyma showing the thermocoagulation effect after microwave ablation are provided for comparison (Figs 5d, Fig 6c).

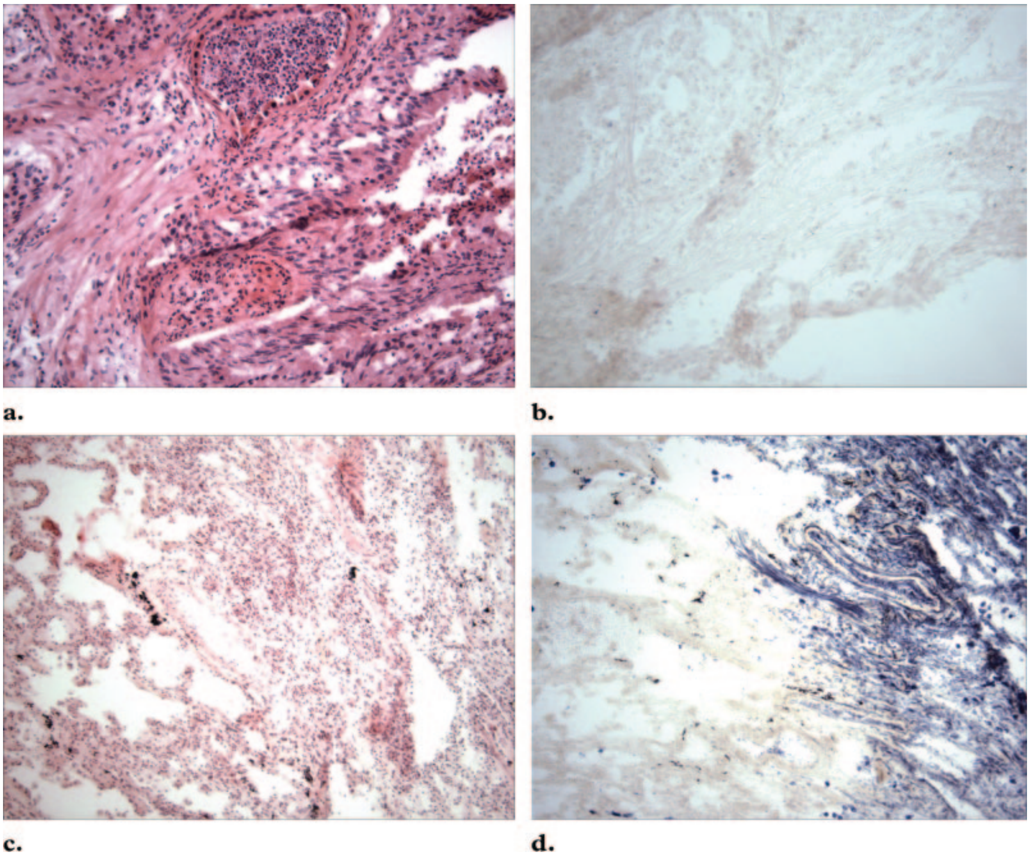


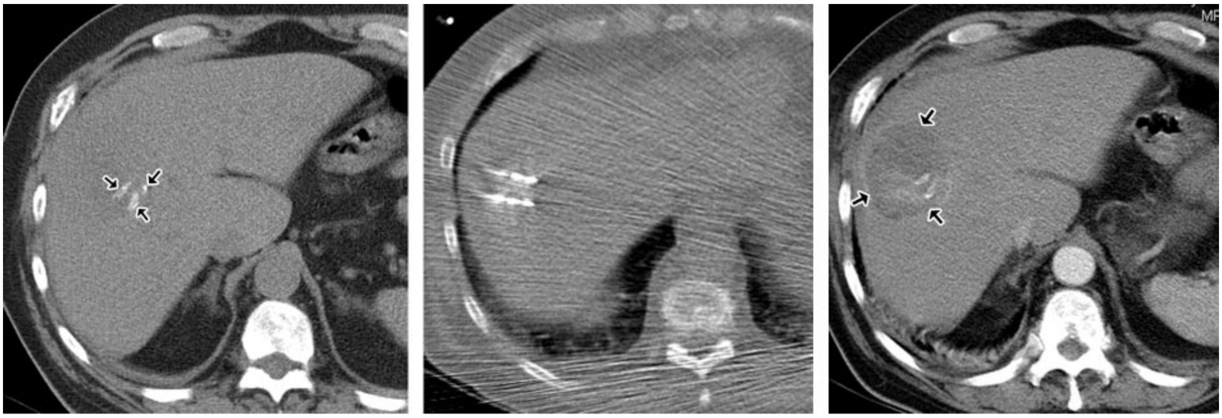
Figure 6. **(a, b)** Photomicrographs (original magnification, ×200) of the same sections of lung adenocarcinoma stained with H-E **(a)** and NADH vital histochemical **(b)** stains show complete microwave thermocoagulation of all areas. **(c, d)** Photomicrographs (original magnification, ×100) of sections from normal lung parenchyma, obtained for comparison after microwave ablation and stained with H-E **(c)** and NADH **(d)** stains, show complete thermocoagulation on the left two-thirds but viable tissue on the right third of the slides. The dark-blue area (viable cells) on the right third is more clearly seen on the NADH-stained slide **(d)**.

Clinical Applications of Microwave Ablation

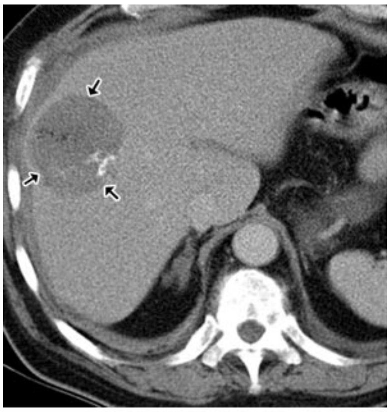
Liver Tumors

Resection of liver tumors has been shown to increase the 5-year overall and disease-free survival (11–13), although many patients have tumors that are surgically unresectable because of either unfavorable anatomy or poor hepatic reserve. Thus, local thermoablative techniques, developed to enable local control of liver tumors without resection, have been widely integrated into the management options currently offered to these patients.

RF ablation remains the most widely used thermoablative technique worldwide. The main criticisms of RF ablation have focused on the high local recurrence rates, particularly in the treatment of masses larger than 3.0 cm in diameter, the potential for incomplete tumor ablation near blood vessels because of the heat sink effect of



a. b. c.



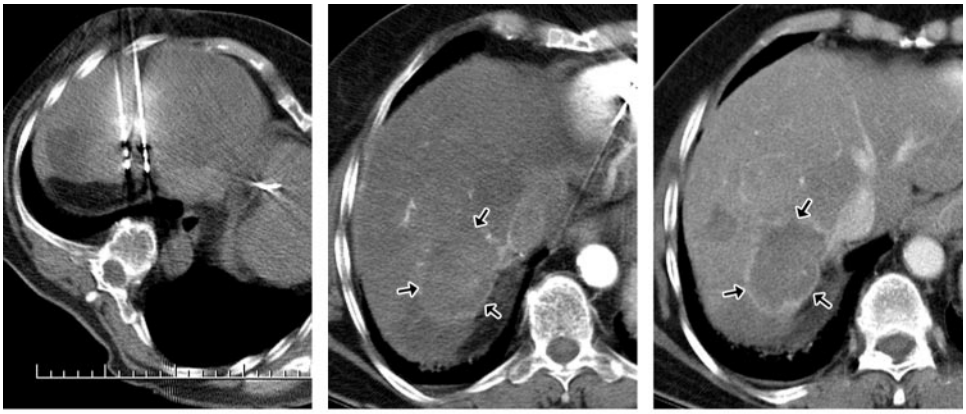
d.

Figure 7. Palliative tumor ablation in a 62-year-old man with a painful 7-cm hepatocellular carcinoma in his liver. **(a)** Axial CT scan obtained before ablation shows internal calcifications (arrows). **(b)** Axial CT scan shows three single microwave antennae, which were positioned with fluoroscopic guidance into the center of the lesion. Two 10-minute, 45-W ablations were performed. **(c, d)** Postprocedure axial CT scans obtained with contrast material enhancement in the arterial **(c)** and portal venous **(d)** phases show a large area of thermocoagulation (arrows) with no internal enhancement. The patient was observed after the procedure and later discharged to home with no immediate complications. His pain resolved within 2 days after the procedure.

local blood flow (14), difficulty in US imaging of RF lesions (15), and evidence of surviving tumor cells even within RF lesions (16).

Microwave ablation offers many of the benefits of RF but has several theoretical advantages that may result in improved performance near blood vessels. During RF ablation, the zone of active tissue heating is limited to a few millimeters surrounding the active electrode, with the remainder of the ablation zone being heated via thermal conduction (17). Owing to the much broader field of power density (up to 2 cm surrounding the antenna), microwave ablation results in a much larger zone of active heating (7). This larger heating zone has the potential to allow for a more uniform tumor kill in the ablation zone, both within the targeted zone and next to blood vessels. RF ablation is also limited by the increase in impedance with tissue boiling and charring (18), because water vapor and char act as electrical insulators. Because of the electromagnetic nature of microwaves, microwave ablations do not seem to be subject to this limitation, thus allowing the intratumoral temperature to be driven considerably higher, resulting in a considerably larger ablation zone within a shorter ablation time.

Hepatocellular carcinoma is one of the most prevalent and fatal of all malignancies worldwide. In the United States, the incidence of hepatocellular carcinoma continues to escalate, correlating with a rise in chronic hepatitis C cirrhosis (19). Given that most patients present initially with unresectable tumors, the use of minimally invasive percutaneous ablative techniques (eg, RF and microwave ablation) has gained great momentum (Fig 7). Because of the drawbacks of RF ablation, several groups have successfully proved the efficacious nature of microwave ablation in the treatment of hepatocellular carcinoma (4–6,20).



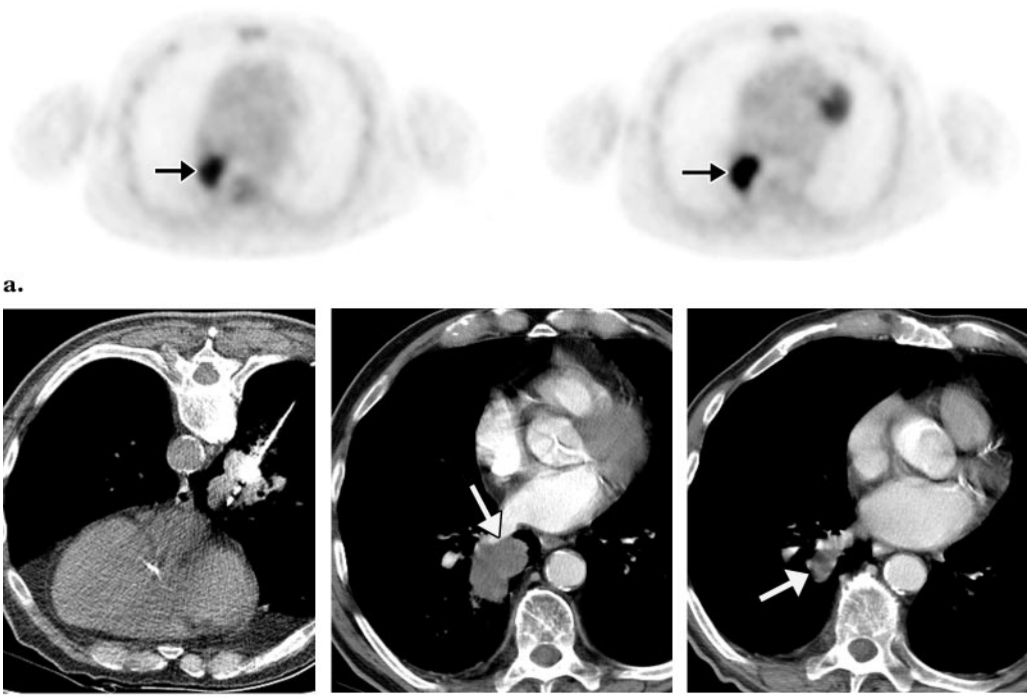
a. b. c.

Figure 8. Microwave ablation of a hepatic metastasis in an 82-year-old woman with a cardiac pacemaker and metastatic colon cancer to both lung and liver. She had responded well to chemotherapy and had only one hepatic lesion, measuring approximately 4.3 cm in greatest diameter, in liver segment 7. **(a)** CT scan shows three single microwave antennae, which were positioned with fluoroscopic guidance in the center of the lesion. Two 10-minute, 45-W ablations were performed. **(b, c)** Contrast-enhanced CT scans obtained immediately after the procedure in the arterial **(b)** and portal venous **(c)** phases show successful microwave ablation of the lesion, with an area of thermocoagulation (arrows) measuring 5.3 cm in greatest diameter. Surrounding peripheral hyperemia represents postablation changes at the site of the lesion. No immediate complications were observed.

Colorectal cancer is the third most common cancer in both men and women. In the United States, an estimated 56,730 deaths are expected to occur in 2004, accounting for about 10% of total cancer deaths (21). Most colorectal cancer deaths are attributed to metastatic disease rather than to the primary tumor. Untreated hepatic metastases have an extremely poor prognosis, with a 5-year survival of less than 2% and a median survival of less than 12 months (21). Selected patients with isolated hepatic metastases who undergo hepatic resection often develop new tumors, given the micrometastatic and multifocal nature of this disease. Although RF ablation remains the most popular minimally invasive thermoablative technique worldwide, high local recurrence rates remain a concern, particularly for hepatic colorectal metastases larger than 3.0 cm in diameter. The improved convection profile of thermocoagulation via microwave ablation may make it more suitable for treating patients with larger hepatic metastases (Fig 8).

Lung Tumors

The majority of patients with primary and secondary lung malignancies are not candidates for surgery owing to poor cardiorespiratory reserve. Conventional treatments for such patients typically include external-beam radiation therapy, with or without systemic chemotherapy. Often, however, no treatment is possible; the outcome in this group of patients has remained dismal (22). Given that many patients present with advanced disease and that the majority of patients with lung cancer (86%) will die of their disease (23,24), it can be deduced that at least one of the following complications will manifest itself during the course of the disease: pain, dyspnea, cough, he-



a. b. c. d.

Figure 9. Microwave ablation of primary lung cancer in an 86-year-old man who presented with a suspicious right lower lobe mass in the azygoesophageal recess. **(a)** Preprocedure positron emission tomographic scans show localized fluorodeoxyglucose activity (arrows) with no nodal disease, findings consistent with stage 1 lung cancer. Results of onsite cytopathologic analysis of the biopsy specimen confirmed the diagnosis of non–small cell lung cancer. The mass was 4.3 cm in greatest dimension. **(b)** CT scan shows a 14.5-gauge microwave antenna that was advanced with fluoroscopic guidance into the mass along its superior portion. Two 10-minute, 45-W microwave ablations were performed. **(c)** On a postprocedure contrast-enhanced CT scan obtained through the lower thorax at the level of the mass, no marked enhancement within the lesion is seen. Note successful coagulation of the tumor up against the right inferior pulmonary vein (arrow). The patient was discharged to home in stable condition. **(d)** CT scan obtained at 9-month follow-up shows interval shrinkage and no enhancement of the mass (arrow).

moptysis, metastases to the central nervous system or musculoskeletal system, tracheoesophageal fistula, and obstruction of the superior vena cava.

Palliation of symptoms therefore becomes an important part of treatment, yet current reports in the medical literature indicate a failure in palliation, with 50% of patients dying without adequate pain relief (25). Since many patients may have disease that is far too advanced for resection, newer alternatives such as percutaneous ethanol injection, embolization of bone tumor vasculature, and RF or microwave ablation may be a viable salvage modality, providing, at minimum, symptomatic relief to patients for whom conventional modalities fail. In addition, thermocoagulation therapies may provide cytoreduction, which theoretically could make external-beam radiation therapy or systemic chemotherapy more effective in these patients. In patients with stage IA disease, microwave ablation may potentially be curative (Fig 9).

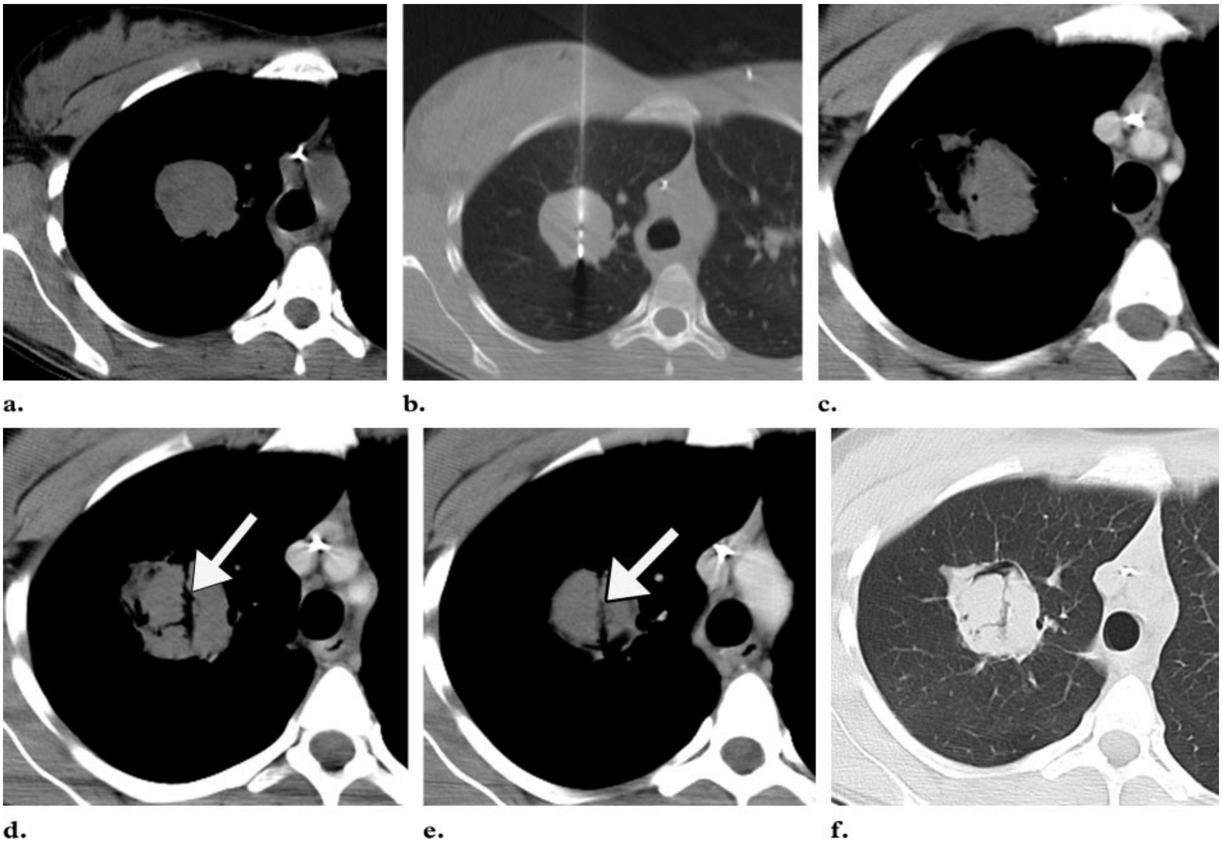
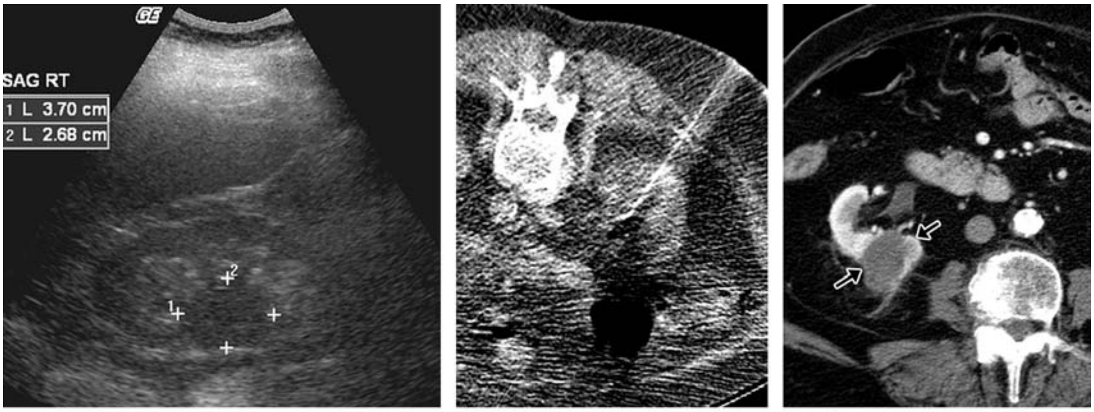


Figure 10. Microwave ablation of metastatic pulmonary lesions in a 15-year-old girl with a history of recurrent rhabdomyosarcoma and lung metastases, in whom systemic chemotherapy had previously failed. **(a)** Preprocedure CT scan shows a right upper lobe metastatic lesion measuring 4.2 cm in greatest diameter. **(b)** CT scan shows three single 14.5-gauge microwave antennae, which were positioned with fluoroscopic guidance into the center of the lesion. One 10-minute 45-W ablation was performed. The patient suffered a pneumothorax with an air leak that required chest tube insertion and hospitalization for 4 days. **(c–f)** Contrast-enhanced CT scans obtained at 1-month follow-up show cavitation and no enhancement in the lesion and persistent tracks from the microwave antennae (arrow). Microwave ablation technology enables the use of multiple antennae in the treatment of pulmonary metastatic disease.

Pulmonary metastatic disease tends to be an indicator of widespread systemic disease. However, it may exist in isolation in certain tumors and certain patients. In these patients with a finite number of metastatic deposits in the lung and in tumors with favorable biologic characteristics (eg, soft-tissue sarcoma [26], renal cell carcinoma [27], and colorectal carcinoma [28]), resection is considered a viable treatment option that improves prognosis (depending on the nodule size, completeness of resection, and lymph node status). However, for patients at high risk of morbidity secondary to thoracotomy, those who refuse surgery, and those with postoperative recurrence, the only treatment alternatives may be systemic chemotherapy or local therapy with external-beam radiation therapy. Microwave ablation may be applied to these patients and to certain others in whom a small number of slowly growing metastases are identified (Fig 10).

Renal and Adrenal Disease

Although to our knowledge no literature exists concerning the application of microwave ablation to renal or adrenal disease, it may still have a role,



a. b. c.

Figure 11. Microwave ablation of a renal tumor in an 85-year-old woman. A solid renal mass of the right kidney was incidentally discovered at US performed for abdominal pain. **(a)** US scan of the right kidney shows a discrete mass 3.7 cm in greatest dimension (cursors). **(b)** CT fluoroscopic scan obtained with the patient prone shows a single microwave applicator within the mass. Two 10-minute ablations were performed. **(c)** Contrast-enhanced CT scan obtained at 4-month follow-up shows lack of enhancement in the mass (arrows).

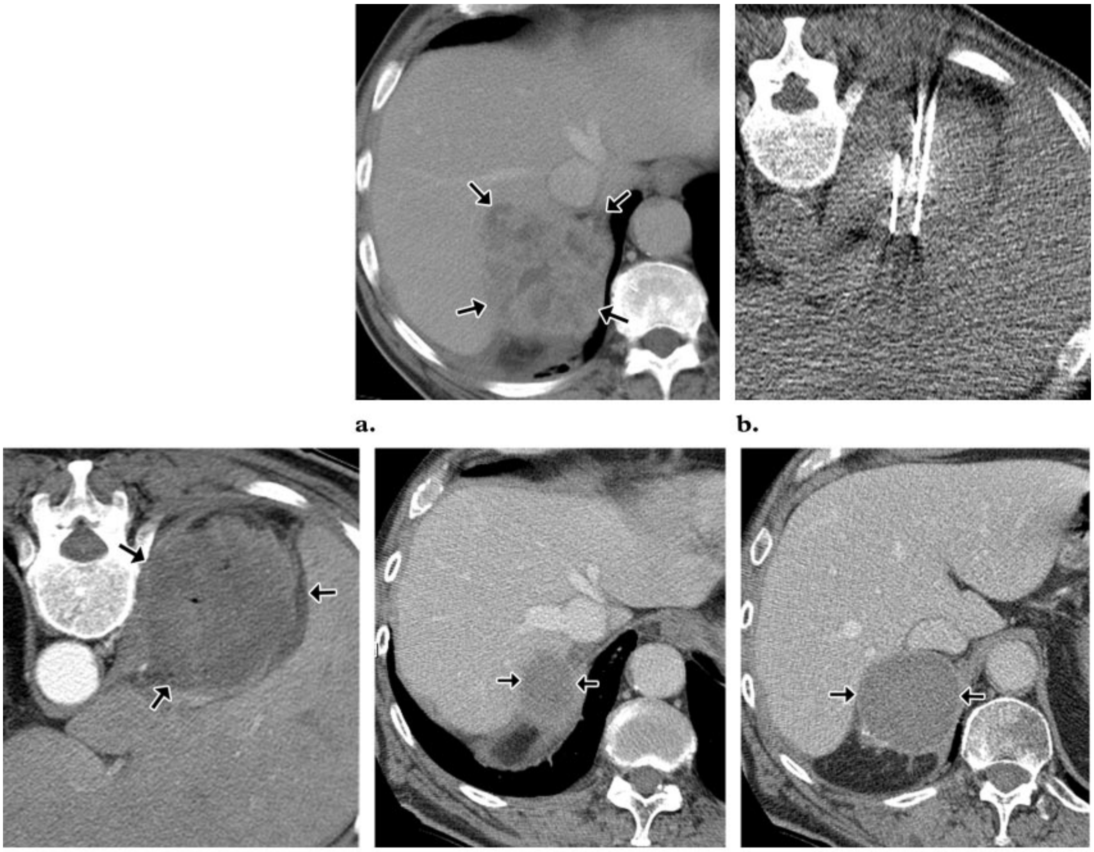
particularly in the treatment of either primary or secondary malignancies. Patients may benefit from a less invasive alternative, especially when compared with surgical resection.

The incidence of renal cell carcinoma is rising (29). In addition, the increase in cross-sectional imaging as a first-line investigation for a myriad of indications has resulted in the earlier detection of asymptomatic renal tumors that may have otherwise remained undetected. The natural tumor history of renal cell carcinoma represents a difficult clinical problem, in that, despite the relative indolence of this tumor, it is impossible to predict the course of growth and metastasis of any cancer, so clinicians feel obligated to treat the disease once it is detected.

Given the morbidity and mortality associated with nephrectomy, less invasive treatment techniques are often sought for smaller and more indolent tumors. A percutaneous technique is desirable, particularly in patients for whom surgical procedures pose a high risk. The focused thermoablative properties of percutaneous microwave ablation (as with those of RF ablation) allow for localized tumor destruction while preserving the uninvolved renal parenchyma. This ability to treat renal cell carcinoma while maintaining renal function makes microwave and RF ablation of solitary renal masses attractive options (Fig 11).

Adrenal tumors represent a heterogeneous group of neoplasms with widely varying prognosis and recommended medical treatments. Although the precise role of thermoablative techniques in the treatment of neoplasms has yet to be determined, benign nonfunctioning adenomas require no treatments, whereas isolated or symptomatic adrenal metastases may warrant surgery, although such management is controversial. Microwave ablation (similar to RF ablation) may be a potential alternative to surgery in this patient cohort, as it has less associated morbidity and mortality and can be performed on an outpatient basis (30).

The primary treatment of choice for adrenal cortical carcinoma remains surgery; however, patients may present with advanced disease or complete surgical resection may not be technically feasible in all patients. Wood et al (31) have shown RF ablation to be effective in local tumor



a. b. c. d. e.

Figure 12. Microwave ablation of an undifferentiated adrenal cortical carcinoma in a 79-year-old man with a history of unsuccessful surgical excision because of involvement of the liver and inferior vena cava. **(a)** Contrast-enhanced CT scan of the abdomen shows a complex large right adrenal mass (arrows) that invades the right lobe of the liver and compresses the inferior vena cava. **(b)** CT scan shows three single microwave applicators, which were positioned with fluoroscopic guidance in a triangular configuration and advanced into the center of the large heterogeneous mass. Four 10-minute 45-W ablations were performed. **(c)** Contrast-enhanced CT scan obtained immediately after the procedure shows complete thermocoagulation of the mass (arrows). The patient tolerated the procedure well and was discharged the same day. Because of the presence of retrocrural adenopathy, he was referred for postablation external-beam radiation therapy to treat these regions. **(d, e)** On CT scans obtained at 7-month follow-up, the nonenhancing tumor mass (arrows) appears smaller and exerts less mass effect on the inferior vena cava.

control for both these groups. We have performed technically successful microwave ablations in patients with adrenal cortical carcinoma (Fig 12) and adrenal metastasis (Fig 13). Given the cystic nature of adrenal metastases and the inability of RF ablation to heat cystic tumors adequately, microwave ablation is considered a better option than RF ablation.

Teaching Point

Bone Malignancies

Over the past 3 decades, many investigators have applied thermally mediated ablative techniques in the treatment of bone tumors. Although much of this preliminary work has been performed in animal models and small limited clinical studies, these studies have shown the efficacious nature of thermoablative techniques in the treatment of specific bone tumors.

Bone malignancies, specifically secondary metastases to bone, remain a common problem in

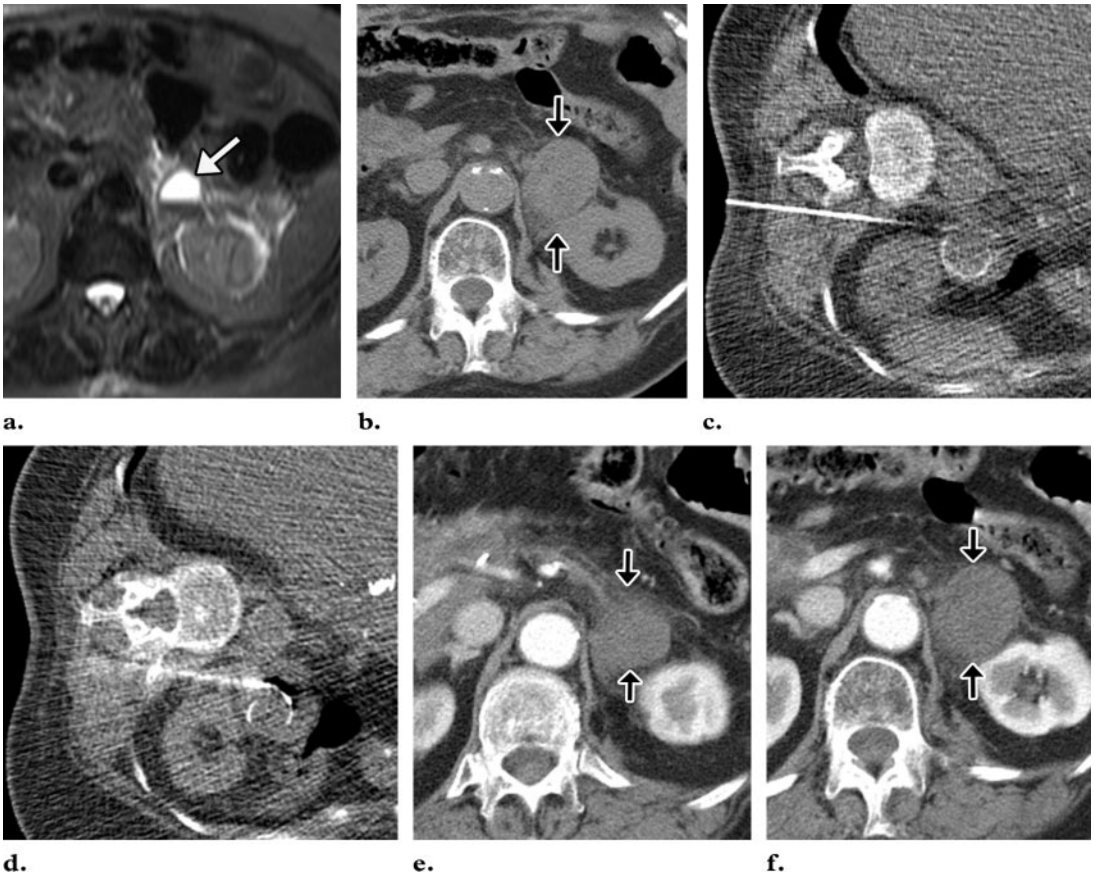
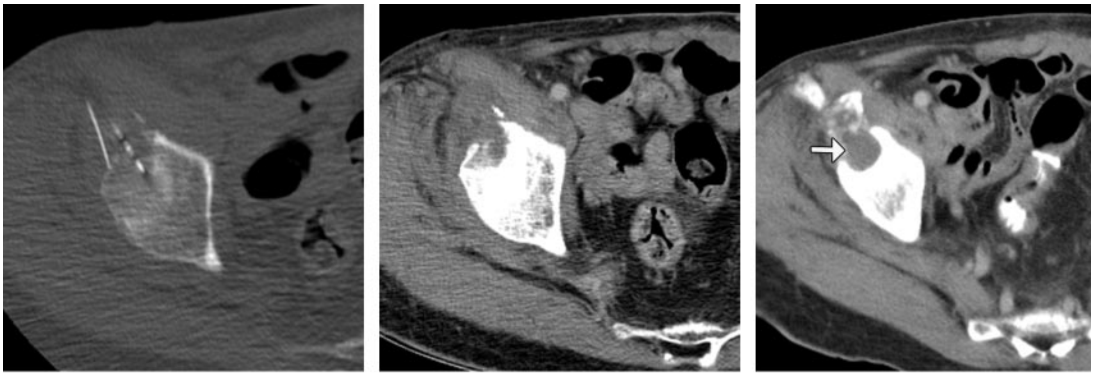


Figure 13. Microwave ablation of a left adrenal metastasis in a 75-year-old woman with a history of previously resected periampullary cancer. **(a)** Preprocedure T2-weighted magnetic resonance (MR) image shows a cystic metastasis (arrow) at the left adrenal gland. **(b)** Preprocedure CT scan of the left adrenal gland shows an enlarged metastasis (arrows), now measuring 4 cm in greatest diameter (compared with the MR imaging appearance). **(c, d)** CT scans show a 15-cm microwave ablation applicator (Trio; Vivant Medical) that was advanced under fluoroscopic guidance into the center of the lesion. The three coiled tines were deployed within the lesion with satisfactory placement. A single 5-minute 60-W treatment was performed. The patient experienced one episode of hypertension during the procedure, which was immediately controlled by beta-blockade. **(e, f)** Contrast-enhanced CT scans of the adrenal glands obtained immediately after ablation demonstrate a large nonenhancing mass (arrows). The patient was observed after the procedure and discharged home later that same day in stable condition and with no immediate complications.

patients with cancer, causing substantial pain and morbidity (32). Up to 85% of autopsies performed in patients who died of breast, prostate, or lung cancer show evidence of bone metastases (33). These metastases frequently give rise to complications such as pain, fractures, and impaired mobility, reducing the functional status and quality of life of the patient.

Current treatment options available for patients with bone metastases are primarily palliative. These options include localized therapies, such as radiation and surgery; systemic therapies such as chemotherapy, hormonal therapy, and bisphosphonates; and analgesics, such as opioids and nonsteroidal anti-inflammatory drugs. Although external-beam radiation therapy remains the standard of care for patients with localized bone pain, up to 30% of patients treated with external-beam radiation therapy do not experience notable pain relief (34). In addition, patients who have recurrent pain at a previously irradiated site may not be eligible for further external-beam radiation therapy secondary to limitations in normal



a. b. c.

Figure 14. Microwave ablation of metastatic bladder cancer in the acetabulum of a 70-year-old man with severe debilitating pain after radiation therapy. **(a)** CT scan shows a 14.5-gauge microwave antenna that was placed into the center of the metastasis with fluoroscopic guidance. A single 10-minute 45-W microwave ablation was performed. Remote thermocouple measurements adjacent to the microwave antenna along the tumor margin demonstrated intratumoral cytotoxic temperatures of 63°C–67°C at the end of the procedure. **(b)** Contrast-enhanced CT scan obtained after microwave ablation shows complete thermocoagulation encompassing the entire metastasis. **(c)** Contrast-enhanced CT scan obtained at 6-month follow-up shows an interval decrease in the size of the bone metastasis, with no pronounced enhancement (arrow). The patient was completely pain-free.

tissue tolerance. Consequently, percutaneous thermoablative techniques such as RF ablation (35) and the newer microwave ablation are rapidly gaining acceptance as viable treatment options for patients with painful bone metastases (Fig 14).

Conclusions

Our preliminary experimental and clinical work illustrates the potential clinical applications and advantages of microwave ablation. The physical properties of microwave technology make it an ideally suited energy source for tumor ablation. As with other thermoablative techniques, controlled trials evaluating local control, symptom palliation, and survival are necessary. This technology is still in its infancy, and future developments and clinical implementation will help improve the care of patients with cancer.

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Teaching Points for Microwave Ablation: Principles and Applications

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The potential benefits of microwave technology include consistently higher intratumoral temperatures, larger tumor ablation volumes, faster ablation times, ability to use multiple applicators, improved convection profile, optimal heating of cystic masses, and less procedural pain (7–10). In addition, microwave ablation does not require the placement of grounding pads.

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Therefore, electromagnetic microwaves heat matter by agitating water molecules in the surrounding tissue, producing friction and heat, thus inducing cellular death via coagulation necrosis.

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Large blood vessels in the resection specimens did not create typical ablation zone distortion because of the minimal heat sink effect observed (Fig 4).

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H-E staining showed a marked thermal-like effect with maximal intensity closest to the antenna site (Fig 5a). NADH staining demonstrated the uniform absence of viable tumor in the ablation zone (Fig 5b). Sections from normal liver parenchyma showing the thermocoagulation effect after microwave ablation are provided for comparison (Fig 5c, 5d).

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Given the cystic nature of adrenal metastases and the inability of RF ablation to heat cystic tumors adequately, microwave ablation is considered a better option than RF ablation.