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Microwave Tissue Ablation: Biophysics, Technology and Applications

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Abstract

Microwave ablation is an emerging treatment option for many cancers, cardiac arrhythmias and other medical conditions. During treatment, microwaves are applied directly to tissues to produce rapid temperature elevations sufficient to produce immediate coagulative necrosis. The engineering design criteria for each application differ, with individual consideration for factors such as desired ablation zone size, treatment duration, and procedural invasiveness. Recent technological developments in applicator cooling, power control and system optimization for specific applications promise to increase the utilization of microwave ablation in the future. This article will review the basic biophysics of microwave tissue heating, provide an overview of the design and operation of current equipment, and outline areas for future research for microwave ablation.

Keywords

Thermal therapies; hyperthermia; microwave ablation

I. BACKGROUND

A. Thermal Therapies

Thermal ablation is an emerging treatment option for several conditions, including cancer, cardiac arrhythmias, varicose veins and menorrhagia. Ablative procedures can be performed at open surgery, laparoscopically, using catheter-based applicators, percutaneously or transcutaneously. Minimally invasive ablations are typically performed using imaging as a diagnostic, guidance, monitoring and treatment assessment tool. Several energy sources are currently used for hyperthermic ablation, including radiofrequency electrical current, microwaves, laser light, and focused ultrasound. Each energy source is characterized by particular advantages and disadvantages in energy application and imaging appearance, which are often application specific. The focus of this review is on the physics, technology and application of microwave energy for thermal ablation therapy (Figure 1).

B. Microwave Energy For Tissue Ablation

Microwaves represent the portion of the electromagnetic spectrum between 300 MHz and 300 GHz. The Federal Communications Commission (FCC) or International Telecommunications Union (ITU) permit several unrestricted frequency bands for industrial, scientific and medical use in several regions, including those most commonly used for microwave ablation procedures: 915 MHz and 2.45 GHz. Other frequencies explored for

therapeutic applications of microwaves include 433 MHz, and broadband pulses with the greatest spectral energy density between 1 GHz and 10 GHz.^{1, 2}

Dielectric properties of biological tissues—The transmission of electromagnetic energy is determined by the dielectric permittivity and magnetic permeability of the media in which the waves propagate. The magnetic permeability of biological tissues is approximately the same as vacuum. However, the dielectric permittivity is significantly larger and contains both a real and imaginary component, which are used to define the more common terms: relative permittivity and conductivity. Relative permittivity, ϵ_r , is the real part of the complex permittivity and quantifies the ability to store electrical energy relative to vacuum. It is frequently referred to as dielectric constant; however, since permittivity is quite variable depending on frequency, temperature and other factors in biological tissues, the term relative permittivity will be used here for clarity.

The effective conductivity, σ , of a material is defined from the imaginary part of the complex permittivity and is used to describe how well a material absorbs microwave energy. It is important to note that effective conductivity describes contributions from moving charges (electrical current) and time-varying electric fields (displacement current), specifically the rotation of dipoles in the material as they attempt to align with and alternating electric field.³ The latter contribution dominates for most biological tissues in the microwave spectrum. This rotation of dipoles generates heat inside of lossy materials such as biological tissues, which will be described next.

Electromagnetic interactions with tissue—The most significant effect of an electromagnetic field applied to biological tissue is conversion of microwave energy to thermal energy. Heat transfer in tissue can be modeled using the so-called bioheat equation:⁴

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k_T \nabla T) + Q_h - Q_p \quad (\text{W m}^{-3}) \quad (1)$$

where ρ is density (kg m^{-3}), C_p is the specific heat capacity at constant pressure ($\text{J kg}^{-1} \text{m}^{-3}$), T is temperature (K), t is time (s), k_T is thermal conductivity (W/mK), Q_h is the rate of heat applied (W m^{-3}) and Q_p is the rate of heat lost to blood perfusion (W m^{-3}). The greatest constituent of most biological tissues is water, the atomic structure of which produces an electric dipole moment. Therefore, water molecules continually rotate to align with an applied electromagnetic field. This continual realignment increases kinetic energy, elevating temperature. The conversion of microwave energy to thermal energy follows the relationship:

$$Q_h = \frac{\sigma}{2} |E|^2 \quad (\text{W m}^{-3}) \quad (2)$$

where σ is effective conductivity (S m^{-1}) and $|E|$ is the applied electric field peak amplitude (V m^{-1}). As described above, effective conductivity dictates how efficiently microwave energy is converted to heat, and is dependent primarily on the type of tissue, its water content, and the frequency of the applied field.

The frequency-dependent relative permittivities and conductivities of many normal and pathologic biological tissues are well-known at baseline conditions.^{5–9} Numerically modeling these properties for the purposes of electromagnetic simulation is accomplished using a multi-pole Cole-Cole model to account for large frequency spectra.⁶ Both relative permittivity and conductivity are also dependent on to other physical influences, such as water content and temperature.^{10–14} For the purposes of this discussion, these factors can

typically be considered within a bulk mass of tissue rather than a cellular level. In most tissues the bulk dielectric properties can be considered isotropic, but in certain tissues such as muscle the properties may be mildly anisotropic.¹⁵ In addition, cellular and subcellular constituents such as protein structure and water binding can affect the bulk dielectric properties.^{13, 16}

Penetration of a microwave field into a tissue medium is also dependent on the dielectric properties of the tissue. For a plane wave in a homogenous, isotropic medium, penetration depth, δ , of an electromagnetic field is defined as the distance required for the electric field of a plane wave to attenuate to $1/e$ ($\sim 37\%$) of its initial value, is:

$$d = \frac{1}{\omega \sqrt{\mu \epsilon} \left\{ \frac{1}{2} \left[\sqrt{1 + \left(\frac{\sigma}{\omega \epsilon} \right)^2} - 1 \right] \right\}^{1/2}} \quad (\text{m}), \quad (3)$$

where ω is angular frequency (rad/s; equal to $2\pi f$, where f is frequency in Hz), μ is magnetic permeability (H m^{-1}), and ϵ is dielectric permittivity (F m^{-1}). The penetration depth can be approximated by assuming the tissue is a good dielectric ($[\sigma/\omega\epsilon]^2 \ll 1$):

$$d \gg \frac{2}{\sigma} \sqrt{\frac{\epsilon}{\mu}} \quad (\text{m}), \quad (4)$$

which is a good assumption for most tissues and microwave ablation frequencies. Note that penetration depth is inversely related to conductivity, but heating rate is proportional to conductivity. Deeper penetration occurs at the expense of slower heating. This makes intuitive sense from a conservation of energy perspective: the primary cause of field attenuation is the conversion of microwave energy to heat. Balancing penetration depth and heat generation is important for evaluating which frequencies are most attractive for a given application. Lower frequencies with slower heating rates but deeper field penetration may be more desirable for large-volume heating applications such as regional hyperthermia.¹⁷ Higher frequencies may be desirable when rapid, controlled heating is desirable, such as ablation of the endometrium.¹⁸

One final point of consideration: much of the energy radiated by microwave antennas in lossy media such as biological tissues is absorbed in the near or Fresnel zones of the antenna and may not propagate as a plane wave. In this case, the aforementioned calculations of attenuation and penetration depth should be viewed as approximations. Electromagnetic simulation and, in particular, simulation of electromagnetic-thermal interactions can provide more accurate estimates of temporal heating when necessary.¹⁹

C. Microwaves Compared To Other Sources of Thermal Therapy

Microwave energy is distinct from other energies for thermal therapy in a number of ways. Perhaps most important is that microwaves propagate through all types of tissues and non-metallic materials, including water vapor, and dehydrated, charred and desiccated tissues created during the ablative process. RF, laser and ultrasound energies can be substantially affected by different tissue types, especially as a result of thermal ablation. For example, flow of RF current is hampered in aerated organs such as lung.^{20, 21} Rapid impedance elevation during RF ablation near 100°C is also known to inhibit electrical current flow, effectively halting further application of RF energy unless the tissue is cooled and allowed to rehydrate, or artificially hydrated using ionic fluid infusion.^{22–24} A similar problem exists with laser and ultrasound energies, where high-temperature heating can inhibit further

energy application.^{25, 26} By comparison, while dielectric properties can change substantially during treatment, microwave propagation is not hindered by these changes.¹⁴ Nor are microwaves prevented from transmitting through tissues with variable water content.¹² As a result, microwaves are an attractive choice for thermal ablation (Figure 2).

Microwaves may also offer more direct heating than other ablation energies, making them more potent in organs with high blood perfusion or near vascular heat sinks. In vivo studies have demonstrated that while RF ablation is relatively ineffective near vessels greater than 3 mm in diameter, microwaves will ablate up to and through similarly sized vessels.^{27–29} Recent comparisons of RF and microwave ablation have demonstrated improved performance with microwaves in liver, lung and kidney, even when the total energy applied was equivalent.^{30–33} Several studies have demonstrated hepatic microwave ablations 3–4 cm in diameter with a single applicator in vivo, with ablations up to 7 cm in diameter noted when using multiple antennas (Figure 3).^{34–36} Other studies have also shown that by using higher powers and shorter treatment times, microwaves may actually be more effective in vivo than ex vivo, an effect not noted with other ablation energy types to date.³⁷

The wavelength and penetration depth of microwaves in tissue is also suitable for a large variety of medical applications. At 915 MHz and 2.45 GHz, wave penetration is 2–4 cm in most tissues, which is often commensurate with the treatment target (eg, 2–4 cm tumors). By contrast, RF power deposition attenuates rapidly away from the RF electrode, making it an effective tool for electrocautery and small-volume thermal therapies. Similarly, the scattering and attenuation of lasers in tissue can be quite rapid and highly dependent on the wavelength of the light.³⁸

Microwave thermal ablation is not without drawbacks, however. As mentioned earlier, the 2–4 cm wavelength penetration of microwave energy in tissue means that heating precision may not be as exquisite as with energies that are more rapidly absorbed. Rapid heating and high temperatures also still need more critical evaluation for safety when applied over a large volume. This is especially true from a monitoring standpoint, when rapid heating might be difficult to capture without realtime imaging.

Microwave energy can also overheat the cabling used to transfer power from the generator to the applicator. This internal cable heating must be offset either by limiting energy transmission, or by active cable cooling to prevent unwanted thermal damage to tissues along the cable length. Recent advances in internal antenna cooling solutions may help alleviate this problem in future microwave ablation technologies.³⁹

Finally, microwave antenna design is critical to device performance. Trade-offs must often be made among the heating pattern produced by the device, its relative invasiveness (for percutaneous applicators), power handling and efficiency of energy coupling into the tissue. In addition, most antenna designs currently produce elongated ablations, which may not be desirable for many applications.^{40, 41} Technical challenges in antenna design and the application-specific nature of many systems increase the barrier to commercial development and widespread adoption. By contrast, RF and laser ablation systems may be simpler and less costly to develop.

II. MICROWAVE ABLATION TECHNOLOGY

The discussion of microwave ablation technologies is not complete without consideration of the entire power generation, distribution and delivery system. However, broad coverage of microwave power generation is beyond the scope of this article. A cursory overview of power generation and distribution will be presented first, with delivery through interstitial antennas to follow.

A. Power Generation and Distribution

Generator design—Microwave power in current systems is generated using either solid-state semiconductor sources, or vacuum-tube devices such as the magnetron. Magnetron sources have the advantage of relatively high power conversion efficiency (usually over 70%), high power output, and are robust devices. However, because the power source is monolithic and not phase controlled, microwave power produced by magnetrons is distributed to multiple antennas (if desired) by passive splitters. Solid state systems suffer from lower efficiency (usually less than 40%) and less output power per channel but are typically easier to control, and can have a cleaner output spectrum and a smaller footprint.⁴²

Coaxial cable considerations—Microwave power is carried from the generator to the antenna through coaxial cables, due to their relative flexibility, transverse electric and magnetic wave propagation, and ease of connectivity. Cable flexibility is a function of cable diameter and construction materials, with improved flexibility in braided conductors and low-density dielectrics. Power handling – the ability of a cable to safely transfer power without overheating or failure – is related to these same factors, as well as the frequency of the applied microwave power (Figure 4). Therefore, the coaxial cables used to distribute power are typically more rigid than their counterparts in RF or laser ablation systems.

Coaxial cables also comprise the underlying structure of most interstitial microwave antennas. Most thermal ablation devices intended for percutaneous use are currently between 1.5 mm and 2.5 mm in diameter. Smaller antenna diameters are preferred for percutaneous applications since data from the biopsy literature suggests that larger needle diameters are associated with increased risk of complications such as bleeding and pneumothorax.⁴³ However, the lower power-handling ability of small-diameter coaxial cables can be problematic. Increased power delivery has been associated with faster and potentially more effective treatments, particularly when targeting large tumors.^{36, 37, 44} At the same time, input powers exceeding the cable power rating can have detrimental effects on performance, and can lead to potentially dangerous heat generation in the flexible cables that carry power to the antenna, or within the antenna itself.^{45, 46} Workarounds such as time-limited power application, active antenna cooling, and antenna arrays can help increase energy delivery while using only small-diameter antennas (see research areas section).³⁹

C. Microwave Ablation Antenna Design

The microwave ablation can be defined in a number of different ways. In surgical and percutaneous applications, the antenna is typically defined as the entire applicator beyond the flexible coaxial power delivery cable (Figure 5). Under this definition, the antenna then contains a normally rigid shaft and the radiating section at the distal end of the applicator. In catheter-based designs, the term antenna usually refers to the most distal radiating element, rather than the entire catheter.

Antenna properties relevant to thermal ablation include both the radiation pattern and reflection coefficient, or return loss. In general, the lowest return loss is desirable to maximize energy transfer from the antenna into the tissue. Energy reflected from the antenna reduces tissue heating, while increasing unwanted heating of the antenna shaft. In extreme cases, high return loss may necessitate short ablation times to prevent thermal damage along the antenna shaft.^{47, 48}

The desired radiation pattern is largely dependent on the clinical application. Most antennas in use currently radiate in the normal (broadside) mode, with propagation directed radially outward from the antenna. This is especially true of antennas designed for tumor ablation applications, where the ideal radiation pattern is focused and omni-directional to match the

approximately spherical shape of many focal tumors. Antennas designed in the axial (end-fire) mode have been developed for cardiac applications to produce localized heating of a spot at the end of a catheter.⁴⁹

To achieve the goals of low return loss and focused energy radiation, several designs have been proposed. Broadly, these can be classified as designs that use a linear element, coaxial slot, loop, or helix as their primary mode of radiation (Figures 6–7). Designs primarily comprised of a linear element include monopoles, dipoles, and triaxial antennas.^{50–54} These antennas are highly efficient, coupling over 95% of input power into the tissue, with good broadside radiation patterns. However, they are relatively narrowband and radiation can be prone to hot-spots or elongated patterns. Tip loading can be used to increase the electrical length of an antenna or alter its heating characteristics.^{55, 56}

Coaxial or annular slot antennas radiate from a smaller point, and can be designed to produce relatively low reflections with acceptable radiation patterns.⁵⁷ Their smaller radiation point can be desirable for ablation of small volumes, but single-slot antennas (like many other microwave antenna designs) suffer from excessive backward heating along the antenna shaft without design modification. Coaxial chokes have therefore been proposed to reduce unwanted backward heating by enforcing the open boundary at the antenna's feed point, thereby eliminating current on the outer surface of the coaxial cable.^{58–62} However, chokes add to the total antenna diameter, making them less attractive for use in percutaneous applications.

Looped or helical designs are less common in practice, but have been described in the literature. Notably, looped designs operating in the axial mode have been described for cardiac ablation, while helices have been proposed for microwave-assisted angioplasty.^{49, 63} Single and multi-loop designs have also been tested for microwave ablation in the liver.⁶⁴

D. Challenges and future research

The major challenge to using microwaves for most clinical applications is controlling the heating zone for a desired clinical outcome without incidentally heating nearby tissues or causing complications. Primary focus has been given to antenna cooling and arrays as a means to safely deliver more power and produce larger ablations, but research has also continued in antenna design, frequency comparisons, and power application algorithms. Finally, clinical implementation of new systems for cardiac and oncologic interventions is ongoing. An overview of these developments and future directions are presented here.

Antenna Cooling—Antenna cooling is an obvious but somewhat challenging solution to the problem of limited power handling in small-diameter antennas. Air and water-cooled antenna designs have existed for several years, with water-cooled microwave ablation antennas recently described in widespread clinical use.^{39, 65} Sufficiently cooling the outer surface of the antenna shaft (ie, the outer conductor of a coaxial cable) prevents unwanted thermal damage that may be produced by heat conduction from inside the antenna shaft, heat conduction from the hot ablation zone along the antenna shaft, or backward heating from the radiating segment. By eliminating excessive heat produced by these three sources, higher powers can be passed through the antenna, resulting in larger ablation zones (Figure 8).

Like coaxial chokes, cooling sleeves add to the overall diameter of the ablation antenna. Thinner cooling jackets limit antenna size, but are also characterized by less water flow and, therefore, reduced cooling capacity. Additional cooling power can be achieved by using cryogenic gas.⁶⁶ Cryogenic cooling may also allow the antenna to be fixed in place by creating a small iceball at the distal end of the antenna, which alleviates the problem of applicator migration after applicator placement prior to energy application.⁶⁷

Antenna Arrays for Microwave Ablation—Due to a theoretical limit to the amount of power able to be distributed by a single antenna, antenna arrays are also being investigated. A recent study by Laeseke et al. demonstrated a fundamental advantage to using multiple antennas: power is more efficiently distributed by using an array of antennas, even when compared to a single antenna delivering the same total power (eg, 90 W in a single antenna versus 30 W in three antennas).⁶⁸ A single antenna delivers power from a single source and much of the energy is spent heating tissues that have already been ablated. An antenna array distributes power to multiple sources so that less energy is wasted heating ablated tissue (Figure 9). In addition, heating produced simultaneously by multiple sources in proximity is known to produce ablation zones larger than might be expected from a sum of each source; an effect termed, “thermal synergy.”^{69–71} Several recent studies have confirmed the effect of thermal synergy when using arrays for microwave ablation, producing ablations up to 7 cm in diameter.^{35, 72, 73}

Seminal studies of phased-controlled antennas for microwave tissue heating have been described in the hyperthermia literature (Figure 10).^{74–81} The objective of many of these studies was to produce a precise zone of low-temperature hyperthermia (41–45 °C) in a target area without heating surrounding structures. Similar investigations for high-temperature microwave ablation are likely to follow. One potentially detrimental effect of antenna interference can occur if the relative phase is not known or controllable, as with multiple-generator multiple-antenna systems. Under this condition, the relative phase between antennas is unknown and the resulting interference may be largely constructive or destructive, leading to somewhat unpredictable results. It is currently unknown how much clinical impact random phase has on the final ablation zone. As an alternative, power may be switched between antennas in the array to eliminate interference, producing more predictable results.⁸² More study is needed to optimize and control power produced by antenna arrays for microwave ablation.

Frequency Considerations For Microwave Ablation—As noted previously, microwave penetration and heating rates in tissue are highly dependent on frequency. Recent investigations comparing 915 MHz and 2.45 GHz for large-volume ablation in the liver have suggested that 915 MHz provides larger ablations.⁴⁰ The hypothesis for this conclusion is that 915 MHz provides deeper field penetration and, thus, a greater volume of microwave heating. However, this study is currently without corroboration. In other studies, ablations produced by 915 MHz did not achieve similarly large ablations, so it is not yet clear how much impact is due to system design, implementation, tissue, frequency or other factors.^{83, 84} Higher frequencies have been used for shallow ablation of the endometrial lining of the uterus.¹⁸ Ongoing investigations should help define the role of frequency in individual applications.

III. APPLICATIONS

A. Cancer

The clinical indications for microwave ablation mirror those of RF ablation. The primary indication is for treatment of focal disease in those patients for whom surgery is not an option, who have refused or failed other treatments, or who require tissue-sparing procedures due to multiple tumor syndromes (eg, Von-Hippel-Lindau) or previous organ resection. The most common anatomic sites for microwave ablation worldwide are the liver, lung, kidney, prostate and bone.⁸⁵ Other areas of interest include the breast, thyroid, brain and spleen.^{86–89}

Liver—Both primary tumors such as hepatocellular carcinoma (HCC) and metastatic tumors originating from colorectal, lung, breast and other sites are treated in the liver. The

primary benefits of using microwaves in the liver appear to be the ability to overcome large heat sinks inherent to this highly vascular organ, and the possibility to treat larger tumors with fewer applicator placements in less time than RF ablation.²⁸ Faster heating provided by microwaves has also reduced treatment time when compared to RF ablation (Figure 2).

Early reports of a survival advantage when using microwave ablation against small HCC encouraged additional engineering and clinical development of clinical technique in Asia in the early 1990s.^{47, 48, 90, 91} A decade later, larger-scale studies demonstrated favorable results similar to RF ablation without significant complications.⁹² Similar trends have been observed in the treatment of colorectal metastases.⁹³ One randomized comparison between microwave ablation and surgery found no significant difference in three-year survival, but reduced blood loss with microwave ablation.⁹⁴ All of these studies were performed with a 2.45 GHz system using relatively small generator powers (~60 W) and short treatment times (~1–2 min).

Advances in technology have allowed increased use of microwave ablation, and more recent studies are confirming early results with some studies reporting three-year survival near 90 percent in small HCC.^{95, 96} Microwaves also appear to be effective against larger tumors (> 3 cm diameter), which have historically plagued RF ablation. Recent reports by Yu and Yin support the use of microwaves, especially with multiple applicators, against medium and large tumors in the liver.^{97, 98} Newer microwave ablation systems utilize both 915 MHz and 2.45 GHz, with most systems now employing dipole antennas.⁴⁰

Lung—The greatest opportunity for microwave ablation may be in the treatment of lung cancer due to improved microwave penetration in lung when compared to other organs, or RF ablation. Preclinical studies have noted faster heating and larger ablations when using microwave devices optimized for lung tissue, and in direct comparison to RF ablation.^{31, 99, 100} Clinical evidence supporting the use of microwaves in the lung are sparse, but early data suggests that microwaves provide good local control with minimal complications in the treatment of lung tumors.⁴⁶

Kidney—Percutaneous treatment for kidney tumors is rapidly increasing in popularity due to recent studies noting reduced cost and morbidity when compared to surgery or laparoscopic treatments.¹⁰¹ Preclinical studies in normal kidney have echoed the results of liver and lung studies: microwaves appear to produce more rapid heating and larger ablations than RF in the kidney.^{30, 84, 102} Emerging clinical data support the use of microwave ablation for treating renal-cell carcinoma, but additional study is needed to verify these promising results.¹⁰³

Bone—RF ablation for osteoid osteomas is now widely accepted, but can be somewhat problematic due to the high impedance and low thermal conductivity in bone. There is reason to suspect that microwaves could improve upon RF ablation treatments, but only a few reports of microwave ablation for osteoid osteomas exist.⁸⁵ Larger series in the treatment of bone tumors and metastatic disease have been reported, with encouraging results.^{104–106}

Prostate—One of the earliest uses for microwave thermal therapies was to treat malignancies and benign hyperplasia in the prostate.¹⁰⁷ Some success has been noted in reducing tumor bulk and delaying growth of the primary tumor.¹⁰⁸ However, enthusiasm for microwave ablation in the prostate has waned in recent years, in part due to challenges in avoiding thermal damage to nearby nerves and collagenous tissues such as the urethra, difficulty in visualizing the ablation zone at imaging, and improvements in other therapies

such as minimally invasive resection, hormone therapy, brachytherapy and cryoablation.^{109–112}

B. Cardiac Arrhythmias

As in cancer treatment, microwave ablation can be used in many of the same ways as RF ablation for the treatment of certain cardiac arrhythmias. With a theoretically deeper penetration of energy, microwaves would seem to again be a logical choice for cardiac ablation as well. Indeed, preclinical and early clinical data have supported the use of microwaves for the treatment of atrial fibrillation, especially when using an ablative approach to the Cox-Maze procedure or pulmonary vein isolation.^{113–116} However, there are some difficulties in getting reliable energy transmission between a microwave applicator and beating heart, and avoiding collateral damaging by stray or fringe fields around the microwave applicator. As a result, some recent reports have deemphasized the role of microwave ablation in cardiac ablation.¹¹⁷ Additional clinical testing and technology development will be necessary to further elucidate the role of microwaves in cardiac ablation.

C. Other

Microwave energy has been proposed and used as a possible treatment for other clinical conditions, most notably for endometrial ablation. During endometrial ablation, an antenna is introduced transvaginally into the uterus. Microwave energy is applied typically at a frequency of 9.2 GHz to produce coagulative necrosis of the endometrial lining. The technique has been shown to be safe, effective and relatively simple means to treat excessive uterine bleeding in nonsurgical patients.¹¹⁸ Other applications of microwave energy which have been investigated but have received mixed clinical attention include microwave-assisted angioplasty, where plaque is warmed using microwave energy to make enlargement easier;¹¹⁹ warming and reshaping of collagenous tissues in the shoulder or knee to reduce the need for surgery;¹²⁰ and vascular ablation to treat varicose veins.¹²¹

CONCLUSIONS

In conclusion, microwave ablation is playing an increasingly important role in the treatment of cancer, cardiac arrhythmias and other diseases. In most cases, devices and equipment used clinically are first or second generation. Recent developments including cooled systems to increase power delivery, antenna arrays to distribute power spatially, and optimization of technology and technique based on the specific tissues have already impacted the clinical utilization of microwave ablation. Additional developments are likely to continue this trend. As technologies improve, increased clinical utilization of this exciting technology is expected.

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Figure 1. Microwave ablation of a liver tumor. The antenna is placed percutaneously into the tumor mass before microwave energy is applied to heat the tumor to cytotoxic levels.

Figure 2.

Temperatures measured 5 mm from a microwave (MW) and RF applicator during ablation of the renal cortex. Temperatures can exceed 100 °C during microwave ablation due to electromagnetic propagation through dehydrated, charred or desiccated tissue. Power was pulsed during RF ablation to prevent charring, limiting the maximum temperature to less than 100 °C. Heating rates during microwave ablation can also be more rapid than during RF ablation at the same power levels.

Figure 3.

Thermal ablations created in the liver (a-b), kidney (c-d) and lung (e-f). In the liver, both single (a) and three-antenna (b) microwave ablation were used, each delivering approximately 65 W for 10 min. In the kidney and lung, both RF (c,e) and microwave (d,f) are compared. In each tissue microwaves produced larger zones of ablation, especially with multiple antennas.³⁰⁻³²

Figure 4. Power handling ability (solid lines) and loss (dashed line, dB/m) of two semi-rigid coaxial cables: UT-47 (black, squares) and UT-85 (red, diamonds). Power loss increases with frequency and decreases with cable diameter, creating a trade-off between antenna invasiveness and power handling ability (www.micro-coax.com).

Figure 5. Cartoon schematic of a typical microwave ablation antenna. Coaxial cable runs the length of the shaft, with the radiating element at the distal end of the antenna. Energy is produced around the radiating element.

Figure 6. Schematic cross sections of five antenna designs for microwave ablation. From top to bottom: slot, monopole, dipole, triaxial and choked slot. Metallic components are represented in dark gray, dielectric insulators in light gray.

Figure 7. Electric fields produced by three different antenna designs, representing designs using a linear element (triaxial, left), a single coaxial slot (center) and choked dipole (right). Approximate antenna diameter and power efficiency (1 – reflection coefficient) are noted to illustrate the design balance in each design.

Figure 8.

Comparison of ablations created by using a triaxial antenna without cooling (above) and with cryogenic gas cooling (below). The uncooled antenna produces a tear-drop shaped ablation with thermal damage to the tissue surrounding the antenna shaft, but the cooled antenna produces a more spherical ablation without shaft heating.

Figure 9.

Ablations created using a total power of 90 W applied by a single antenna with 2.2 mm diameter (left), two antennas with 1.5 mm diameter each (45 W per antenna, center), or three antennas with 1.2 mm diameter (30 W per antenna, right). Simultaneous application of multiple antennas produces ablations with greater size and equivalent shape to a single antenna due to improved spatial distribution of energy.⁶⁸

Figure 10.

Cross-section of electric fields produced by four antennas with phase control: a) all antennas at equal phase, b) left and right antennas 180° apart, c) top and bottom antennas 180° apart, and d) diagonal antennas 180° apart. Zones of constructive and destructive interference can be created with phase control of each channel.