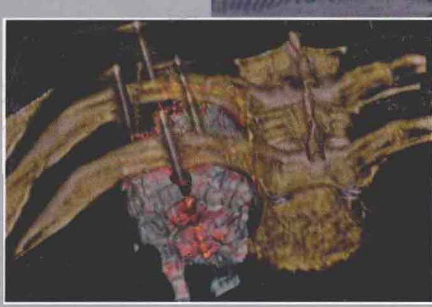
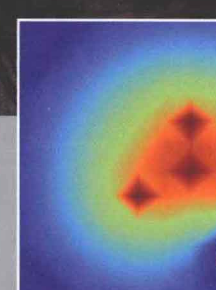
Percutaneous Tumor Ablation

Strategies and Techniques

Kelvin Hong
Christos S. Georgiades

DVD-ROM included





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Percutaneous Tumor Ablation
Strategies and Techniques

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Percutaneous Tumor Ablation
Strategies and Techniques

Thieme

To my parents, David and Linda Hong, and my family, Jessica and Preston

K.H.

To Marianna

C.S.G.

DVD-ROM Contents

Foreword

We are honored to write this foreword for the book *Percutaneous Tumor Ablation: Strategies and Techniques*, edited by Drs. Hong and Georgiades. It is especially gratifying for us to do so because we have known both Dr. Hong and Dr. Georgiades for much of their careers. We hope our mentoring and guidance during the past few years had something to do with their success, culminating in this very important text. The book covers all the key aspects of tumor ablation that practitioners need to develop a successful practice. It includes in-depth organ-based reviews of clinical results, detailed mechanistic information for each ablation device, and tips on practice development. All chapters have been written by true internationally recognized experts in the field.

Perhaps more importantly, by filling a gap in the oncology literature, this textbook may help pave the way for more widespread incorporation of interventional oncologists into the multidisciplinary cancer care team. It is clear that during the past decade the field of oncology has evolved from a single discipline to a multidisciplinary one, in which radiation, surgical, medical, and now interventional oncologists all sit at the same table to provide optimal therapies for cancer patients.

Percutaneous Tumor Ablation will make a valuable and practical reference for interventional oncologists (beginners and experts alike), whether in an academic or private practice. By addressing not only the technical aspects of tumor ablation but also the clinical issues related to the care of the patient, this text will also serve all cancer care physicians who recognize the increasingly valuable role of percutaneous ablation and its potential benefits for their patients. Drs. Georgiades and Hong should be commended for making such a significant and relevant contribution to the oncology knowledge pool.

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Preface

A few years ago, as we embarked on building an image-guided ablation service at our institution, we were hindered by the lack of a comprehensive technical and clinical textbook on the subject. We were surprised that no such book had been published. A great deal of time and effort went into exploring the available technology and uncovering the relative advantages and disadvantages of each system, many times through trial and error. This inevitably slowed the clinical growth of the service, at least initially. One of the objectives of *Percutaneous Tumor Ablation: Strategies and Techniques* is to guide physicians who are starting an ablation service through the technology maze. The early chapters showcase the available ablation systems and probes, illustrate the ablation protocols, and explain pertinent physics.

Equally importantly, we want this textbook to be a clinical reference source for physicians at every stage in their career, early and advanced. Because of the unique clinical and technical challenges associated with each of them, we divide the clinical service into organ-based areas: lung, liver, kidney, musculoskeletal, and others. Cognizant of the differences in clinical experience among physicians offering ablation services, we incorporate a large number of visual aids and many illustrative cases. The types of cases range from technically simple ones in medically uncomplicated patients to technically challenging ones in high-risk patients.

Additional chapters address other challenges faced by physicians offering image-guided ablation services. For example, the preoperative and postoperative care of patients is of paramount importance for good outcomes, as is proper patient selection. We also include a chapter on practice building to help ensure a smooth initial transition for beginners, and another chapter addresses the issue of evidence-based practice and available data, highlighting the most salient peer-reviewed publications.

For image-guided physicians, a picture paints a thousand words. To supplement and enhance the print-based chapters, a multimedia DVD is included that contains four video clips of patients undergoing thermal ablation procedures to illustrate some of the many practical tumor ablation strategies and techniques discussed herein. The narrated videos cover the four most common organ sites treated with radiofrequency ablation and cryoablation in clinical practice currently: liver, kidney, lung, and bone tumors.

Because *Percutaneous Tumor Ablation* addresses both technological and clinical issues, we expect that it will be a useful aid for physicians offering an image-guided ablation service at any stage in their career.

◆ Acknowledgments

We sincerely thank our contributing authors for their expert input and contributions to their respective chapters. We also express our gratitude to Nefeli Massia, the Greek-born, Baltimore-based artist for the cover art. Nefeli is a renowned artist who blazes new abstract trails, fusing art, literature, and psychology.

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Contents

1

Radiofrequency Ablation: Mechanism of Action and Devices

Kelvin Hong and Christos S. Georgiades

The application of radiofrequency (RF) energy and its thermal effects on tissue were described as early as 1891 by d'Arsonval, when RF waves that passed through tissue were observed to cause an increase in local tissue temperature. RF energy became incorporated into practical medicine via the invention of the Bovie knife used for both cauterization and cutting tissue by varying the RF current. A pulsed current caused cauterization of tissue, whereas a more continuous current caused cutting of tissue. The first-generation Bovie knife was a crude monopolar RF electrode with surface adhesive skin pads closing off the circuit. Use of RF application in thermal ablation was first reported by Rossi and by McGahan et al independently in 1992 for liver tumor ablation.

Since the early RF description, over 100,000 estimated liver RF ablation (RFA) procedures have been performed worldwide. The interest in percutaneous tumor ablation has considerably evolved with introduction of several other thermal modalities, including microwave, cryoablation, high-intensity ultrasound, irreversible electroporation, and interstitial laser.[1] The evidence thus far suggests, however, that RFA should remain the prototypical ablation device, particularly for lesions <3 cm, and should still be the cornerstone of any ablation practice.[2,3] It is the most frequently used ablative technique, and it has the longest track record.[4] Familiarity with the RFA mechanism of action, clinical rationale, and techniques remains critical for the success of an ablation practice.[5]

◆ Physics and Principles

Radiofrequency refers to the part of the electromagnetic (EM) spectrum bounded by the frequencies of 3 Hz and 300 GHz (**Fig. 1.1**). EM radiation includes (in addition to radio waves) infrared radiation, the visible spectrum, ultraviolet radiation, x-rays, and γ-rays, in increasing frequency.

Even though all EM radiation subtypes have the same basic physical properties, their interactions with matter can be very different depending on their frequency and the type of matter. RF waves, as applied in medicine, cause thermal ablation of a defined volume of tissue. The RFA probe acts as the cathode of an electrical circuit that is closed by the application of dispersing pads on the patient's thighs (**Fig. 1.2**). Because of the small cross-sectional area of the probe tip, there is a very high energy flux around it. On the other hand, the large cross-sectional area of the grounding pads disperses the energy, minimizing the energy flux. As a result, tissue damage is limited to the part of the circuit that surrounds the probe tip.[3]

RF ablation results in coagulative necrosis of tissue at high temperatures. The dipole molecules (mostly water) adjacent to the tip of the RF electrode attempt to remain aligned in the direction of current and are forced to vibrate as a rapidly alternating current is applied. Molecules farther away from the probe are set into motion by other vibrating molecules near them. The frictional energy losses between adjacent

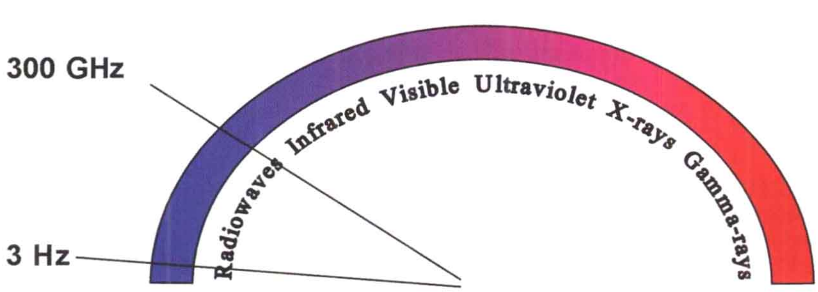

Fig. 1.1 The electromagnetic (EM) spectrum is modeled as a continuous frequency spectrum of vibrating massless energy quanta. The EM radiation is composed of both an electric and a magnetic field oriented at 90 degrees to each other. The EM radiation whose frequency is between 3 Hz and 300 GHz is defined as radiowaves.

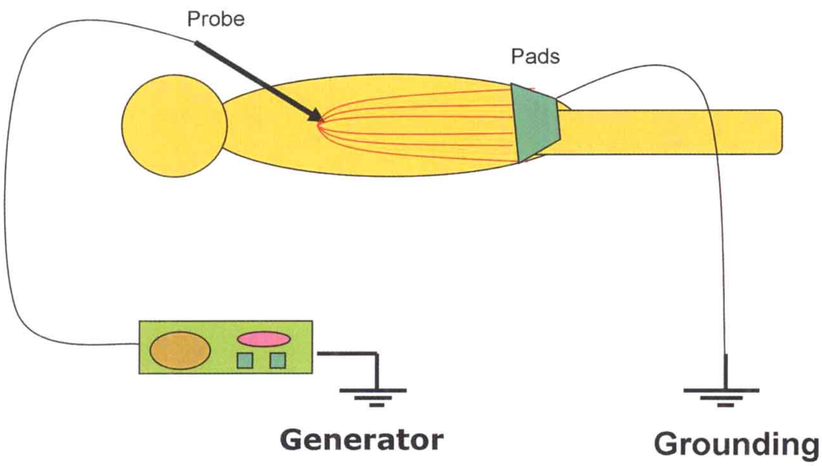

Fig. 1.2 The radiofrequency ablation circuit. The probe acts as the cathode and the pads as the anode. The patient is actually part of the circuit, and tissue conductivity is important in achieving adequate ablation zone.

molecules result in local energy deposition and temperature increase. As one moves away from the source (probe), energy deposition and thus temperature both drop (**Fig. 1.3**). The RF electrode itself is not the source of heat and is not hot to the touch. It generates an alternating EM field that sets adjacent molecules into motion and intense agitation. The molecules immediately adjacent to the probe are the source of the heat, which is transmitted farther by tissue conductivity.

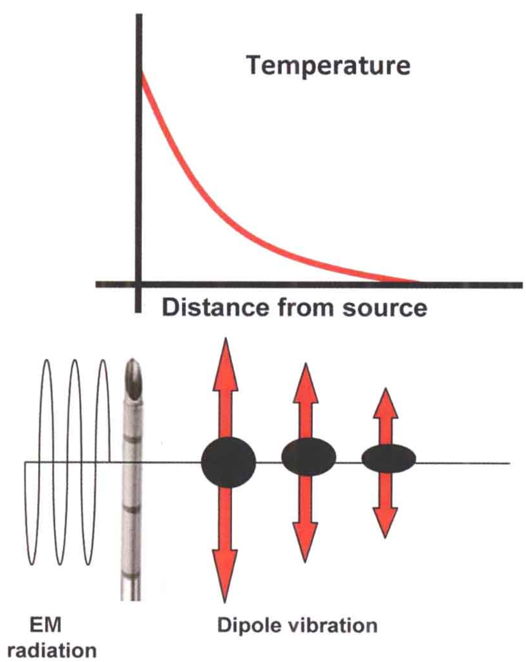

Fig. 1.3 The radiofrequency probe itself is not the source of heat. It generates an alternating electromagnetic field that sets adjacent molecules into motion. The molecules immediately adjacent to the probe are the source of the heat, which is transmitted farther by tissue conductivity.

One of the limitations of RFA is that it is heavily dependent on good electrical and thermal tissue conductivity for effective ablation.[3] If one pushes the generator's power too high too quickly, the tissue around the probe becomes desiccated (charred). The desiccated tissue acts as an insulating "sleeve" around the probe, which limits the transmission of further electrical or thermal energy (**Fig. 1.4**) and limits any further extension of desired tissue destruction. It is instructive to note that time is just as crucial in achieving a large ablation zone as the maximum temperature reached. **Figure 1.5** demonstrates the approximate time needed for tissue death at various temperatures. Mammalian tissue is very sensitive to temperature changes. At 55°C, for example, tissue death results within 2 seconds. At 100°C, death is instantaneous as evaporation occurs. Microbubbles are produced and represent gases, primarily nitrogen, that are released from the cells. This, however, is not desired in RFA because of the insulating effect of charred tissue. Thus, a slow, methodical energy deposition is more effective than a quick temperature rise for purposes of enlarging intentional tissue ablation (**Fig. 1.6**).[6] The objective is to heat tissues to 50° to 100°C for 4 to 6 minutes without causing charring or vaporization. If temperatures greater than 105°C are rapidly reached, this causes boiling, vaporization, and carbonization, all of which decrease energy transmission and consequently limit larger ablation sizes.

Extrapolated from surgical data, the goal of the RFA technique is to intentionally ablate a zone of healthy tissue around the target tumor, analogous to a "surgical margin" (**Fig. 1.7**). This margin should be 0.5 to 1.0 cm of ablated normal tissue, based on the difficulty in truly identifying exact tumor margins and the concerns for microscopic tumor extension beyond those confines. That means for a 2-cm tumor, one would need to produce an ablation of approximately 3 to 4 cm.[5,6]

There is considerable heterogeneity of heat deposition through any RFA tissue volume. The extent of coagulation necrosis is dependent on the energy deposited, which is the local tissue interaction minus the heat lost from cooling effects such as the "heat sink" of adjacent blood vessels.[5] The

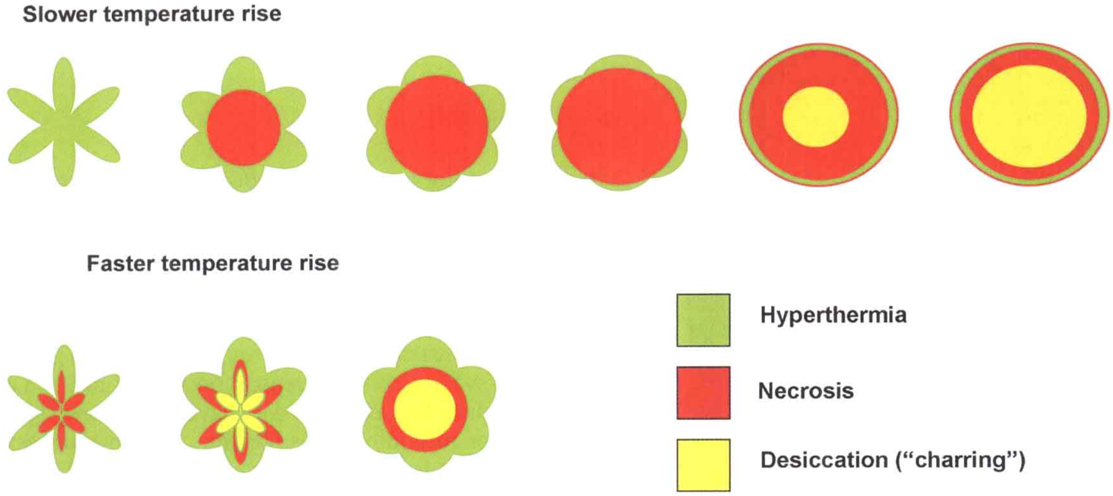

Fig. 1.4 A “thought” experiment using an umbrella-type radiofrequency probe seen in cross section. The top row shows an eventual larger zone of ablation compared with the bottom row. This is so because the faster increase in energy input (bottom row) results in a faster temperature rise in the tissue immediately around the probe. This tissue is charred before the maximum ablation zone is achieved. Once charring occurs, further energy deposition is impossible, as resistance is too high.

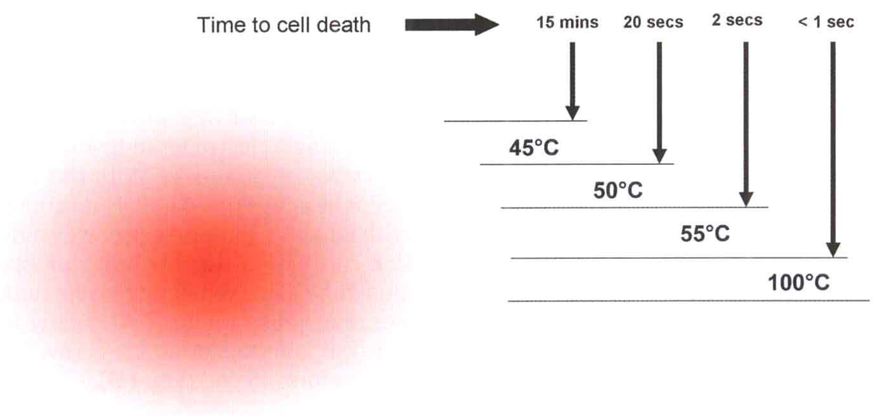

Fig. 1.5 The time needed for tissue death at various temperatures. Mammalian tissue is very sensitive to temperature changes. At 55°C, for example, tissue death results within 2 seconds. At 100°C, death is instantaneous as evaporation occurs. This is not desired in radiofrequency ablation, however, because of the insulating effect of charred tissue. Thus a slow, methodical energy deposition is more effective than a quick temperature rise.

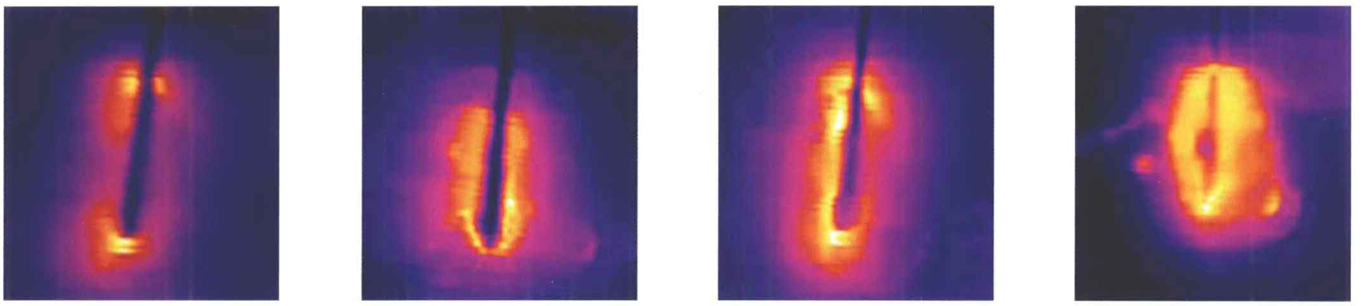

Fig. 1.6 Progression of a radiofrequency ablation by color representation of surrounding slow thermal changes without charring.

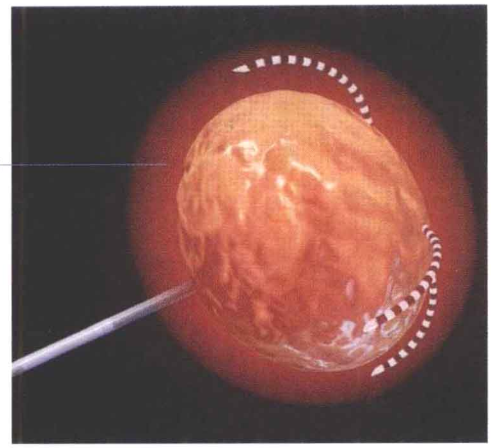

Fig. 1.7 A zone of 1-cm surgical margin beyond the visible tumor confines.

heat-sink effect is a phenomenon that limits the effectiveness of all thermal ablation methods. When the target lesion abuts a blood vessel 3 mm or larger, the flowing blood prevents large temperature variations in the part of the tumor near the lesion, thereby keeping the tissue "cooler" (**Fig. 1.8**). This potentially leaves behind residual unablated tumor near the vessel wall, increasing the chance of local tumor progression. Factors that influence local tumor progression after RFA include tumor-related factors (size, site, orientation, organ, tumor histology, tumor biology) and technical factors (electrodes, generator power, heat sink, time).

Data in RFA of liver primary tumors have demonstrated that 3 cm or less is the optimal size, and there is a persistent effort to improve and enlarge ablation size, through improved RFA techniques. Goldberg and Dupuy[6] simplified an approach to the basis of RFA: Induced coagulation necrosis = (energy deposited × local tissue interactions) – heat loss. Investigators have suggested different approaches to solve these physical constraints by modulating tissue characteristics, increasing RF energy deposition, or modifying blood flow.

◆ Generators

Early RF generators for percutaneous application produced modest outputs of 50 W. Today, generators manufactured by the three major RFA companies in the United States are all capable of outputs of 150 to 200 W, delivering high-frequency (460–500 kHz) alternating current via RF electrodes (usually 14- to 17-gauge) of varying configurations. However, the three systems have distinctly different electrode designs and philosophies, varying energy deposition algorithms, and ablation end points. No definitive data have shown one system to be superior to another. Despite the company-suggested algorithms, there is great variability among users. Personal preference and familiarity still play distinct roles in the best and most consistent achievable patient outcomes.

◆ Electrode Modifications

Given the limited ablation zone with solitary electrodes such as the Bovie knife, a clear need was identified to increase the zone of necrosis by elongating the active areas in any given system. Modifications included developing expandable electrodes or using several straight electrodes in a cluster. These designs resulted in cylindrical ablation zones that did not uniformly conform to and cover the typical spherical nature of most small malignancies. As a further modification, the ability to place up to three single electrodes individually has been used as well to increase ablation size. With this technique, it is crucial to keep the active tips parallel and approximately 1 cm apart. With increasing inter-electrode distance, the area of coagulation can have a dog bone or dumbbell shape, with the potential for leaving remaining viable tumor between the electrodes. This illustration is particularly important when building compound ablation areas (overlapping ablations) for large tumors (>5 cm) (**Fig. 1.9**).

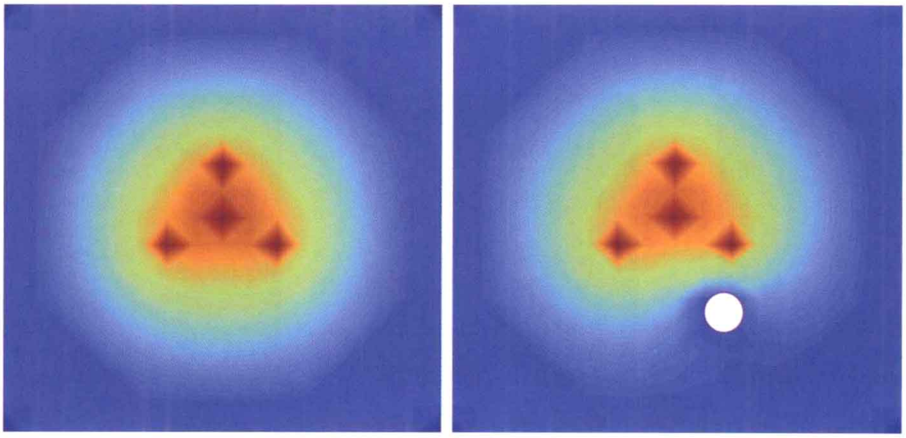

Fig. 1.8 The heat-sink effect is a phenomenon that limits the effectiveness of all thermal ablation methods. When the target lesion abuts a blood vessel that is 3 mm or larger, the flowing blood prevents large temperature variations in the part of the tumor near the lesion, thereby keeping the tissue "cooler."

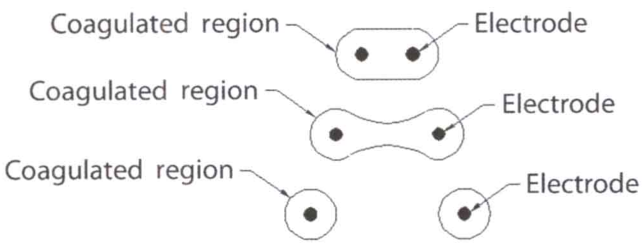

Fig. 1.9 If the electrodes are placed to far apart (>1 cm), the resulting overlapping area of affected tissue would change shape. As the distance between electrodes increases, the area of coagulation would have a "dog bone" or "dumbbell" shape. As the electrodes are placed further apart, this shape would evolve into distinct and separate areas immediately around each electrode, leaving viable tumor/tissue in between. This factor is particularly important when building compound ablation areas (overlapping ablations) for large tumors >5 cm.

Multitined Expandable Arrays

Improving on the original single monopolar needle, LeVeen described a novel approach of having multiple curved uninsulated prongs deployed from the needle tip central cannula, creating the shape of an umbrella. Each prong caused a separate area of coagulation necrosis that slowly increased in size by administering increasing amounts of RF energy in a stepwise fashion and eventually coalescing with the neighboring prong, creating a reproducible volume of necrosis (**Fig. 1.10**). Currently, this type of system is represented commercially by the LeVeen device (Boston Scientific, Natick, MA) (**Fig. 1.11A**). Other manufacturers pursued a stepwise deployment in a forward-orienting electrode, for example the Starburst XLi probe (AngioDynamics Inc., Queensbury, NY) (**Fig. 1.11B**).

Internally Cooled Electrodes

Goldberg described in 1996 an innovative approach whereby chilled saline is pumped through the chamber shaft of the needle, with the resultant reduction in charring and impedance, and increased tumor volume ablation.[6] Cool-Tip electrode (Covidien, Boulder, CO) is the commercial prototype for this concept, which was then modified further by clustering three electrodes together (**Fig. 1.12**) for a synergistic coalescence of each thermal ablation.

Perfusion Electrodes

Perfusion electrodes were developed whereby saline or hypertonic saline is injected or infused into target ablation tissue, capitalizing on the concept that high local sodium chloride ion concentration can expand the volume of tumor ablation by altering tissue electrical conductivity. Commercial examples of perfusion electrodes are the XLi-Enhanced and Talon electrodes (AngioDynamics Inc., Queensbury, NY), which are multitined devices with saline pump perfusion enhancement, creating ablation diameter volumes of up to 7 cm.

Bipolar Radiofrequency Ablation Electrodes

A recent advance has been the development of bipolar systems, whereby two or more bipolar electrodes are placed into the tumor, and the applied RF current runs from one electrode to another without the need for grounding pads. This essentially ensures that all electrodes within the tumor are active, with minimal energy loss, allowing greater ablation volumes more efficiently and faster. Bipolar systems

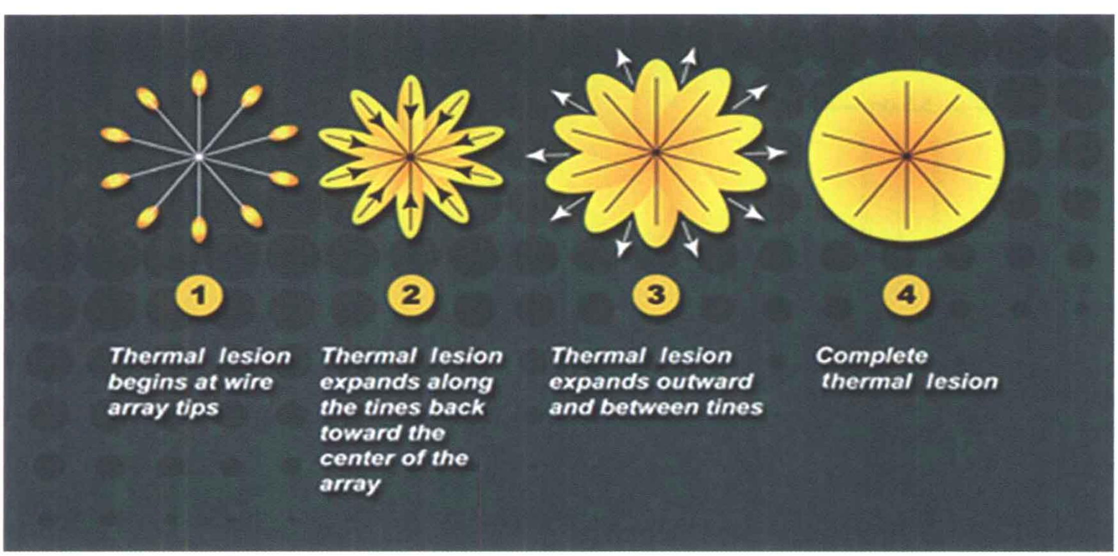

Fig. 1.10 Concept diagram of coalescing areas of coagulation necrosis from a multitined electrode.

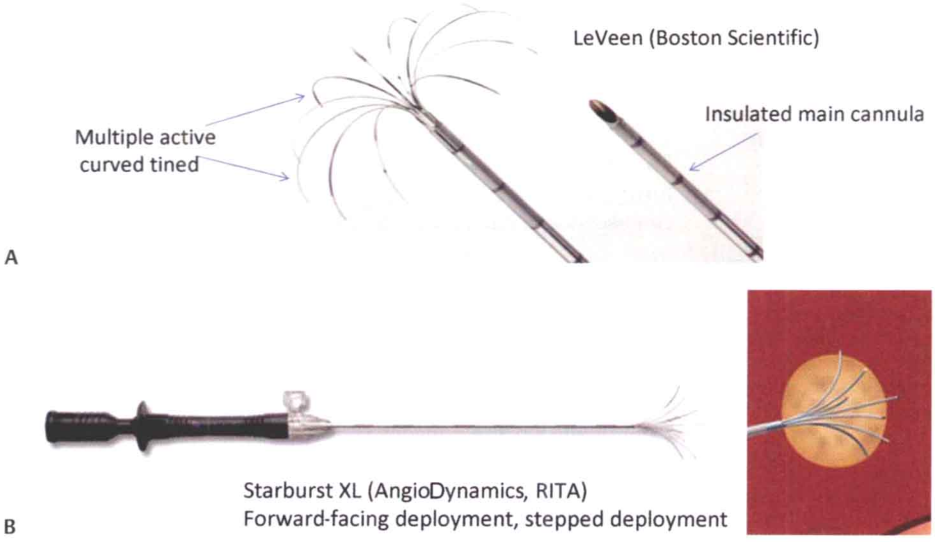

Fig. 1.11 (A,B) Multitined radiofrequency electrodes.

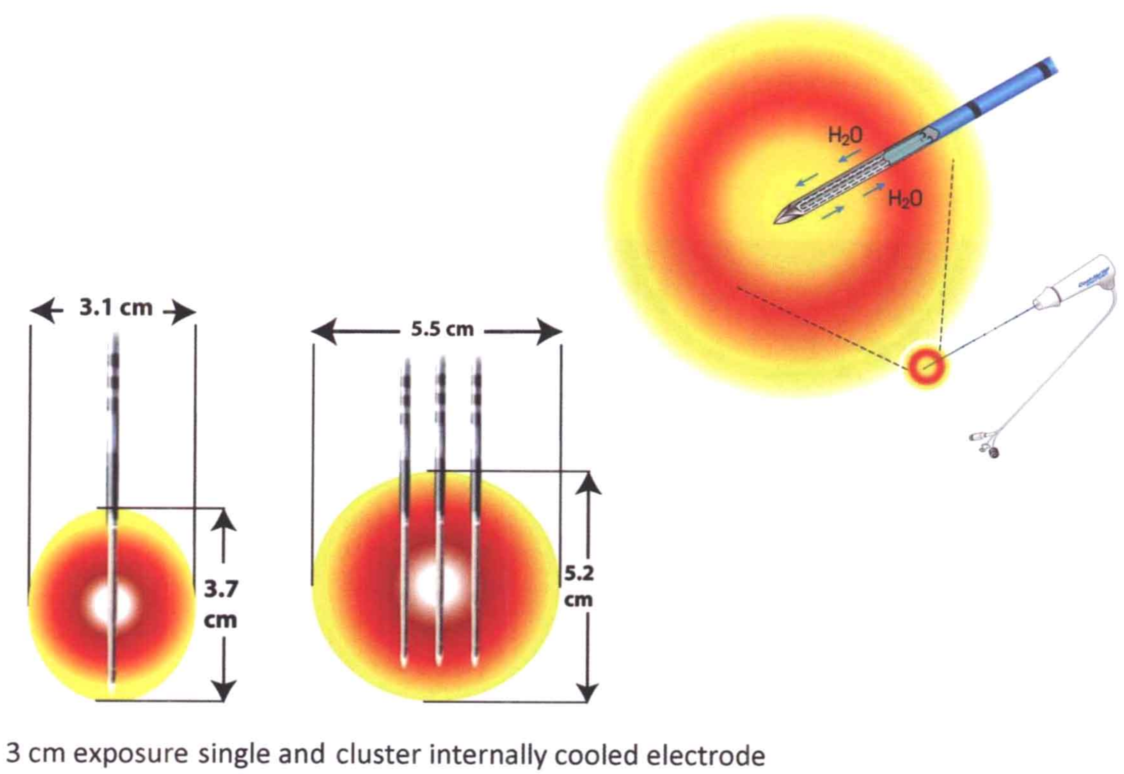

Fig. 1.12 Internally cooled electrodes. (Courtesy of Covidien.)

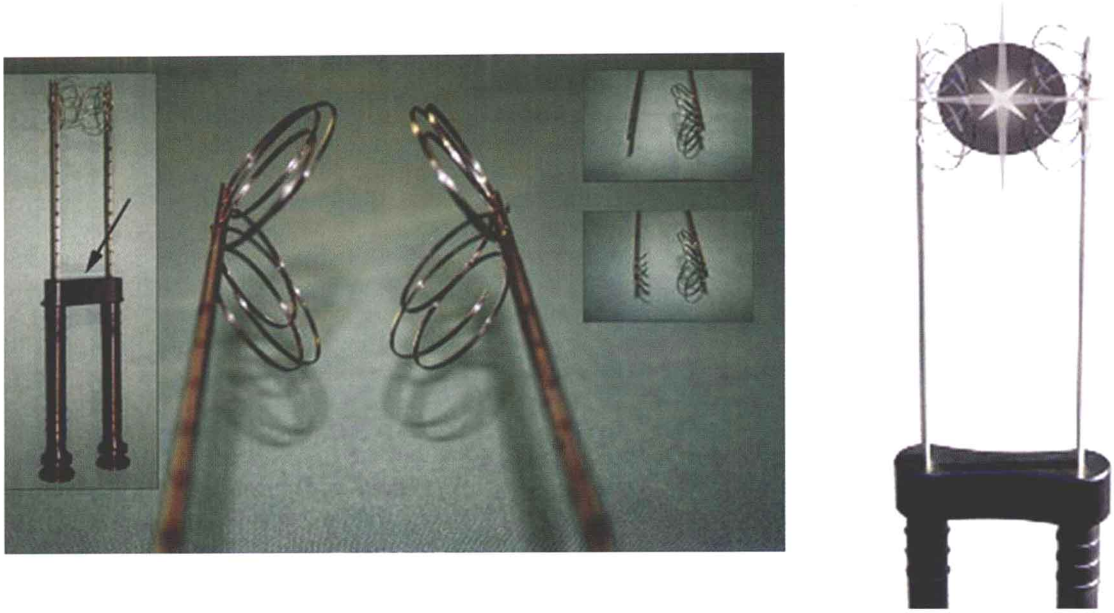

Fig. 1.13 Bipolar InCircle electrode. Two electrodes are placed parallel around the tumor, with each probe being an active energy pole. The *arrow* denotes a guiding spacer to optimize the distance between the poles of the circuit.

also do not require grounding pads and negate the risks of skin pad burns. The InCircle bipolar device (RFA Medical, Freemont, CA) is a U.S. Food and Drug Administration (FDA)-approved system that is compatible with most available generators from other manufacturers. The InCircle electrode is unusual in that two probes are placed on each side of the tumor without penetrating the integrity of the lesion, and the electrode surrounds the lesion (**Fig. 1.13**). This electrode may be helpful in circumstances where mobile or hard tumors may not have to be penetrated. This bipolar system attains large burns quickly in early reports, and may show promise for larger ablation volume compared with monopolar

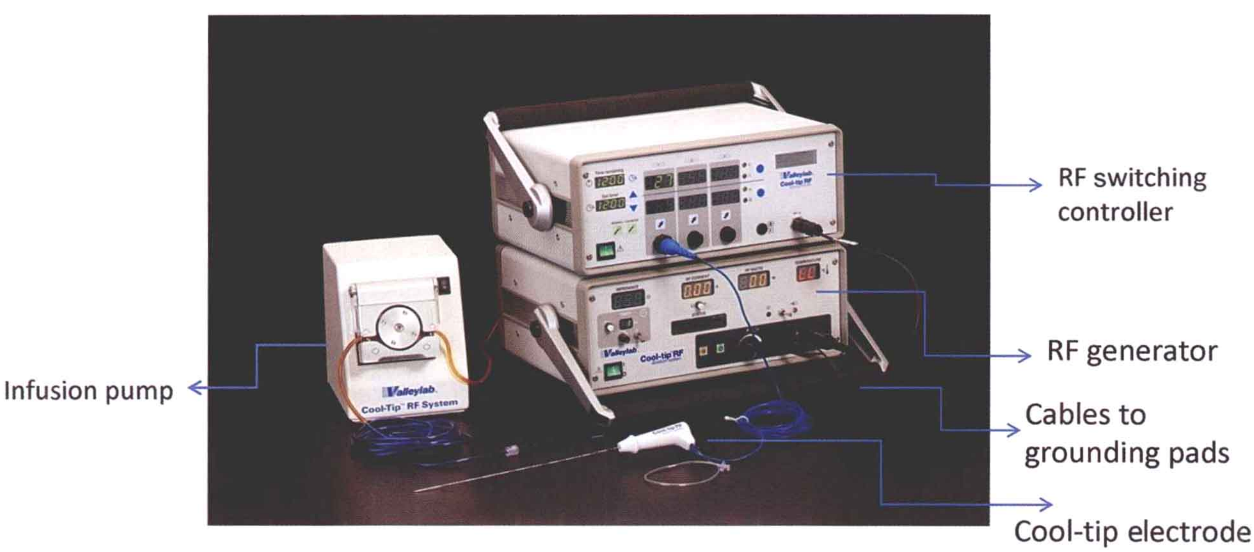

Fig. 1.14 Covidien Cool-Tip RFA system. (Courtesy of Covidien.)