European Journal of Radiology 75 (2010) 32–36

Contents lists available at ScienceDirect

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

Stereotaxy: Breaking the limits of current radiofrequency ablation techniques

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ARTICLE INFO

Article history:
Received 25 March 2010
Accepted 31 March 2010

Keywords:
Coagulation necrosis
Radiofrequency ablation
Stereotaxy
Navigation
Reliability

ABSTRACT

Radiofrequency ablation (RFA) allows for local curative tumor treatment by inducing coagulation necrosis with high-frequency alternating current. However, the tumor size is the major limiting factor due to a mismatch of the tumor volume and the induced necrotic zone. RFA probes have to be optimally distributed in and around the tumor in order to produce overlapping ablation zones. Due to different guidance and ablation strategies the result is strongly operator dependent and there is a lack of reliability. These challenges can be managed by 3D-planning using a frameless stereotactic navigation system, allowing for the simultaneous display of multiple trajectories. The spatial information gained from 3D imaging is available in coordinates and thus forms an accurate input for performing the intervention. Stereotaxy enables highly accurate probe positioning. Stereotactic radiofrequency ablation (SRFA) may substantially improve the safety and efficacy in clinical practice, especially in the treatment of large and irregularly shaped tumors. The proposed methods may also be used for similar percutaneous local tumor treatments.

1. Introduction

Radiofrequency ablation (RFA) is an effective technique to irreversibly destroy tumor tissue at different sites in the body. Coagulation necrosis is achieved with high-frequency alternating current that is delivered by electrodes placed in the tumor. Frictional heat is created by the movement of ions within the tissue. As the temperature approaches 60 °C, cellular proteins become denatured and, ultimately, thromboses in the microvasculature interrupt the blood supply. Due to its efficiency and its minimal invasiveness, percutaneous image-guided RFA has become widely accepted as the first-line local tumor therapy for surgically untreatable primary and secondary liver malignancies.

Rates of complete tumor ablation, local recurrence and survival are excellent for the treatment of small tumors measuring less than 3 cm [1–3]. However, the results of lesions that are large (diameter > 3–5 cm) and irregularly shaped (non spherical), subcapsular, as well as lesions that are close to major vessels, are unsatisfying and argue for excluding such lesions from RFA-treatment. The most important risk factor for residual tumor and local recurrence is the tumor size due to a mismatch of the tumor volume, including a safety zone (margin of apparently healthy tissue adjacent to the lesion) and the necrotic area achieved by RFA, imprecise probe placement, insufficient overlapping of multiple ablation spheres, the heat-sink effect due to the proximity to large vessels resulting in reactive tissue cooling [2], and the insufficient application of energy.

However, the main problem in current RFA is the lack of reliability of the ablation therapy due to different guidance and ablation strategies. There is a strong demand for a repeatable and reliable standardized procedure that is, as much as possible, operator independent.

In this context, the potential role of stereotaxy to improve the results of percutaneous radiofrequency ablation, especially of large and irregularly shaped tumors, is discussed.

2. Critical issues of planning reliable tumor ablation

2.1. Size of the tumor and the required number of electrodes or electrode positions

It is essential to ablate the entire lesion, including a safety margin of 0.5–1 cm around the tumor. Expandable electrodes create rather spherical shaped lesions, and needle-like electrodes create ellipsoidal shaped lesions (Fig. 1). The achieved ablation necrosis is limited and for ablation including a 1 cm tumor-free margin in a single ablation model, 3-, 4-, and 5 cm ablation spheres can ablate tumors measuring 1-, 2-, and 3 cm, respectively [4]. Therefore, larger tumors will need additional electrodes or several electrode positions for the generation of overlapping ablation necroses. A theoretical computer analysis [4] showed that if six ablation spheres are placed in orthogonal planes around a spherical tumor, the

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doi:10.1016/j.ejrad.2010.04.013

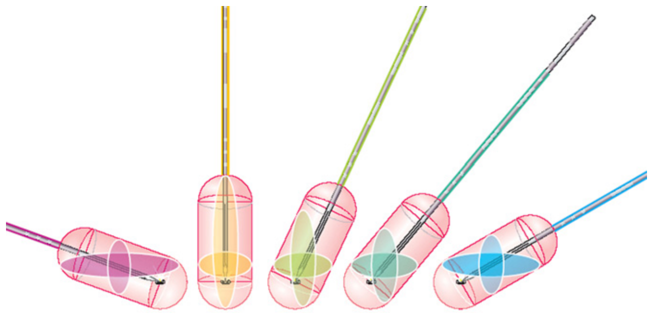

Fig. 1. Different angles of probe introduction result in different intersection shapes of the ablation zones with axial and sagittal planes.

largest tumor that may be treated with a 3 cm ablation device has a diameter of 1.75 cm, whereas 4- and 5-cm ablation spheres can be used to treat tumors measuring 3 and 4.25 cm, respectively. With 14 ablation spheres, the treatable tumor size is increased to 3, 4.6, or 6.3 cm, depending on the diameter of the ablation sphere induced. The analysis showed that the size of the composite thermal injury created by overlapping multiple thermal ablation spheres is surprisingly small relative to the number of ablations performed.

2.2. Distance between needles

Needle-like probes can be used as single, dual, triple, or multiple electrodes and can be activated in consecutive, simultaneous or switching modes. There are mainly two deviceclasses: monopolar and bipolar. Monopolar probes have only a single electrode with a non-insulated tip; multipolar probes are equipped with 2 electrodes. Therefore, to close the circuit, monopolar radiofrequency devices require application of a grounding pad onto the patient's skin; multipolar systems focus the current flow between the probes' tips. However, in order to reach complete tumor destruction, a maximum distance of 2.5 cm along the entire active tip between probes is recommended. A minimum distance of 1 cm is required in order to prevent a short-circuit. If multipolar electrodes are used, care must be taken that the planned probe tips are parallel for consistent and complete formation of coagulation necrosis.

2.3. Irregularly shaped lesions

Irregular margins and satellite lesions have to be taken into account for 3D-planning of the approach (Fig. 2a and b). Especially large and non-spherically shaped lesions cannot be ablated according to the basic models described above since the condition of a more or less spherically shaped volume is not met.

2.4. Vessels close to the tumor

In case of lesion proximity to large vessels, the number of probes and the energy must be increased in order to counteract the associated cooling effects leading to a higher probability of recurrence. In addition, the electrodes and thus the central part of the developing necrosis must be placed as close as possible to the vessel without damaging it.

2.5. Approach

A very important aspect is the selection of safe trajectories from the skin entry points to the targets. Many different obstacles including the ribs, pleura, lung, stomach, intestine and large vessels must be avoided (Fig. 3). Perforation of such anatomical structures may lead to severe complications and thus are unacceptable. It must be emphasized that the movement of the target lesion and the obstacles due to respiration must be taken into account.

3. Limitations of current techniques for RFA

At present, radiofrequency electrodes are positioned free-hand under ultrasound (US), Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) guidance. Due to its universal availability and ease of use, US is the most commonly used imaging modality [5]. Furthermore, it offers real-time monitoring of the probe during positioning without radiation exposure. However, US-guided interventions are strongly user-dependent and the development of gas bubbles during ablation may obscure probe repositioning in larger lesions. Some lesions may not be visible with US guidance (e.g. lesions in the liver dome).

CT guidance can improve the visibility of target lesions. However, the electrode must be introduced incrementally, interrupted by control scans resulting in additional radiation exposition [6]

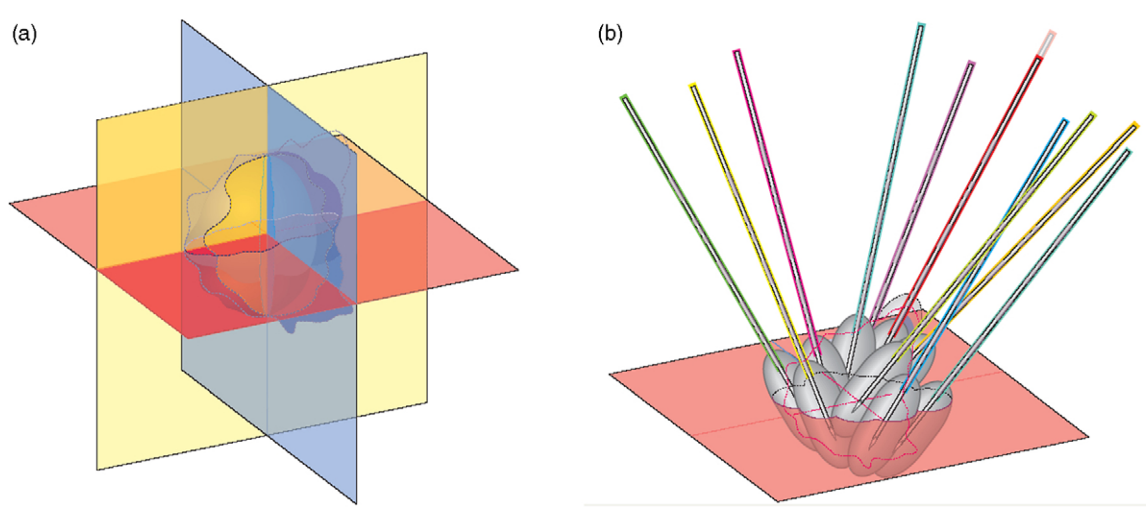

Fig. 2. (a and b) For safe and tissue sparing ablation of large irregularly shaped lesions multiple overlapping ablation zones are required. Thus, the positions of multiple RFA probes have to be introduced with high precision. (a) Intersections of the axial, sagittal and coronal plane with an irregular shaped tumor. (b) The resulting overlapping ablation zones by using multiple straight RFA probes.