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Radiofrequency and microwave ablation of the liver, lung, kidney and bone: What are the differences:

“Organ-specific thermal ablation”

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Abstract

Radiofrequency (RF) ablation is becoming an accepted treatment modality for many tumors of the liver and is being explored for tumors in the lung, kidney and bone. While RF energy is the most familiar heat source for tissue ablation, it has certain limitations that may hamper its efficacy in these new organ systems. Microwave energy may be able to overcome the technical limitations of RF energy but has technical hurdles that must be overcome as well. This paper outlines the physics behind RF and microwave heating, discusses relevant properties of the liver, lung, kidney and bone for thermal ablation and examines the roles of RF and microwave ablation in these tissues.

INTRODUCTION

Thermal tumor ablation is becoming increasingly important for treating cancers of the liver, lung, kidney and bone ^{1,2}. Radiofrequency (RF) ablation is currently the most popular and widely studied thermal ablation modality, while microwave ablation is rapidly being rediscovered and developed for clinical use ³⁻⁸. The term “ablation” refers to the destruction of a material; both RF and microwave ablation ablate tissue by heating it to cytotoxic temperatures. Temperatures in excess of 60 °C are known to cause relatively instantaneous cell death, while temperatures from 50-60 °C will induce coagulation and cell death in a matter of minutes, depending upon temperature and previous thermal injury. While both RF and microwave energy can heat tissue to cytotoxic levels, the mechanisms of RF and microwave heating are quite different and must be considered for ablation of different tissue types.

Radiofrequency ablation

Radiofrequency ablation relies on electrical conduction through the tissue: a complete electrical circuit is created through the body. RF current is able to pass through tissue because of the abundance of ionic fluid present; however, tissue is not a perfect conductor and RF current causes resistive heating (the Joule effect). Direct RF heating occurs within a few millimeters of the applicator (electrode), but a large portion of the final ablation zone is created when thermal conduction pushes heat into more peripheral areas around the electrode.

RF current can be applied using “monopolar” or “bipolar” modes (Figure 1). In monopolar mode, a single interstitial electrode (or group of electrodes) is used to deliver current at the tumor site, while surface electrodes (ground pads) complete the electrical circuit through the body. In bipolar mode, current flows between multiple interstitial electrodes. Bipolar mode generally has the advantages of: 1) focused and more effective heating in the area between the

electrodes, 2) reduced dependence on background conductivity and 3) no need for ground pads. However, bipolar mode requires additional electrode insertions, does not heat well outside the array and often requires saline infusion to improve results. On the other hand, monopolar mode has the advantages of: 1) a wider zone of heating around each electrode, 2) limited invasiveness and 3) wide clinical availability. The relative importance of these pros and cons differs in each organ system and will be discussed later.

Microwave ablation

Microwave ablation is a special case of dielectric heating, where the dielectric material is tissue. Dielectric heating occurs when an alternating electromagnetic (EM) field is applied to an imperfect dielectric material. In tissue, heating occurs because the EM field forces water molecules in the tissue to oscillate. The bound water molecules tend to oscillate out of phase with the applied fields, so some of the EM energy is absorbed and converted to heat. The best EM absorbers contain a high percentage of water (e.g., most solid organs) while less heating occurs in tissues with low water content (e.g., fat). A common measure used to describe how efficiently a material will absorb EM energy is effective conductivity (σ), but it is important to note that effective conductivity is different than the electrical conductivity discussed in RF ablation. Radiofrequency electrical conductivity refers to an alternating flow of electrons, while effective conductivity encompasses effects related to the rotation of dipoles. At microwave frequencies (typically 915 MHz or 2.45 GHz for ablative technologies), heating is more efficient in materials with a high conductivity.

The major distinction between microwave and RF heating is that microwave heating occurs in a volume around the applicator antenna, while RF heating is limited to areas of high current density (Figure 2). RF heating requires an electrically conductive path while microwaves do not; thus, microwaves are capable of propagating through materials with low or zero conductivity. For example, wireless communications rely on microwave propagation through air, which has essentially zero conductivity. This means that low-conductivity tissues inhibit RF current flow but allow better microwave propagation. This distinction between RF and microwave heating becomes more important as ablation of tissues outside of the liver becomes more common.

Microwaves also provide improved techniques for multiple-applicator ablation. Volume heating means that multiple antennas can be operated continuously and simultaneously in close proximity, or in separate locations. Currently, RF energy requires switching between electrodes when arrays are used. Microwaves may also be uniquely phased to further enhance heating within a multiple-antenna array by exploiting electromagnetic field overlap. When fields are overlapped correctly, heating increases by N^2 , where N is the number of fields applied (Figure 3).

One important factor when comparing RF and microwave ablation will be the tumor's host organ and location within the organ, since the tissue properties of normal liver, lung, kidney and bone are quite different. The properties of ablated tissue and normal tissue are also very different and must be considered for both RF and microwave ablation. This paper will attempt to outline the tissue properties of liver, lung, kidney and bone, and identify the strengths and weaknesses RF and microwave ablation have for treating tumors within each tissue.

Tissue properties

For RF ablation, the important tissue properties are electrical conductivity and thermal conductivity. It should be noted that the tissue impedance more commonly quoted in the literature and displayed by RF ablation systems is inversely proportional to conductivity. High electrical conductivities (i.e., low impedances) allow more current flow and more power to be

applied from the generator, while low electrical conductivities (i.e., high impedances) inhibit current flow. Thermal diffusion is also important to consider because it regulates how quickly heat can be transferred from the zone of direct heating into the surrounding tissue.

For microwave ablation, the important properties are relative permittivity and effective conductivity. Relative permittivity (sometimes called “dielectric constant,” though this term is misleading since its value varies substantially with temperature and frequency) is a measure of how well a material will accept an electric field and is measured relative to the permittivity of a vacuum ($\epsilon_r = \epsilon_{\text{material}}/\epsilon_0$). Relative permittivity determines the wavelength of an applied field at a given frequency, which impacts how well energy will propagate through the tissue and how the antenna is designed. Higher permittivities lead to shorter wavelengths. Effective conductivity, as previously mentioned, is a measure of how well the tissue will absorb microwave energy. High-conductivity tissues have a high water content and readily absorb microwaves, while low-conductivity tissues have low water content and readily allow microwave propagation.

The electrical, thermal and mechanical properties of tissue depend on many factors, but are primarily influenced by water content and cellular makeup. Heating a tissue to temperatures near or above 100 °C causes water to boil off and escape as gas, leading to tissue dehydration and dramatic changes in electrical properties. In addition, irreversible cellular changes that occur at temperatures above 50 °C must also be considered. RF current cannot generally pass through tissues heated above 100 °C because the water needed for ion flow is boiled off. This is what causes the characteristic increase in impedance during RF ablation (Figure 5). On the other hand, microwaves will pass through and heat tissue at any temperature or water content. Changes during ablation can degrade antenna efficiency, but advances in generator and antenna design can make these changes less relevant.

Finally, the rate of blood perfusion in each tissue is important for both RF and microwave ablation. For any thermal ablation modality, perfusion will always mediate ablation zone size because it tends to sink heat away from the ablation zone periphery. At some point, the rate of heat lost to perfusion will always be greater than the rate of heat generated at ablation zone periphery. Perfusion can be overcome more effectively by producing larger zones of active heating or by increasing the thermal gradient created by the zone of active heating.

The electrical, thermal and mechanical properties of liver, lung, kidney and bone are provided in Table 1 at RF and microwave frequencies⁹. Several qualitative predictions about each tissue can be made from this table:

1. The low electrical conductivities of lung and bone will likely hamper RF current flow but permit better microwave propagation.
2. Kidney and liver have high perfusion rates and likely require larger zones of active heating for effective thermal ablation. This is especially true next to large hepatic vessels or in the central portion of the kidney.
3. The high electrical conductivity of kidney allows faster microwave energy absorption but reduces field penetration.
4. Lung and bone have poor thermal conduction and may restrict the ablative margin.

In the next section, we will discuss the properties of each tissue type, giving empirical examples to demonstrate how drastic the difference between RF and microwave heating in each organ can be.

ORGAN-SPECIFIC CONSIDERATIONS

Liver

RF ablation has become a popular treatment modality in the liver, particularly for tumors less than 3.0 cm in diameter. Many centers now consider it a first-line treatment option for small hepatocellular carcinomas (HCCs) and colorectal metastases to the liver ^{10;11}. However, RF energy has been limited in its ability to heat larger volumes of tissue (>3 cm in diameter) or to heat tissues in high-perfusion areas, such as tumors that abut vessels larger than 3 mm in diameter ¹². Device and technique developments have improved the efficacy of RF ablation in the liver, but many of these devices require the deployment of multiple prongs or use of multiple interstitial electrodes, which increase procedural invasiveness ¹³⁻¹⁷. Surgical techniques and pharmacologic agents have also been shown to reduce liver perfusion and increase ablation zone sizes, but the increased invasiveness and/or drugs required may not be desirable in most cases ^{18;19}.

Microwaves offer all of the benefits of RF energy for thermal ablation in the liver, but microwaves have also been shown to ablate tissue up to and around large vessels, and seem to create larger zones of ablation in the same high-perfusion areas where RF energy is limited (Figure 4) ^{20;21}. One reason for this improved performance may be the faster heating and higher temperatures provided by microwave energy (Figure 6). Heating scales with power delivery, so using higher powers can also improve the performance of microwaves in the liver ^{4;22;23}. To date, the main limitation for microwaves has been that increasing applied power has often meant increasing antenna diameter to sizes incompatible with percutaneous use. However, new small-diameter devices are now showing promise for creating large volumes of ablation in the liver ^{5;7}.

Lung

The treatment of pulmonary tumors with RF energy is increasing in popularity. However, the success of RF ablation in lung has been limited. RF energy has a reduced ability to penetrate through the low conductivity of aerated lung, which increases the impedance “seen” by the generator and decreases the amount of power than can be applied. This problem is exacerbated by the poor thermal conduction of aerated lung (the so-called “oven-effect”) that limits thermal conduction needed to create an ablative margin and, thus, limits the ability to kill satellite cell clusters in the lung ²⁴.

High-conductivity tumor surrounded by low-conductivity tissue leads to higher impedances, but heating may actually be enhanced in a small margin surrounding the tumor ²⁵. It remains to be seen whether this observation has relevant clinical impact since studies have so far been limited to computational and phantom experiments. In addition, several sites have begun testing saline infusion as a technique to increase the conductivity of normal lung and, hence, increase the amount of power than can be applied from a given RF device ^{26;27}. Reports of excessive ablation caused by hypertonic saline and unpredictable saline movement make the need for more research in this area evident ²⁸⁻³⁰. In addition, RF systems used to treat lung tumors were originally developed for treating liver tumors. The vast difference in the properties of each tissue points to the fact that new systems – generators, power delivery algorithms and applicators – optimized for treating tumors in the lung are needed.

By contrast, the lower permittivity and conductivity of aerated lung allows deeper microwave penetration than in the liver or kidney. The lack of electrical conduction in microwave heating also means that heating is not substantially hampered by low-conductivity background tissue. Preclinical studies have shown that microwaves can actively heat larger volumes of normal lung than RF devices comparable in size and form (Figure 7) ^{31;32}. However, the properties of

lung tumors tend to be more like those of solid organs so more studies are needed to determine whether the improved heating of normal lung will translate into better treatment of lung tumors. Early clinical studies have demonstrated that microwave heating of lung tumors is both feasible and effective ^{6,33}.

Another conceivable advantage to using microwaves in the lung is that the increased thermal gradient created by microwaves may provide better passive heating of the tumor margin. While the maximum temperature in an RF ablation zone is limited to less than 100 °C, temperatures in microwave ablation zones can exceed 150 °C. Because microwave energy propagates so well in normal lung, and changes in tissue properties during ablation do not affect microwaves as much as RF energy, microwaves may be ideally suited to treating lung tumors.

Kidney

High perfusion rates in the kidney (particularly near the calyx and hilum) are problematic for thermal ablation. The constant flow of blood and fluid creates a significant heat sink that may cause areas to be under-treated by thermal modalities. RF energy has been used to effectively treat small renal-cell carcinomas (RCC), but studies have shown RF energy to be relatively ineffective for large or centrally located tumors, citing an increase in tumor recurrence and reduced treatment efficacy for tumors greater than 3 cm in diameter or in proximity to the collecting system ². The high electrolyte content in urine may also cause unwanted overheating of sensitive structures or redirection of RF current flow if in direct contact with the electrode.

The high water content of the kidney reduces EM field penetration somewhat, but increases the heat generation rate with microwave energy. A decrease in penetration may be less relevant because of the increased heat generation. In addition, microwave propagation may actually be improved during ablation since the permittivity and conductivity tend to decrease as tissue becomes dehydrated. The fast, volume heating of microwaves also presents an increased ability to overcome perfusion. In recent animal studies, microwaves were able to ablate much larger volumes of tissue in normal kidneys than RF energy (Figure 8) ^{34,35}. However, there is a relative paucity of preclinical or clinical data on using microwaves for renal tumor ablation, so many predictions about microwaves role in treating renal cancers are speculative at this point in time. As the role of ablative therapies continues to emerge, we expect to see more research and development of RF and microwave devices for renal tumor ablation.

Bone

Many of the same principles that apply to the lung may also apply to the bone. The low conductivity and poor thermal conduction in bone are limiting factors for RF ablation. Nevertheless, many sites perform RF ablation to treat osteoid osteomas and palliation of painful bone metastases ³⁶⁻³⁸. Due to bone's low conductivity and relative permittivity, microwaves may penetrate deeper, be less affected by tissue heating or dessication and be more effective for heating bone tumors than RF energy. However, as with the kidney, few reports of microwave ablation for bone tumors have been published in the scientific literature and much more study is needed to determine whether these predictions are true ³³. There is also some evidence that cryoablation may be a more effective option for reducing pain cause by bone tumors than heat-based therapies ³⁹. As interest grows in bone ablation, more research into optimized techniques and devices for both RF and microwave energy will hopefully follow.

Conclusions

While RF ablation has been an effective tool for treating tumors of the liver, lung, kidney and bone, there are substantial drawbacks fundamental to RF heating. In particular, RF heating is limited in areas of high perfusion (kidney and liver), in tissues with poor electrical and thermal

conductivity (lung and bone), and in areas near large heat sinks (liver, lung and kidney). Microwaves offer all of the same benefits as RF energy for thermal ablation, but are not as dependent on tissue properties and have the ability to heat faster in a larger volume. Thus, microwaves are less susceptible to perfusion or heat sinks and may be able to penetrate deeper into low-conductivity materials (lung and bone).

The fact remains that there are no widely-available microwave systems for clinical use. This has hampered the study of microwaves for tumor ablation and resulted in many speculations about its efficacy without a great deal of scientific data to stand on. Commercial and academic development is ongoing to create microwave ablation systems that are less invasive and easier to use so that the promises of microwave energy for tumor ablation can be finally realized in the clinic. Until then, RF energy will most likely remain the dominant modality for thermal tumor ablation in the liver, lung, kidney and bone. It is the author's hope that systems will soon be optimized for use in each tissue.

References

1. Rose SC, Thistlethwaite PA, Sewell PE, Vance RB. Lung cancer and radiofrequency ablation. *J Vasc Interv Radiol* 2006;17:927–951. [PubMed: 16778226]
2. Gervais DA, McGovern FJ, Arellano RS, McDougal WS, Mueller PR. Radiofrequency ablation of renal cell carcinoma: part 1, indications, results, and role in patient management over a 6-year period and ablation of 100 tumors. *AJR Am J Roentgenol* 2005;185:64–71. [PubMed: 15972400]
3. Ahmed, M.; Goldberg, S. Image-guided tumor ablation: basic science. In: van Sonnenberg, E.; McMullen, W.; Solbiati, L., editors. *Tumor ablation: principles and practice*. 2005. p. 23–40.
4. Hines-Peralta AU, Pirani N, Clegg P, Cronin N, Ryan TP, Liu Z, Goldberg SN. Microwave ablation: results with a 2.45-ghz applicator in ex vivo bovine and in vivo porcine liver. *Radiology* 2006;239:94–102. [PubMed: 16484351]
5. Yu NC, Lu DSK, Raman SS, Dupuy DE, Simon CJ, Lassman C, Aswad BI, Ianniti D, Busuttill RW. Hepatocellular carcinoma: microwave ablation with multiple straight and loop antenna clusters--pilot comparison with pathologic findings. *Radiology* 2006;239:269–275. [PubMed: 16493013]
6. He W, Hu X, Wu D, Guo L, Zhang L, Xiang D, Ning B. Ultrasonography-guided percutaneous microwave ablation of peripheral lung cancer. *Clin Imaging* 2006;30:234–241. [PubMed: 16814137]
7. Brace CL, Laeseke PF, Sampson LA, Frey TM, van der Weide DW, Lee FTJ. Microwave ablation with a single small-gauge triaxial antenna: in vivo porcine liver model. *Radiology* 2007;242:435–440. [PubMed: 17255414]
8. Kuang M, Lu MD, Xie XY, Xu HX, Mo LQ, Liu GJ, Xu ZF, Zheng YL, Liang JY. Liver cancer: increased microwave delivery to ablation zone with cooled-shaft antenna--experimental and clinical studies. *Radiology* 2007;242:914–924. [PubMed: 17229876]
9. Duck, FA. *Physical properties of tissue: a comprehensive reference book*. Academic Press; 1990.
10. Lencioni R, Cioni D, Crocetti L, Franchini C, Pina CD, Lera J, Bartolozzi C. Early-stage hepatocellular carcinoma in patients with cirrhosis: long-term results of percutaneous image-guided radiofrequency ablation. *Radiology* 2005;234:961–967. [PubMed: 15665226]
11. Solbiati, L.; Tiziana, I.; Michela, B.; Luca, C. Radiofrequency ablation of liver metastases of colorectal origin with intention to treat: local response rate and long-term survival over 7-year follow-up. *Radiological Society of North America Annual Meeting*; Chicago, IL. 2006.
12. Lu DSK, Raman SS, Vodopich DJ, Wang M, Sayre J, Lassman C. Effect of vessel size on creation of hepatic radiofrequency lesions in pigs: assessment of the "heat sink" effect. *AJR Am J Roentgenol* 2002;178:47–51. [PubMed: 11756085]
13. Goldberg SN, Solbiati L, Hahn PF, Cosman E, Conrad JE, Fogle R, Gazelle GS. Large-volume tissue ablation with radio frequency by using a clustered, internally cooled electrode technique: laboratory and clinical experience in liver metastases. *Radiology* 1998;209:371–379. [PubMed: 9807561]
14. LeVeen HH, Wapnick S, Piccone V, Falk G, Ahmed Nafis. Tumor eradication by radiofrequency therapy. responses in 21 patients. *JAMA* 1976;235:2198–2200. [PubMed: 775137]

15. Goldberg SN, Gazelle GS, Solbiati L, Rittman WJ, Mueller PR. Radiofrequency tissue ablation: increased lesion diameter with a perfusion electrode. *Acad Radiol* 1996;3:636–644. [PubMed: 8796727]
16. Tacke J, Mahnken A, Roggan A, Günther RW. Multipolar radiofrequency ablation: first clinical results. *Rofo* 2004;176:324–329. [PubMed: 15026944]
17. Lee FTJ, Haemmerich D, Wright AS, Mahvi DM, Sampson LA, Webster JG. Multiple probe radiofrequency ablation: pilot study in an animal model. *J Vasc Interv Radiol* 2003;14:1437–1442. [PubMed: 14605110]
18. Rossi S, Garbagnati F, De Francesco I, Accocella F, Leonardi L, Quaretti P, Zangrandi A, Paties C, Lencioni R. Relationship between the shape and size of radiofrequency induced thermal lesions and hepatic vascularization. *Tumori* 1999;85:128–132. [PubMed: 10363079]
19. Hines-Peralta A, Sukhatme V, Regan M, Signoretti S, Liu Z, Goldberg SN. Improved tumor destruction with arsenic trioxide and radiofrequency ablation in three animal models. *Radiology* 2006;240:82–89. [PubMed: 16720872]
20. Yu, N.; Raman, S.; Kim, Y. “heat-sink effect” of hepatic veins on microwave coagulation: a porcine pilot study. *Radiological Society of North America Annual Meeting; Chicago, IL.* 2004.
21. Brace CL, Laeseke PF, Sampson LA, Frey TM, van der Weide DW, Lee FTJ. Microwave ablation with multiple simultaneously powered small-gauge triaxial antennas: results from an in vivo swine liver model. *Radiology* 2007;244:151–156. [PubMed: 17581900]
22. Strickland AD, Clegg PJ, Cronin NJ, Swift B, Festing M, West KP, Robertson GSM, Lloyd DM. Experimental study of large-volume microwave ablation in the liver. *Br J Surg* 2002;89:1003–1007. [PubMed: 12153625]
23. Brace CL, Laeseke PF, van der Weide DW, Lee FT. Microwave ablation with a triaxial antenna: results in ex vivo bovine liver. *IEEE Trans Microw Theory Tech* 2005;53:215–220. [PubMed: 18079981]
24. Liu Z, Ahmed M, Weinstein Y, Yi M, Mahajan RL, Goldberg SN. Characterization of the rf ablation-induced ‘oven effect’: the importance of background tissue thermal conductivity on tissue heating. *Int J Hyperthermia* 2006;22:327–342. [PubMed: 16754353]
25. Solazzo SA, Liu Z, Lobo SM, Ahmed M, Hines-Peralta AU, Lenkinski RE, Goldberg SN. Radiofrequency ablation: importance of background tissue electrical conductivity--an agar phantom and computer modeling study. *Radiology* 2005;236:495–502. [PubMed: 16040906]
26. Lee JM, Jin GY, Li CA, Chung GH, Lee SY, Han YM, Chung MJ, Kim CS. Percutaneous radiofrequency thermal ablation of lung vx2 tumors in a rabbit model using a cooled tip-electrode: feasibility, safety, and effectiveness. *Invest Radiol* 2003;38:129–139. [PubMed: 12544076]
27. Gananadha S, Morris DL. Saline infusion markedly reduces impedance and improves efficacy of pulmonary radiofrequency ablation. *Cardiovasc Intervent Radiol* 2004;27:361–365. [PubMed: 15366219]
28. Giorgio A, Tarantino L, de Stefano G, Coppola C, Ferraioli G. Complications after percutaneous saline-enhanced radiofrequency ablation of liver tumors: 3-year experience with 336 patients at a single center. *AJR Am J Roentgenol* 2005;184:207–211. [PubMed: 15615976]
29. Gillams AR, Lees WR. Ct mapping of the distribution of saline during radiofrequency ablation with perfusion electrodes. *Cardiovasc Intervent Radiol* 2005;28:476–480. [PubMed: 16001137]
30. Kim TS, Lim HK, Kim H. Excessive hyperthermic necrosis of a pulmonary lobe after hypertonic saline-enhanced monopolar radiofrequency ablation. *Cardiovasc Intervent Radiol* 2006;29:160–163. [PubMed: 16184331]
31. Furukawa K, Miura T, Kato Y, Okada S, Tsutsui H, Shimatani H, Kajiwaru N, Taira M, Saito M, Kato H. Microwave coagulation therapy in canine peripheral lung tissue. *J Surg Res* 2005;123:245–250. [PubMed: 15680385]
32. Durick NA, Laeseke PF, Broderick LS, Lee FTJ, Sampson LA, Frey TM, Warner TF, Fine JP, van der Weide DW, Brace CL. Microwave ablation with triaxial antennas tuned for lung: results in an in vivo porcine model. *Radiology* 2008;247:80–87. [PubMed: 18292471]
33. Simon CJ, Dupuy DE, Mayo-Smith WW. Microwave ablation: principles and applications. *Radiographics* 2005;25(Suppl 1):S69–83. [PubMed: 16227498]

34. Kigure T, Harada T, Yuri Y, Fujieda N, Satoh Y. Experimental study of microwave coagulation of a vx-2 carcinoma implanted in rabbit kidney. *Int J Urol* 1994;1:23–27. [PubMed: 7627833]
35. Laeseke, P.; Sampson, L.; Frey, T.; van der Weide, D.; Lee, F.; Brace, C. Thermal ablation in kidneys: microwave ablation with a triaxial antenna results in larger zones of coagulation than rf. Radiological Society of North America Annual Meeting; Chicago, IL. 2006.
36. Davis KW, Choi JJ, Blankenbaker DG. Radiofrequency ablation in the musculoskeletal system. *Semin Roentgenol* 2004;39:129–144. [PubMed: 14976842]
37. Callstrom MR, Charboneau JW. Percutaneous ablation: safe, effective treatment of bone tumors. *Oncology (Williston Park, N.Y.)* 2005;19(11 Suppl 4):22–26.
38. Cantwell CP, O’Byrne J, Eustace S. Radiofrequency ablation of osteoid osteoma with cooled probes and impedance-control energy delivery. *AJR Am J Roentgenol* 2006;186:S244–8. [PubMed: 16632683]
39. Callstrom MR, Atwell TD, Charboneau JW, Farrell MA, Goetz MP, Rubin J, Sloan JA, Novotny PJ, Welch TJ, Maus TP, Wong GY, Brown KJ. Painful metastases involving bone: percutaneous image-guided cryoablation--prospective trial interim analysis. *Radiology* 2006;241:572–580. [PubMed: 17057075]

Figure 1. Simulated initial current densities of RF ablation in monopolar (left) and bipolar (right) modes. Contour maps indicate electric field isocontours and arrows indicate current density within each inset. Monopolar mode tends to disperse current more freely, while bipolar mode creates high current densities that are confined between electrodes.

Figure 2. Heating pattern around a triaxial microwave ablation antenna. Note that the zone of active heating is nearly 2 cm in diameter and no ground pads are needed. This larger zone of heating results in better performance near blood vessels and improved multiple-antenna capabilities.

Figure 3.

Simulated heating profiles of arrays using a) two, b) three, c) four and d) six antennas. The heat generation rate at the center of the array is improved by a factor of a) four, b) nine, c) 16 and d) 36 over a single antenna by using constructive antenna phasing.

Figure 4.

Images of perivascular ablations created using RF (left) and microwave (right) energy. Both ablations were created using a three-applicator system in normal swine liver. Applicator locations are marked with an 'X'. The large vessel (arrow) prevented conglomeration of the RF ablation zone, despite the close proximity of all three electrodes. By contrast, the microwave ablation extends around and beyond a large vessel (arrow) despite being at the normal ablation zone periphery.

Figure 5.

Approximation of impedance versus temperature during RF ablation. As temperature approaches 100 C, water tends to boil off, causing a rapid increase in impedance as “seen” by the generator. This increase inhibits current flow and substantially reduces heat generation.

Figure 6.

Temperatures recorded during RF and microwave ablation illustrating the faster heating and higher temperatures achievable with microwave energy. The RF system included a 17-gauge cooled electrode and 200 W generator using an impedance-feedback algorithm (Valleylab), while the microwave system consisted of a 17-gauge triaxial antenna and 2.45 GHz generator with a continuous 60 W output. Temperatures were measured 0.5 cm from the applicator while heating normal porcine kidney.

Figure 7. Zones of ablation created in normal porcine lung using RF (left) and microwave (right) ablation systems. Note the larger area of complete necrosis created by the microwave system. RF system performance can be improved using saline infusion but with some associated risk.

Figure 8.

Zones of ablation created in the lower poles of normal porcine kidneys using RF (left) and microwave (right) ablation systems. Slices were stained to demarcate the zones of complete necrosis. While the high perfusion rate and conductivity limit the effectiveness of RF energy, microwaves seem to perform exceptionally well in the kidney.

Table 1

Tissue properties at RF and microwave frequencies at 37 °C⁹.

	Units	Liver	Lung (aerated)	Kidney	Bone
RF conductivity (@ 480 kHz)	S/m	0.148	0.122	0.226	0.022
Relative permittivity (@ 2.45 GHz)		43.3	20.5	52.8	11.4
Effective conductivity (@ 2.45 GHz)	S/m	1.68	0.804	2.43	0.394
Wavelength (@ 2.45 GHz)	cm	1.8	2.5	1.5	3.6
Thermal conductivity	W/m K	0.564	0.302	0.54	0.4
Density	kg/m ³	1050	260	1050	1990
Specific heat capacity	J/kg K	3600	2500	3890	1300
Perfusion rate	ml/min kg	1000	200	3000-4000	50