THERMAL ABLATION:
UNDERSTANDING THE BREAKTHROUGH TO PREDICTABLE AND SPHERICAL ABLATIONS WITH THERMOSPHERE™ TECHNOLOGY

Introduction

Numerous technologies have been developed for the thermal ablation of tissue including radiofrequency and microwave ablation. Radiofrequency (RF) energy was initially used to thermally ablate liver tumors in the late 1980s.[1] Shortly following the development of radiofrequency ablation (RFA), microwave ablation (MWA) was introduced as an alternative energy.

The goal of thermal ablation is to eradicate diseased tissue. Historically, ablation device performance and local anatomical environment has influenced the predictability of ablation zone size and shape. A lack of predictability can prevent complete ablation of diseased tissue, ultimately resulting in local recurrence.[2] For decades, technological evolution of ablation systems has focused primarily on delivering more energy to the tissue to achieve larger ablation volumes. Unfortunately, increasing energy delivery alone has not delivered predictable effects, which could potentially affect safety and efficacy.

The latest technological breakthrough, Thermosphere™ technology, was born from another approach. The goal was to develop an ablation system which could spatially control energy to unlock predictability. This was realized by first understanding the fundamentals of current-based (RFA) and field-based (MWA) ablative technologies.

Active and passive zone components of a thermal ablation zone

Figure 1

Active and passive heating

Regardless of a technology, thermally ablative devices coagulate and necrose tissue with two types of heating; active heating and passive heating (Figure 1). Active heating occurs where the electrical energy delivered by a probe is converted into heat within the tissue. The rate of active heating can be much higher than the physiology's ability to compensate.[3] The active heating profile is the foundation of an ablation zone's size and shape.

Passive heating occurs secondarily to active heating from conductive and convective heat transfer. Heat can move from the core of the ablation zone into the surrounding tissues. Passive heat transfer has the potential to spread thermal energy beyond a device's active heating profile, however passive heating is difficult to predict. Tissue structure at macroscopic[4] and microscopic[1] levels cause variation in the extent and shape of heating. The inherent ability of local physiology to circumvent thermally damaging temperatures plays a dominant role.

Oven effect

When ablating encapsulated or ischemic lesions, or near the organ's surface, the thermally advantageous nature of the tissue boundaries can accentuate passive heating effects (Figure 2).[5,6] Also referred to as an 'oven effect', an analogous comparison to a kitchen oven. This effect can be useful for debulking large diseased tissue volumes over longer ablation times. However as with the walls of a kitchen oven, achieving meaningful passive heating outside the boundaries of a tumor can be difficult. Achieving ablative margin with oven effect may not be possible.[6]

Medtronic
Further, Together

Heat sink

Ablating diseased tissue adjacent to large vasculature can be particularly difficult due to the heat sink effect. Heat sink occurs when body temperature blood flows through an area of heating tissue, dispersing the heat into the surrounding body through convective cooling. Thermal sink is particularly noticeable when passive heating is relied upon to ablate tissue around a vessel (Figure 3). The flowing blood prevents passive heating from achieving thermally toxic temperatures in proximity to the cooling vasculature.[4] Conversely, ablation zones grow larger within a background of ischemic tissue due to minimized convective cooling and accentuated conductive heat transfer.

Oven-effect enhancement of ablation zone

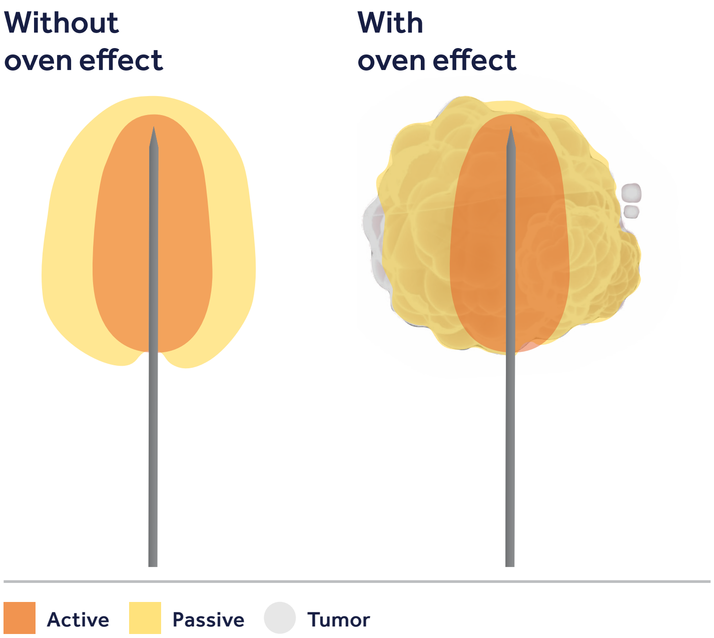


Figure 2

Anatomical distortion of passive heating

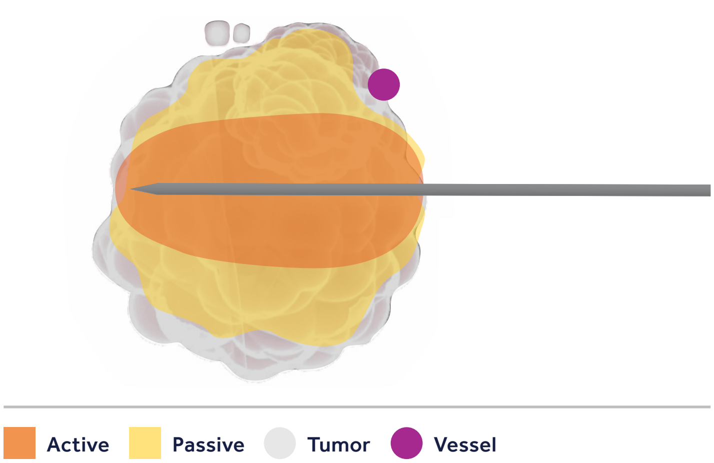


Figure 3

RFA and MWA — how do they work?

Current-based technology (RFA)

RFA is a current-based technology that actively heats tissue with electrical current. The electrical current is flowing ions, driven through the patient between two electrodes. The ions 'bump' off of obstacles along their journey through the tissue, resulting in frictional heating.

Current-based technologies actively heat in the same way as an electric stove top, where electrical current passes through a resistive heating element. With an electric stove, where the heat dissipates is predictable. The resistive heating element (see Figure 4a) has a uniform impedance and unchanging cross-sectional size across its length. This leads to a consistent flow of current and uniform heating across the element.

In contrast, with current-based ablation, the cross-sectional size of the tissue is very small near to the ablation electrode and very large a short distance away. As a result, the flowing ions can spread out as they move to and from the return electrode. This dissipation of current density results in an active heating profile which drops off just millimeters from RFA ablation electrodes (Figure 4b).

Mechanism of heating with current-based technology

Stove top oven uniform heating

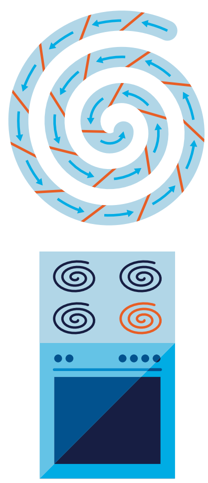


Figure 4a

Current-based ablation rapid drop off in heating

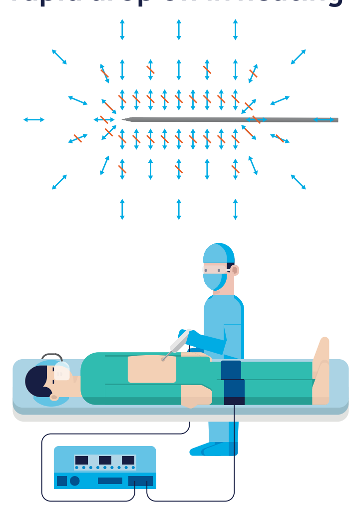


Figure 4b

Complicating RFA further is the inhomogeneity of tissue impedance. Tissue impedance varies in space due largely to blood vessels, which can distort the shape of RFA active heating profiles. The distortion leads to a non-symmetric active heating profile about the electrode (Figure 5). The impedance of tissue also varies considerably depending upon tissue type,[7] and as tissues heat and desiccate, impedance rises dramatically.[8] Rising impedance reduces current flow; shrinking the size of the RFA active heating profile as an ablation progresses (Figure 6). With RFA, individual patient anatomy determines the active heating profile as much as a current-based probe design,[9,10] presenting a challenging combination of circumstances to achieve predictable ablations.

Field-based technology

MWA is a field-based technology that heats tissue with an electromagnetic near-field. Microwave energy is directed along a waveguide within the shaft of the probe and flows out of the waveguide onto the radiator. The microwave energy induces electrical currents on the conductive surfaces of the probe. These induced electrical currents create an oscillating electromagnetic field surrounding the probe.

Active heating with MWA results due to polar molecules (primarily water) within the tissue rotating to align with the oscillating electromagnetic near-field (Figure 7b). This is very similar to how microwave ovens heat food (Figure 7a).

A foundational design consideration for field-based technology is that the active heating profile is determined by these currents flowing on the conductive surfaces. Selecting the geometry of the conductive surface and the electrical properties of materials in proximity to these surfaces are important design considerations.[11]

With conventional MWA probes, ceramics or thin coatings are applied to radiator surfaces. Thin coatings allow the dynamics of tissue dessication to remain close to the radiating surfaces and therefore dominant in determining the active heating profile. Ceramic-loaded MWA probes attempt to push tissue away from the radiating surfaces but unfortunately, ceramics do not have stable electrical properties when heated, leading to unpredictable field-shapes.

Conventional probes have failed to isolate the microwave radiator from a turbulent environment, resulting in unstable active heating profiles and unpredictable ablation zones. Historical changes to system operating frequency (915 MHz or 2450 MHz)[2,12] or increasing power levels (45 W, 60 W, or 140 W)[13] did not solve this lack of predictability.

Current-based ablation:
a non-symmetric active heating profile

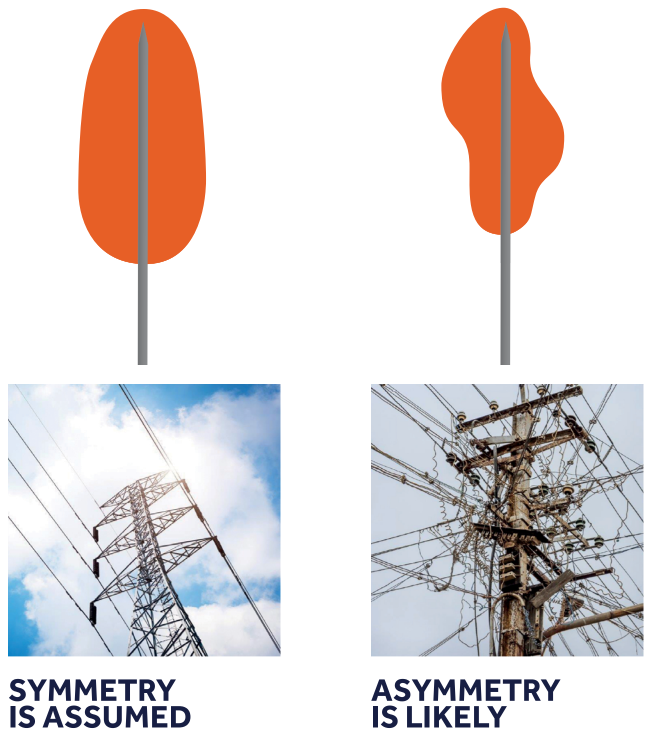


Figure 5

Current-based ablation:
a shrinking active heating profile

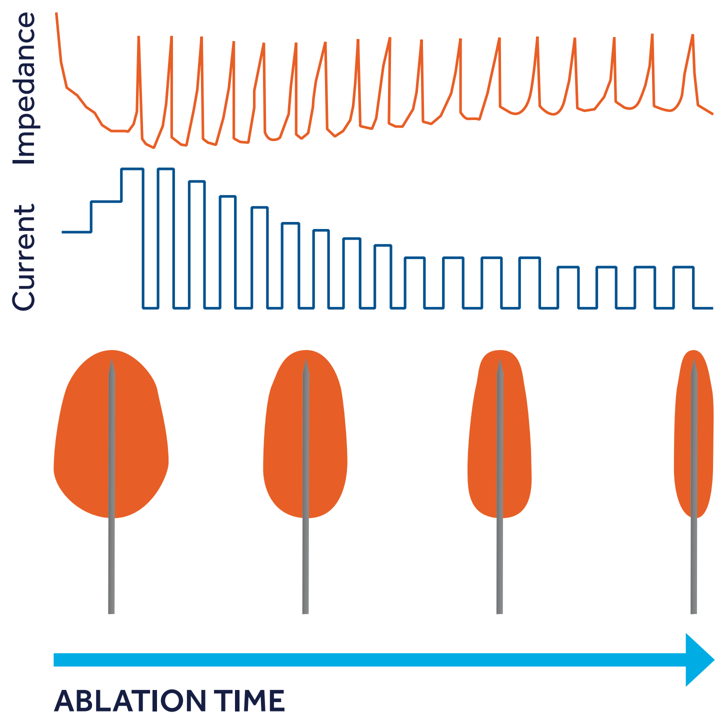


Figure 6

Mechanism of heating with field-based technology

Microwave oven
outside in heating

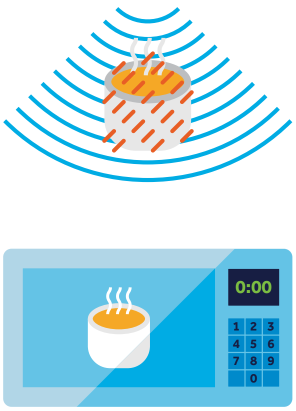


Figure 7a

Microwave ablation
inside out heating

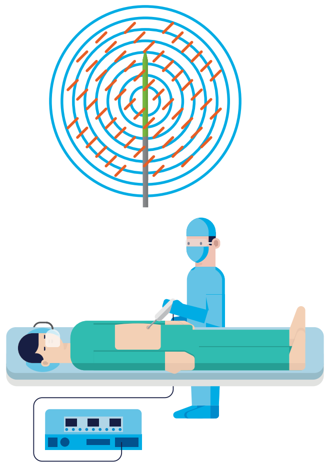


Figure 7b

MWA versus RFA

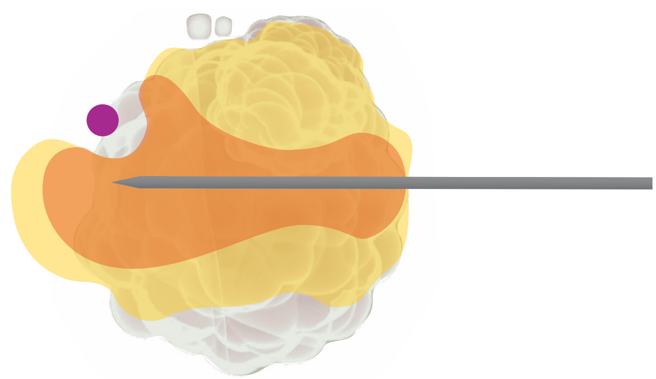
With RFA, ablation near large vessels is not recommended, as the combinatory effect of electrical and thermal sink increases the risk of local recurrence.[2] Why do large vessels have more of an adverse impact on RFA than MWA? Consider that the vascular tree, nerve fibers, and other structures present a network of electrically conductive, low impedance pathways to current-based energy. Low impedance pathways are 'shortcuts' for RF current to reach the return pad. These 'shortcuts' cause a loss of symmetry in the active heating profile about RFA electrodes.[14] (Figure 8 and Figure 9). This can be thought of as an electrical energy sink.

Conversely, MWA field-based technologies demonstrate effective coagulation of tissue around large vasculature.[15,16] This is due largely in part to field-based energy not being susceptible to electrical energy sink. The active heating profile with MWA is determined by the location and intensity of flowing electrons on the radiator, not the flow of current through tissue. This is a technological advantage, as it enables field-based technology to maintain symmetric active heating profiles in the cross-needle axis when in proximity to large vasculature (Figure 10).[14]

Interesting fact

Microwave ablation devices are not technically antennas, they are probes. To satisfy the definition of an antenna, the device must transmit or receive energy in the far-field, like satellite or cell phone antennas. Microwave ablation devices are probes because they heat tissue within a near-field, centimeters from the device.

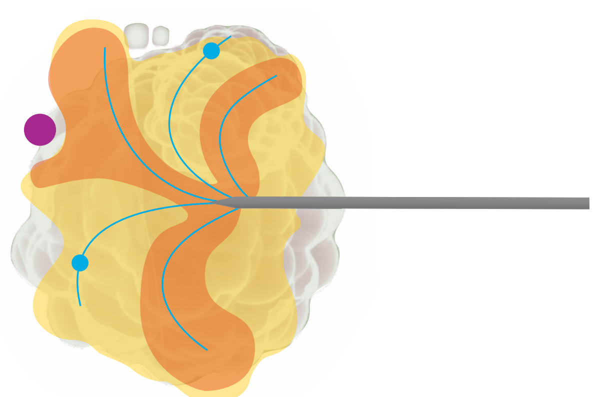
Anatomical distortion of ablation zone
with current-based energy (straight-needle device)



Active Passive Tumor Vessel

Figure 8

Anatomical distortion of ablation zone
with current-based energy (deploying-tine device)



Active Passive Tumor Vessel

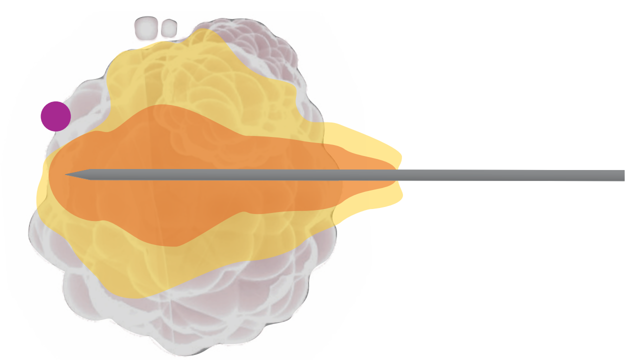
Figure 9

Advancing ablation technology: next steps

For both RFA and MWA, attempting to achieve ablative margins with unpredictable active heating patterns and passive heat transfer will continue to complicate ablative procedures. To simplify thermal ablation, we must move toward reliance on a predictable active heating pattern. To enable this change, ablation technology must deliver an improved active heating pattern. The active heating must be stabilized and of appropriate shape and size to ablate most tumors (Figure 11). **This breakthrough ablation technology exists.** Its innovation was guided by the following ideas:

- Use field-based energy to create symmetrical active heating profiles in proximity to large vessels
- Optimize the microwave radiator to deliver a spherical and scalable active heating profile
- Isolate the radiator from varying material properties to stabilize the active heating profile
- Provide clinically relevant ablation planning data to accurately predict ablation zones

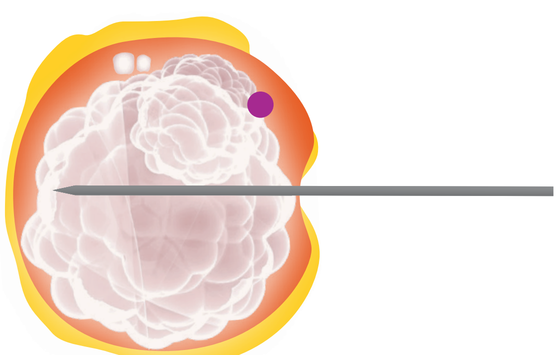
Anatomical distortion of ablation zone with conventional field-based energy



Active Passive Tumor Vessel

Figure 10

Resilience to anatomical distortion of ablation zone with Thermosphere™ technology



Active Passive Tumor Vessel

Figure 11

Thermosphere™ technology: combining three types of energy control

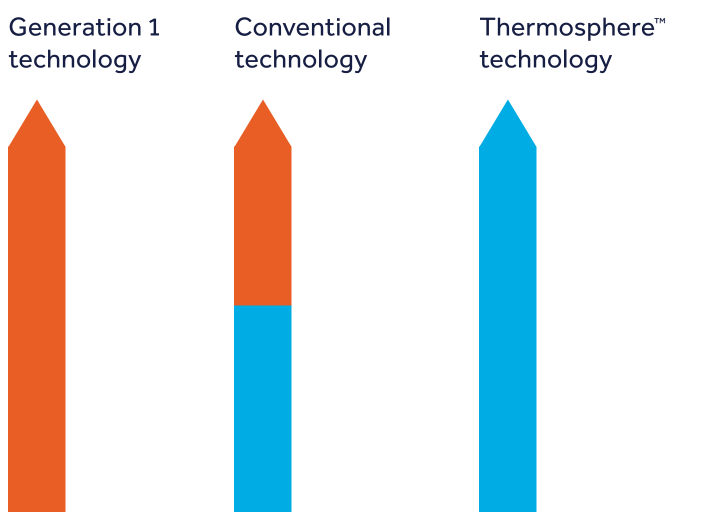
Thermosphere™, a field-based ablation technology, produces an active heating profile which is scalable, spherical, and not distorted by variations in tissue environment. Three types of energy control are leveraged, which together bring reality to the vision of a predictable ablation system.

Thermal control

Thermal control is the simplest type of energy control employed by Thermosphere™ technology. In fact, almost every field-based technology uses some type of thermal control. Why must thermal control be used in field-based technologies? The waveguides used to direct energy from the field-generators to the ablation probes heat as the electromagnetic fields pass through them. They therefore must be cooled to reduce contact temperatures along the device shaft.

Thermosphere™ circulates sterile saline as a cooling fluid within the device shaft to maintain safe temperatures. Thermal control with Thermosphere™ takes a step further than conventional field-based probes. The cooling fluid is circulated along the entire length of the ablation needle, over the radiator, and within millimeters of the device tip (Figure 12).

Thermal control: cooling the device to limit conductive heating from hot waveguides



Device without thermal control Device with thermal control

Figure 12

Field control

Field control is the second type of energy control used in Thermosphere™ technology and is rooted in the fundamentals of microwave radiator design. As discussed earlier, electrons moving along the surfaces of a probe induce the electromagnetic fields around the probe (Figure 13). Engineers are trained to sculpt radiator geometries into creative structures which determine the location and intensity of electron movements. In doing so, they can produce desired field shapes.

Although radiator design is esoteric and challenging, it is commonly done in several industries. Take for example telecommunications, where wide bandwidths and signal integrity challenge the engineer. A design advantage with these more mainstream applications is they assume the materials surrounding the radiators remain largely unchanged. Ablation probes do not benefit from an unchanging environment. They are in constant and intimate contact with the dynamics of ablating tissue. Therefore, a third type of energy control must be used to realize effective field control with field-based ablation technology.

Field control: applying principals of microwave radiator design to shape the active heating profile

Conventional technology minimal field control

Thermosphere™ technology advanced field control

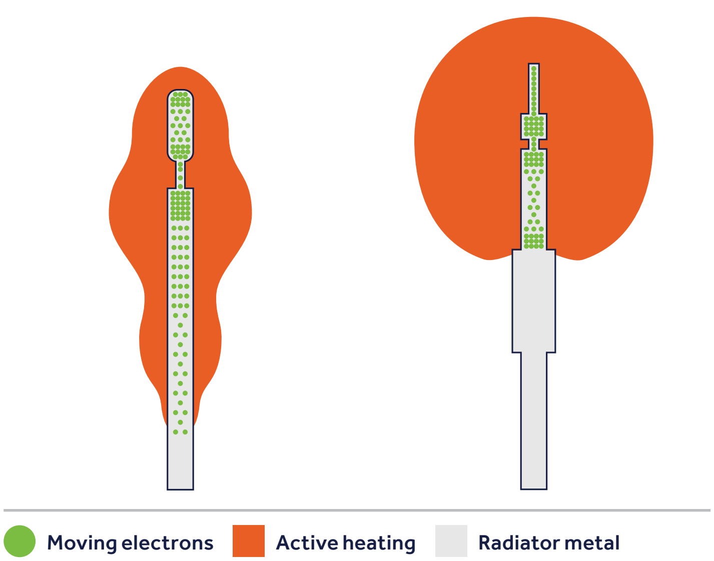


Figure 13

Wavelength control

As tissue coagulates and desiccates, fluids move peripherally away from the ablation probe. This is important in field-based technologies, as dielectric constant varies widely with changes in fluid concentration (Figure 14). An inflated lung has less than half the dielectric constant of a liver, and desiccating either tissue can further drop their dielectric constant by hundreds of a percent.

What is dielectric constant and why is it important to field-based technology? The dielectric constant of a material determines how far apart polarity inversion occurs in an electromagnetic wave. This distance between polarity inversions is the wavelength, and lowering dielectric constant increases this wavelength. Accounting for wavelength in radiator design is critical, as it determines where peaks and nulls occur in the electrons movements along the surface of the radiator.

Dielectric constant of tissue influences the wavelength of field-based energy

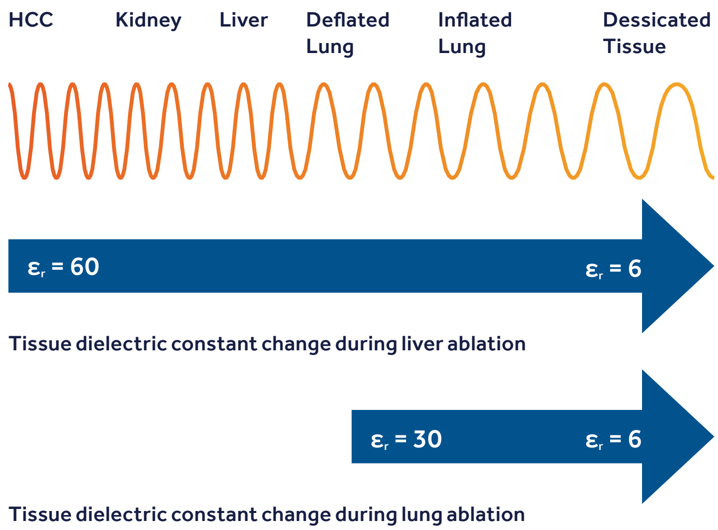


Figure 14

Conventional MWA probes allow the materials in contact with the radiator to determine the wavelength. In doing so, they allow wavelength to elongate during an ablation. As wavelength elongates, microwave currents spill off the radiator down the needle shaft and away from the device tip. This results in the well-known comet shaped ablation with MWA (Figure 15).

Change in active heating profile during an ablation without wavelength control

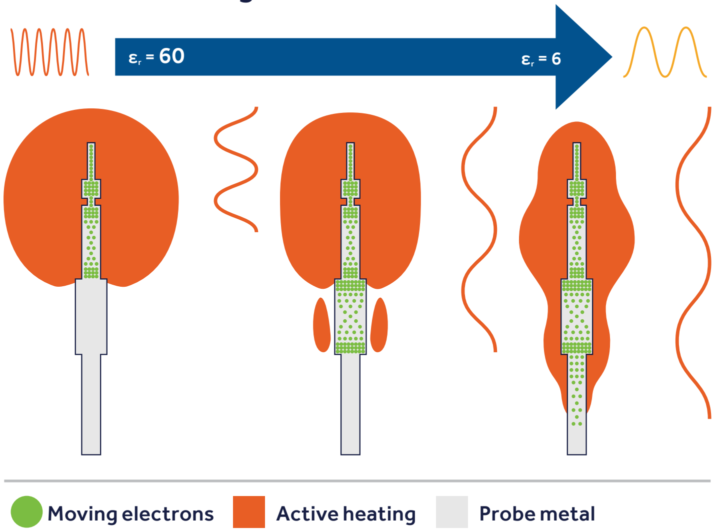


Figure 15

Thermosphere™ technology prevents wavelength elongation with a unique probe design. The radiator is miniaturized and hidden inside a reservoir of circulating high dielectric fluid: a saline loaded radiator. The saline loaded radiator of Thermosphere™ is a significant advancement beyond the conventional bare metal and ceramic loaded technologies (Figure 16). The dynamics of changing materials, properties are pushed away from the radiating surfaces, empowering the probe geometry to realize and hold field control. With field and wavelength control working in concert, Thermosphere™ technology consistently produces a spherical active heating profile regardless of the surrounding tissue condition (Figure 17).

An evolution in field-based technology to realize a stable active heating profile

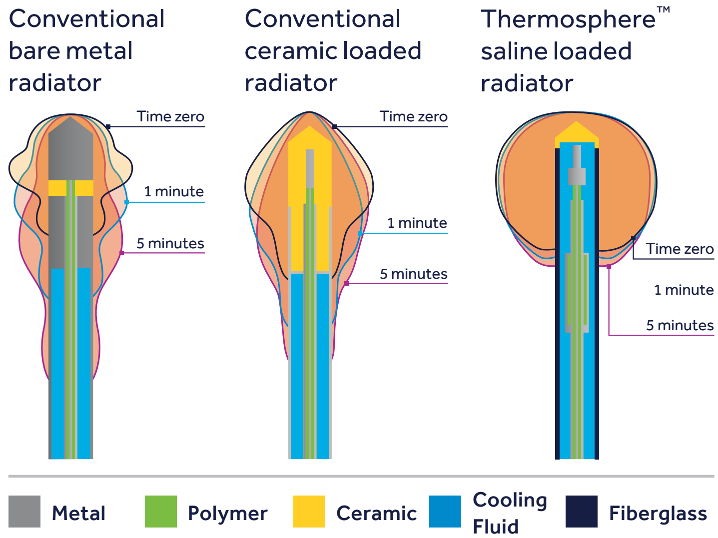


Figure 16

Wavelength control: stabilizing the active heating profile by preventing wavelength elongation on the radiator

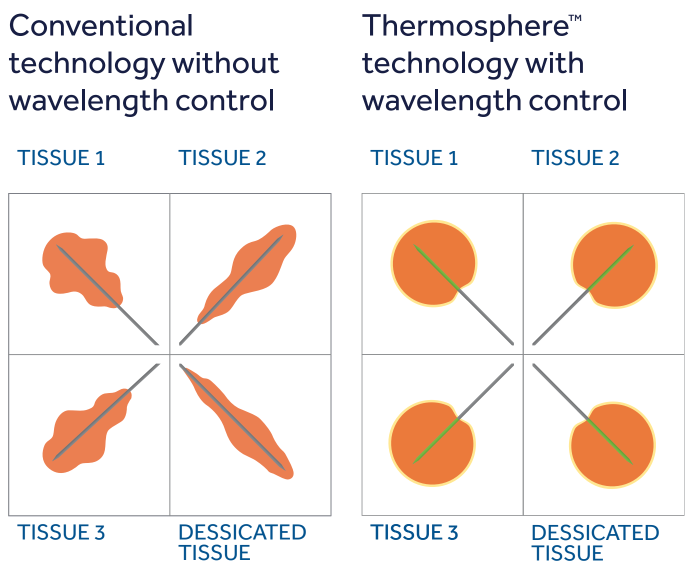


Figure 17

Emprint™ ablation system with Thermosphere™ technology

The goal of delivering a predictable and spherical ablation tool is not unique. Device companies have pursued this goal for years. Yet when conventional technologies ablate in vivo tissue, they produce ablation zones with shapes and sizes much different than claimed in manufacturer's ex vivo data.[10] Only after dozens of clinical procedures do users become comfortable with how conventional devices may perform within a given disease type, such as a CRLM.[9,17]

The development of the Emprint™ ablation system sought to overcome this lack of predictability which was significantly complicating ablation procedures. By leveraging Thermosphere™ technology, the Emprint™ ablation platform offers a new standard of active heating control. Thermal ablation is simplified with spherical and predictable ablations. The data supports these achievements.

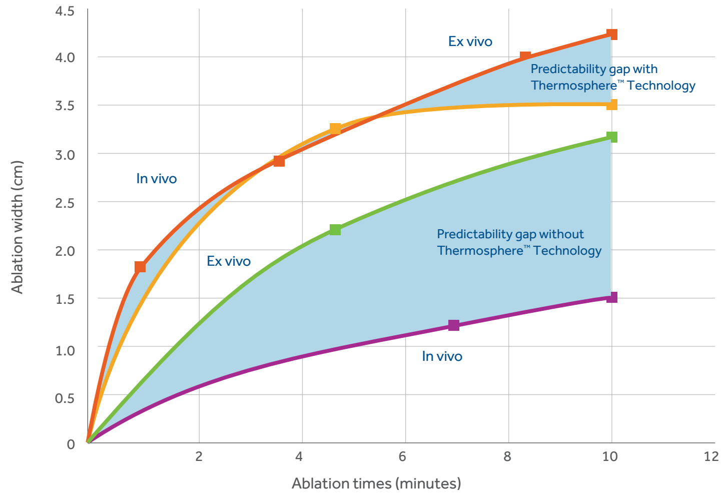
With Emprint™, Medtronic provides in vivo and ex vivo zone charts within the product labeling, delivering the most comprehensive translational ablation performance data in the industry.[18] Furthermore, Medtronic uses a chilled (17dC) ex vivo tissue model to avoid exaggerating expected clinical ablation performance.[19,20] A foundational investigation[19,20] on the Emprint™ system, compared the in vivo ablation diameters to ex vivo ablation diameters. As shown in Figure 18, ablations in both models were nearly identical, dramatically shrinking a 'predictability gap' present with conventional technology.

As of January 2018, many thousands of ablation procedures have been performed with Emprint™ across the world. Independent clinical studies are beginning to be published on the clinical experience.

One such study[21] compared the effects of Thermosphere™ technology on human liver in vivo versus the Medtronic provided ex vivo animal model data. The author's concluded: "Thermosphere™ technology produces easily controllable and predictable effects on liver parenchyma in vivo, little influenced by different pathophysiologic, hemodynamic, and operative conditions."

Another clinical study[22] sought to assess Thermosphere™ technology for treatment of liver malignancies in comparison to conventional microwave technologies. Results demonstrated Thermosphere™ produced more spherical ablation zones, realizing two to three times larger minimal ablative margins than conventional microwave technology. The authors attribute the spherical ablation shape as the reason larger margins were achieved with less ablative volume than the prior technologies.

Enhancing predictability of field-based ablation with Thermosphere™ technology



Ex vivo with Thermosphere™ technology

Ex vivo without Thermosphere™ technology

In vivo with Thermosphere™ technology

In vivo without Thermosphere™ technology

Figure 18

Another independent clinical study[23] from the Cleveland Clinic evaluated the rate of local recurrence with Thermosphere™ ablation in the treatment of liver malignancies. The investigators conclude Thermosphere™ technology produces predictable and spherical ablations, with "local tumor control rates comparing favorably with that reported for radiofrequency and other microwave technologies in the literature."

Add Thermosphere™ technology to your practice. Observe how control of active heating can unlock predictability and simplify your ablation procedure. Seeing is believing.

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