Basic Principles of Microwave Ablation

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SUMMARY

- Microwave ablation (MWA) describes the minimally-invasive application of eletromagnectic energy at either 915 MHz or 2450 MHz to rapidly generate heat and destroy tumors and soft tissues.
- Tissue heating occurs from dielectric heating (frictional heating) and collision of polarized ions. Tissue desiccation occurs when temperature rises to above 60°C.
- Microwave ablation may provide a more uniform and complete treatment zone, quicker treatment time, and larger treatment zone when compared to radiofrequency ablation.
- Clinical indications for MWA include percutaneous ablation of small renal masses and treatment of benign prostatic hyperplasia (TUMT).

1. INTRODUCTION

Microwaves describes the wavelength ranging between 300 MHz and 300 GHZ along the electromagnetic spectrum (**Figure 1**). The therapeutic use of microwaves was first proposed by H.E. Hollman (Germany) in 1938 when he discussed the possibility that the waves could be focused to heat deep tissues without excessive heating of the skin. The original microwave generators, (magnetron in 1938 and klystron in 1939), were solely used for military radar systems during World War II.

The first therapeutic application of microwaves began at the Mayo Clinic in 1946 in which laboratory animals were irradiated with a microwave field (3000 MHz, power 65W) from an external source. Needle applicators then made it possible to harness and deliver microwave energy through the needle medium to an internal localized target in the body. In the late 1970's, an apparatus for the controlled local heating of tumors using microwave radiation at the frequency of 915 MHz and 2450 MHz and an applicator consisting of a coaxial cable terminating in a radiating antenna was designed and studied. The investigators stated that the applicator could "induce heating within a spherical volume and is therefore particularly suitable for insertion into a body cavity" and "appears to have an important potential for the treatment of tumors contained in body cavities". The earliest example of microwave irradiation in kidneys using a needle probe was conducted in Japan in 1994.

Microwave ablation (MWA) is a term now used to describe the application of eletromagnectic energy at either 915 MHz or 2450 MHz to rapidly generate heat and destroy tumors and soft tissues.

2. PHYSICS

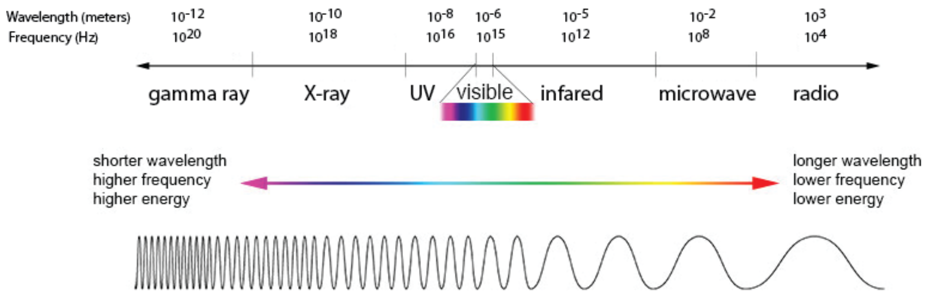

Figure 1: The electromagnetic spectrum (imagine.gsfc.nasa.gov).

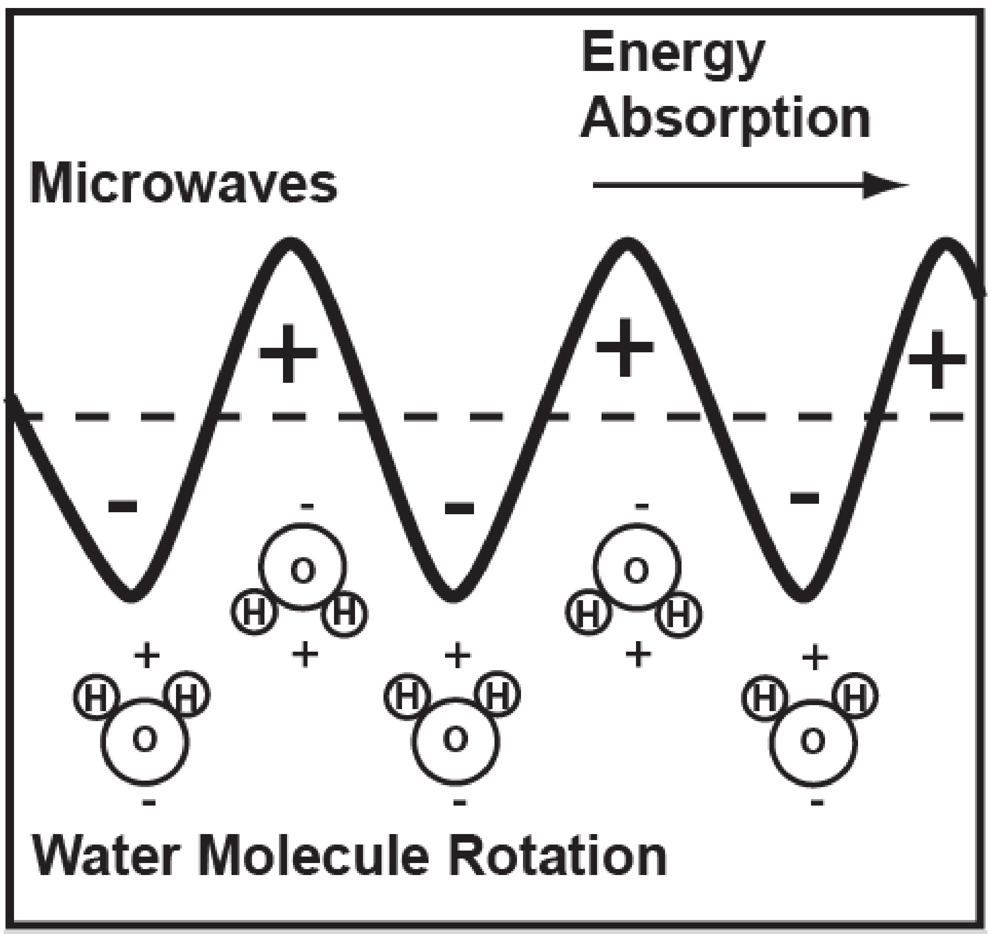

Figure 2: Interaction of microwave energy with water molecules to cause rotation. Printed with permission of Karli Pease.

The propagation of energy of electromagnetic radiation can be represented by a wave with wavelength, λ, measured as the distance between two peaks of the wave. The frequency of electromagnetic radiation, f, is determined by dividing the speed of light by the wavelength. Electromagnetic waves that have long wavelengths will thus have lower frequencies than waves with short wavelengths. The electromagnetic spectrum extends from the high frequencies of gamma radiation at the short-wavelength end to the low frequencies used for modern radio communication at the long-wavelength end. (**Figure 1**)

Under induction of a microwave field, water molecules, which have weak unequal dipoles, attempt to orient themselves within the field. The oscillation of the electromagnetic wave between negative and positive charges causes polar molecules to rotate, generating frictional heating and coagulative necrosis when temperatures rise to above 60°C. This is known as dielectric heating. Heat is also generated in part when polarized ions within the energy field gain kinetic energy and collide with other ions.

Depth of Microwave Penetration

Depth of penetration, δ, for microwaves is defined as the distance required for the electric field of a plane wave to attenuate to 1/e (~37%) of its initial value. The depth achieved with microwave energy depends on several factors including the relative permittivity and conductivity of the tissue. These dielectric properties depend on the frequency of the microwave energy, temperature, and other factors in biological tissues, including water content. The frequency-dependent relative permittivity and conductivity of many normal and pathologic biological tissues are known at baseline conditions.

Penetration depth of an electromagnetic field is inversely proportional to both frequency and conductivity. In general, electromagnetic waves of higher frequencies have shallower penetration depths than lower frequencies. The heating rate, though, is proportional to conductivity, meaning deeper penetration occurs at the expense of slower heating. 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 appropriate for a given application. Lower frequencies with slower heating rates but deeper field penetration may be more desirable for large-volume heating applications.

Relevant Definitions

- **Dielectric heating**: the rapid and uniform heating throughout a nonconducting material by means of a high-frequency electromagnetic field.
- **Permittivity**: the ability of a material under the influence of an electric field to store electrical potential energy, measured by the ratio of the capacitance of a capacitor with the material as dielectric over its capacitance with vacuum as dielectric.
- **Conductivity**: the ability to move heat or electrical energy from one place to another: the power to conduct heat or electricity.

3. MECHANISM OF DELIVERY

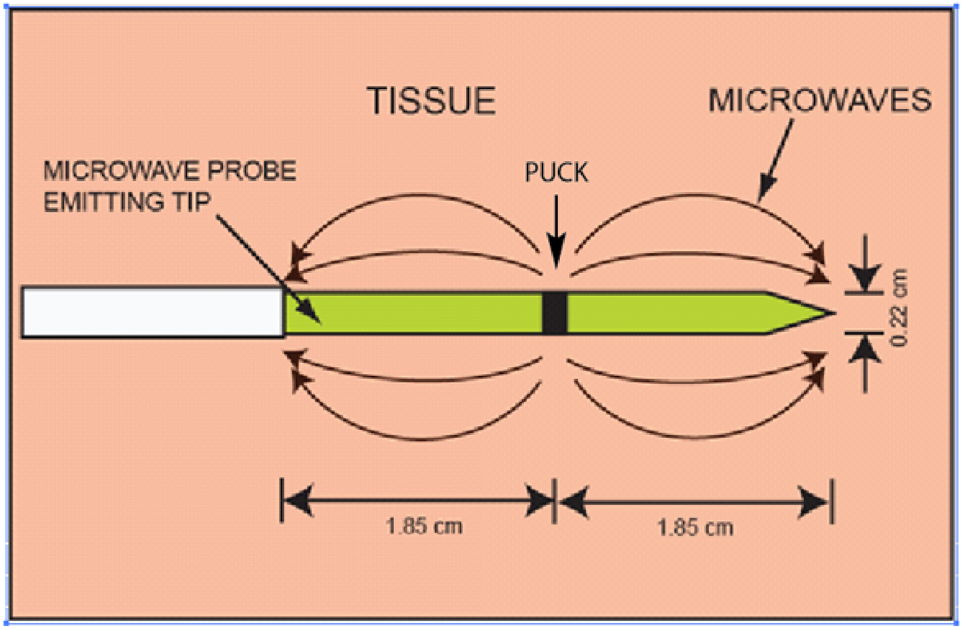

Figure 3: Example of an emitting tip of microwave needle. Printed with permission of Karli Pease.

A MWA system generally consists of three main components:

- microwave generator
- flexible coaxial cable(s)
- microwave antenna(e)

Microwaves are typically generated through a magnetron, a high-powered vacuum tube that generates microwaves via the interaction of a stream of electrons with a magnetic field, similar in application to an x-ray tube.

The antenna needle is connected to the magnetron by the coaxial cable and the microwave energy is delivered via the emitting tip region of the antenna. The emitting length of the antenna can range in lengths from 0.6 to 4.0 cm and provides different ablation sizes. After traveling down the coaxial cable, the microwave energy leaves through a small gap in the outermost sheath, known as the "puck", and travels out into the tissue and along the probe (**Figure 3**). The heat is generated in the tissue as described in the previous section. As the energy travels back up the shaft of the probe, the needle may also become hot. Many probes are internally cooled with either room-temperature fluid, such as saline solution, or gas, such as carbon dioxide, to reduce conductive heating and to prevent undesired tissue damage beyond the tumor location. The needle can be inserted into the site of the tumor either percutaneously under CT, Ultrasound (US) or Magnetic Resonance imaging (MRI) guidance or laparoscopically using direct vision.

System parameters can be adjusted on the MWA generator in order to control the ablation size. The most common adjusted parameters are output power and irradiation time. Many systems also offer the simultaneous use of multiple probes to increase total ablation size. The procedure can take up to

15 minutes, depending on the system selected and size of the tumor.

4. SAFETY

MWA offers many theoretical advantages over other needle-based ablative therapies, such as radiofrequency ablation (RFA) and cryoablation (CRYO). MWA has a larger zone of direct heating due to a larger energy field, and is thus less susceptible to heat sink effects due to blood flow when compared to RFA. A larger zone of direct heating helps to minimize desiccation and charring around the probe tip. Higher temperatures are achieved within a shorter duration, ideally resulting in a more complete and uniform zone of necrosis within shorter treatment times. With many MWA systems, multiple probes can be utilized at the same time, allowing for larger or multiple small tumors to be simultaneously treated. The simple set up and ease of use also allow for quicker OR times and cost savings. No grounding pads are needed, as with RFA, and there is no need for large gas canisters, nor risk of cracking/bleeding upon thawing as with CRYO.

MWA is very dependent upon local water content, though, and should be used cautiously in organs with high water content (i.e., urinary bladder, kidney). To ensure adequate coverage of a tumor, often a margin of 0.5 cm is ablated beyond the rim of the tumor.

5. DEVICES

Currently, there are six MWA systems commercially available in the United States that operate at either 915 MHz or 2450 MHz and provide different output powers, irradiation durations, and antennae configurations. The systems and features are summarized in **Table 1** and **Table 2**.

Table 1. Commercially available MWA systems and features

System	Frequency	Power	Time	Antenna(e)
Evident, Covidien, Mansfield, MA	915 MHz	Up to 45 W	0 to 10 minutes	13 G, 2.0 and 3.7 cm emitting length, 12-22 cm shaft length, saline solution cooling
MicrothermX, BSD Medical, Salt Lake City, UT	915 MHz	180 W, 60 W per channel maximum	0 to 10 minutes	14 G, 2.0 and 4.1 cm emitting length, up to three (3) antennas, Saline solution cooling
Avecure, Medwaves, San Diego, CA	902-928 MHz	10-32 W (power or temp mode); reflection monitoring, temperature monitoring	0 to 15 minutes	12-16 G, 1-4 cm emitting length, 7-30 cm shaft length; No cooling required
Acculis MTA, Microsulis, Hampshire, England	2450 MHz	30 to 180 W; reflection monitoring	0 to 8 minutes	1.8 and 5.6 mm diameter, 1.4 cm emitting length, ceramic trocar cutting tip, 14 -33.4 cm shaft length; Saline solution cooling

Amica, Hospital Service, Rome, Italy	2450 MHz	Up to 100 W; reflection monitoring	Up to 10 minutes	11, 14, and 16 G, 2 cm emitting length, with miniaturized choke
Certus 140, Neuwave, Madison, WI	2450 MHz	Up to 140 W on single channel, 65 W each on three channels	Up to 10 minutes	17 G, 1-2 cm emitting length, tri-axial probes, 15-20 mm shaft length, gas cooled

Table 2. Commercially available TUMT systems and features

System	Frequency	Power	Time	Antenna(e)
CoreTherm, Prostalund, Concord, MA	915 MHz	Up to 100 W	Up to 70 minutes	2.5 cm and greater prostatic urethral length, watercooling
Targis System, Urologix, Minneapolis, MN	902-928 MHz	Up to 75 W	28.5 to 60 minutes	2.5 cm and greater prostatic urethral length, sterile water cooling

6. CLINICAL USE/PROCEDURES

Preliminary studies on MWA applications in the field of Urology have been conducted primarily in kidneys and adrenal glands for tumors, and prostate for benign prostatic hyperplasia.

For treatment of tumors by MWA, patients are selected to undergo a laparoscopic or percutaneous procedure according to the feasibility of a percutaneous approach, which includes the proximity of the bowel or other organs to the tumor, anterior versus posterior tumor location, patient medical comorbidities, and patient preference. In patients undergoing laparoscopic surgery, a transperitoneal or retroperitoneal approach can be used. After exposure of the kidney and tumor localization, single or multiple, MWA surgical antennae are introduced through separate skin incisions. MWA begins once the microwave antenna(e) are guided into the tumor. In patients undergoing percutaneous CT-guided MWA, single or multiple microwave antennae are placed under CT guidance. The remainder of the procedure is identical to the laparoscopic procedure.

For both methods, thermal sensors can be placed either at the tumor periphery or near vital adjacent structures to monitor temperatures and treatment endpoint of > 60°C. If the temperature goals are not reached in all peripheral thermal sensors, the needle can be repositioned. Most clinicians do not utilize this added safety measure as it may add to procedural time.

The ablation time and power used is based on the information from the manufacturer or previous experience with a specific system. For example, a power of 45 W creates a theoretical 3.9-cm x 2.2-cm ablation ellipse after 5 minutes and 4.1 cm x 2.7 cm after 10 minutes when using the Covidien Evident MWA system with a single 3.7 cm emitting tip surgical antenna. Parameters should be selected to ablate the entire tumor plus an additional margin. Multiple probes can be used to ablate larger volumes based on the manufacturer's recommendations. Patients should receive follow-up with periodic contrast-enhanced imaging (CT or MRI) to ensure adequate destruction.

While focal therapy for prostate cancer is emerging as a treatment option for selected prostate cancer, the current opinon regarding the use of microwave energy for such purposes remains in question and is only available in clinical trials.[1] More commonly, the application of microwaves has been used for treatment of BPH through transurethral microwave thermal therapy (TUMT).

According to the AUA guidelines, TUMT is effective in partially relieving LUTS secondary to BPH and may be considered in men with moderate or severe symptoms but with known higher surgical retreatment rates compared to TURP (*Conditional Recommendation; Evidence Level: C*). **AUA BPH Guidelines 2018, amended 2020**, Treatment is generally performed on an outpatient basis with prophylactic antibiotics and analgesics administered before treatment. Before inserting the treatment catheter, viscous lidocaine gel and other solutions such as lidocaine/bupivacaine and antispasmodic medications, are administered. After treatment, patients are administered anti-inflammatory drugs and antibiotics, and temporarily require an indwelling catheter.

7. COMPLICATIONS

The primary aim of ablation is to destroy malignant tissue while sparing surrounding normal tissue. Intraoperative and postoperative complications resulting in poor oncologic outcomes can occur with MWA. Pain or paresthesia at the operative site are the most commonly observed complications. Other reported complications include fever, perinephric hematomas, urinoma, urine leak, transient hematuria, ureteropelvic junction obstruction, liver, spleen, and pancreatic injury, and post-procedure ileus. Intra-ablative hypertension has been seen in adrenal cases. Complication rates range from 0 to 38% in reported human studies. Optimal patient selection can minimize patient complications when tumor location, size, depth, and proximity to hilum are considered. Understanding of the relationship between the treatment parameters and the resulting thermal lesion size can also lead to better pre-planning. Patients should be informed of the risks associated with MWA prior to treatment.

Videos

Presentation Video 1

Presentations

Basic Principles of Microwave Ablation Presentation 1

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