Interactive Approximation of the Ablation Zone incorporating Heatsink Effects for Radiofrequency Ablation

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Abstract:

Percutaneous radiofrequecy ablation (RFA) is becoming a standard minimal invasive procedure in the clinical routine. However, the control of shape and size of the ablation zone is unsatisfactory, especially close to large vessels. In this work, our aim is to present a novel image based, fast approximation of the ablation zone with respect to the cooling blood flow, which decreases thermal ablation. For that, patient independent numerical precomputations of the ablation zone are performed and stored in a look-up table. Subsequently, the look-up table is used to approximate the patient dependent necrosis. In our prototypical software assistant, the physician is able to place RF applicator models with corresponding approximated ablation zones, to interactively evaluate the estimated necrosis caused by ablation.

Keywords: Radiofrequency Ablation, Visualization, Image-guided Procedures

1 Purpose

Image-guided ablation therapies using thermal energy, particularly the radiofrequency ablation (RFA), have been developed as a minimal invasive alternative in contrast to the surgical resection of liver tumors[2]. Due to its common technical procedure, low complication rate and low cost, RFA has taken a significant part in the clinical routine. The principle of the RFA is the placement of RF applicator electrodes into the tumor. Subsequently, a high-frequency electric field is induced, which causes a local heating and leads to a coagulative necroses as a result of cell destruction. The choice of an appropriate applicator type and the exact placement of electrodes are essential to achieve complete destruction of cancer cells with respect to the heat-sink effect of vessels, located in the vicinity of the tumor[3]. Typically, the ablation zones are described as ellipsoids around the RF applicator[7], which are specified by the applicator manufacturers in homogenous tissue. During patient individual planning of the intervention, this description of the ablation zone is questionable, because blood vessels in the vicinity of the RF applicator can lead to a cooling effect and thus decrease the coagulation size[4]. To overcome this issue, numerical simulations have been developed to allow an accurate estimation of the ablation zone incorporating heat-sink effects[6]. Nonetheless, the major drawback of this method is the high amount of computation time for the calculation of the ablation zone. In our method, we present a fast approximation of the necrosis, to allow an interactive visualization of the final ablation zone, which has been precomputed with a numerical simulation.

2 Methods

The idea of our method is to precalculate the patient independent part of the numerical simulation and subsequently approximate the patient dependent part. For that, we calculate the cooling effect of blood vessels, depending on the vessel radius and its distance to the RF applicator electrode for a given RF applicator and generator type. Results of this calculation are stored in a look-up table, which allows for fast estimation of the cooling effect for a given patient dependent applicator placement.

For the simulation, we assume a simplified setting where a single blood vessel of infinite length and oriented parallel to the electrode of the RF applicator is considered. Furthermore, we assume that the cooling effect of the vessel depends on the radius of the vessel r_v and the distance d_e from the electrode to this vessel. The cooling effect is quantified by the length of the radius of the necrosis r_n, measured from the center of the electrode in all directions orthogonal to the electrode axis (see Fig. 1). Taking this setting into account, we define a function of the angle α between the direction under consideration and the direction in which the vessel center is located, the vessel radius r_v and the distance d_e from the electrode to the vessel: $(r_v, d_e, \alpha) \rightarrow r_n$

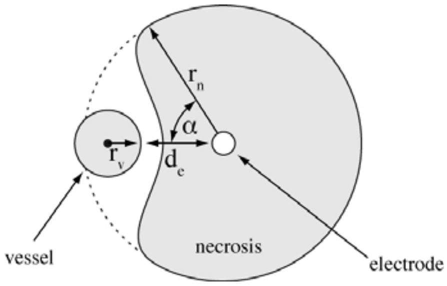


Fig. 1: Illustrative description of our simplified model; r_v is the vessel radius, r_n the radius of the necrosis, d_e the distance from electrode to vessel and α the angle between d_e and r_n.

For a complete vessel tree, we simplify our model by assuming an independent cooling effect. If multiple vessels are in the vicinity of the electrode, for each vessel a corresponding necrosis is estimated individually, and the intersection is calculated (see Fig. 2). This setting can be assumed as a clinically sufficient good approximation.

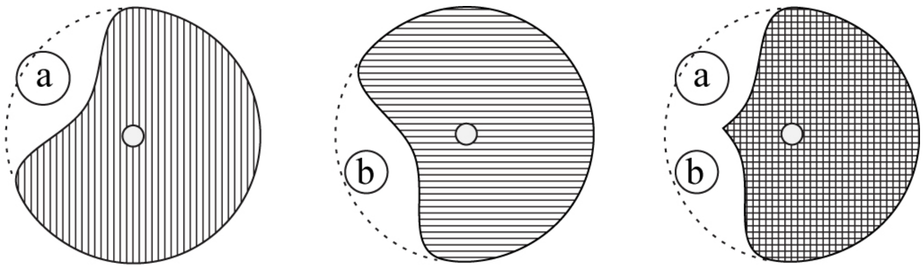


Fig. 2: In our approach we assume an independent cooling effect. If multiple vessels are in the vicinity of the electrode, for each vessel a corresponding necrosis is estimated individually, and the intersection is calculated.

To precalculate all possible configurations of our simplified model, a forward simulation is calculated as described in Kröger et al.[8], the well-known electrostatic potential and bio-heat equation (with Dirichlet boundary at the vessel) are numerically solved via a finite element approach. Since the precalculation requires a vast amount of calls of the forward simulation, the calculating time for this precalculation is reduced by using a simplified steady state solution of the forward simulation assuming constant material parameters. Moreover, due to the assumption of a parallel arrangement of the RF applicator relative to the vessel, the temperature is calculated in only two dimensions.

In our example, the considered values of the vessel radius r_v range from 1.0 to 7.4 mm (vessels with radius below 1 mm are assumed to occlude during the ablation). The applicator-to-vessel distance d_e varies from 2.0 to 14.8 mm distance (at distances above 14.8 mm the vessel influence of the ablation zone is negligible). And finally, the angle α takes values between 0° and 180° (angles between 180° and 360° are not considered due to reasons of symmetry). The resulting sparse look-up table consists of 526 nodes (i.e. entries for the radius r_n of the necrosis) in the (r_v, d_e) plane and 65 nodes in the α direction.

In our prototypical application, the physician is able to place multiple RF applicators using two spatial coordinates for each probe, which define the electrode's orientation and position. As a preprocessing step, blood vessels have to be segmented using a semiautomatic segmentation procedure[5]. After placing a marker into a vessel in the vicinity of the tumor, the vessels are segmented and analyzed automatically. During application run-time, the following steps are calculated for every voxel:

In a loop over all blood vessels with diameter larger than 2 mm (since smaller ones will usually be destroyed by blood clots[1]), the minimal distance d_e from vessel to applicator electrode and the corresponding angle α is calculated. Subsequently, a look-up into the table is performed with the vessel diameter, the distance from the vessel to the electrode and the angle. If the resulting radius of the necrosis in the considered direction is less than the minimal distance from the current voxel to the electrode, the voxel is classified as part of the ablation zone. Otherwise, the voxel cannot be ablated due to the presence of blood vessels. The complete procedure is repeated whenever the RF applicator configuration, e.g. position of the electrode, is changed. To allow for interactive frame rates, the approximation is calculated slice-based and the result is overlaid on top of the anatomical image.

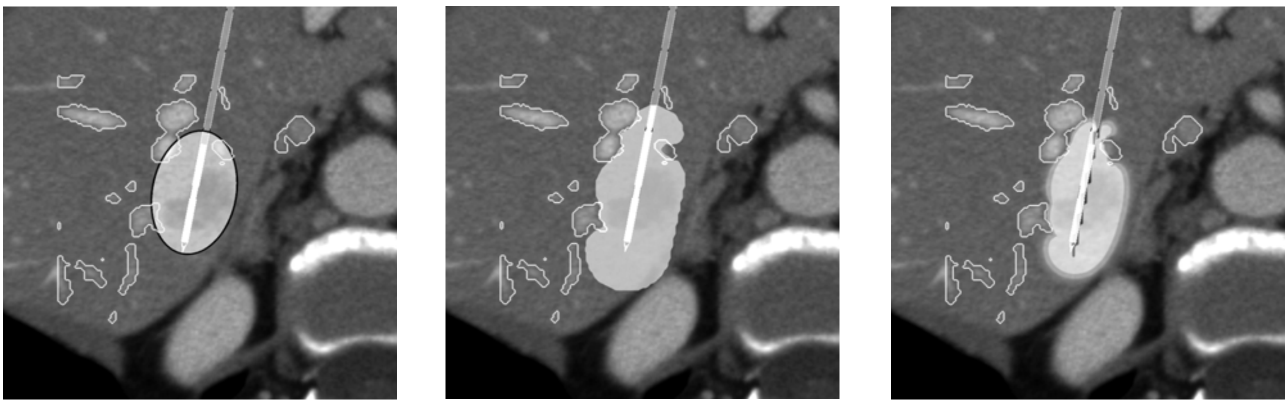
3 Results

We integrated the proposed method in a software assistant for planning of RFA therapies. In this software tool, the ellipsoid, the interactive approximation of the necrosis as well as the numerical simulation can be calculated for a selected type of RF applicator (see Fig. 3). Although the ellipsoid as specified by the manufacturers does not estimate the patient individual ablation zone, it is used in medical workstations as a simple and fast visualization tool in 2D as well as in 3D (see Fig. 4). However, if particular large vessels are present in the vicinity of the applicator, the question whether all cancer cells can be ablated is not as easy to answer. In contrast, using a numerical simulation, the cooling of the blood vessels can be taken into account. Thus, a patient individual ablation zone can be calculated. Moreover, the numerical simulation allows for the visualization of the thermal field. The drawback of this method is, that vessels have to be segmented and the calculation of the forward simulation is complex, which results in long computation times (10-15 minutes, see Table 1). Furthermore, a repositioning based on the result of the simulation and a subsequent re-simulation may be too time consuming for the clinical routine. To reduce this computational effort during application runtime, we developed the interactive necrosis approximation as described in Section 2. Therefore, vessels have also to be segmented, and for every applicator and generator type a corresponding look-up table has to be computed in advance. Using the look-up table we are able to perform a simplified necrosis approximation interactively.

	Performance 2D	Performance 3D	Heat-sink effect	Output
Ellipsoid	Real-time	Real-time	No	Necrosis
Interactive Approximation	Real-time	3 seconds	Yes	Necrosis
Numerical Simulation	10-15 minutes	10-15 minutes	Yes	Necrosis & Thermal field

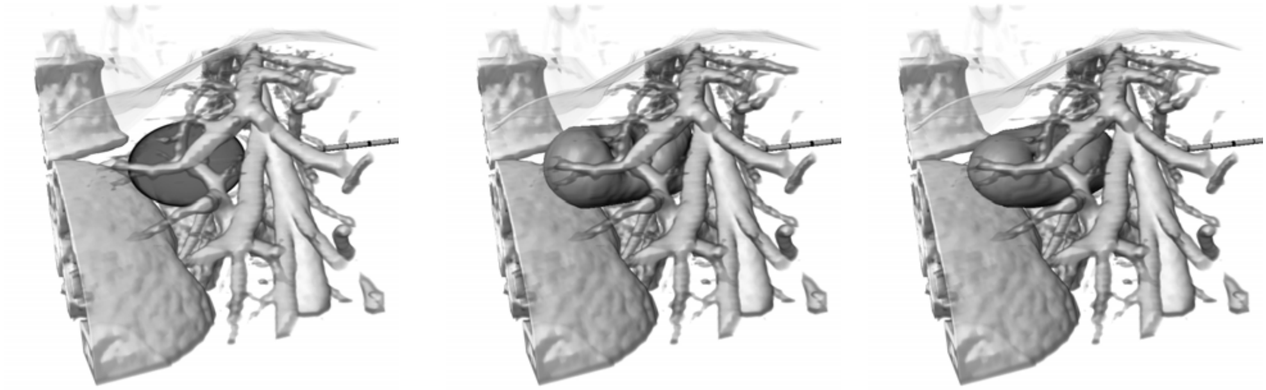
Table 1: Comparison of the three discussed methods.

In the current implementation, a relationship between the radius of a vessel, the distance of the electrode of an RF applicator to the vessel, and the cooling effect due to this vessel is established in the look-up table based approximation. However, additional parameters such as vessel type, tumor tissue or liver parenchyma properties are not taken into account. We will evaluate the dependence of these parameters in future work. Also, in our simplified 2D model, every point of the electrode is assumed to destroy a ball-shaped tissue-region of uniform size if no blood vessels are present. Thus, the basic shape of the necrosis in our approximation consists of the union of spheres along the points of the electrode (Compare Fig 3. (b) and (c)). We plan to extend the model from 2D to 3D in order to reach a more realistic (more ellipsoidal) shape such as the necrosis of the numerical simulation. Furthermore, preliminary results of our ongoing validation state that the assumption of the independent cooling effect is critical, particularly if vessels are close together.



(a) (b) (c)

Fig. 3: a) Ellipsoid visualization of the ablation zone in 2D, b) the interactive approximated ablation zone in 2D and c) the resulting heat distribution of the numerical simulation after 10 minutes calculation time in 2D.



(a) (b) (c)

Fig. 4: a) Corresponding visualization of the ablation zone in 3D, b) the interactive approximated ablation zone in 3D and c) the resulting heat distribution of the numerical simulation in 3D.

4 Conclusions

In this work we described an interactive approximation of the ablation zone, that incorporates the heat-sink effect of blood vessels, and assists physicians in preinterventional RFA planning. We integrated a vessel segmentation algorithm to support knowledge of local anatomy such as the vessel diameter. In contrast to an accurate but computational intensive numerical forward simulation, our simplified method allows for the interactive visualization of the expected ablation zone. Due to the intuitive positioning of RF applicators and the corresponding necrosis approximation incorporating the cooling of the blood vessels, the physician may be able to find an optimal placement configuration for a complete destruction of all tumor cells considering the patients individual anatomy.

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5 References

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