Virtual Radiofrequency Ablation of Liver Tumors

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Abstract. In the last few years, radiofrequency ablation has become one of the most promising techniques to treat liver tumors. But radiologists have to face the difficulty of planning their treatment while only relying on 2D slices. We present here a realistic radiofrequency ablation simulation tool, coupled with a 3D reconstruction and visualization project. They help radiologists to have a better visualization of patients anatomic structures and pathologies, and allow them to easily find an adequate treatment.

1 Introduction

Recent advancements in medical imaging have allowed to develop several kinds of minimally invasive techniques for the ablation of liver tumors that used to be considered as being non-resectable. Among them, percutaneous thermal ablation has been studied in different forms, such as microwave, laser, high intensity focused ultrasound, cryotherapy, and radiofrequency (RF) that appears to be the easiest, safest and most predictable [1].

Radiofrequency is a tumor denaturation method using heat created by ionic agitation generated by the principle of a microwave located at the tip of a needle-like probe. It leads to cell death and coagulative necrosis when enough heated. The probe may be positioned several times in order to treat a larger zone. Radiologists burn the whole tumor volume with a 1 cm security margin [2], which is mandatory to prevent local recurrence of a tumor after treatment, and to reduce the effects of a possible inaccuracy of needle placement.

The three important criteria for the success of such a treatment are the choice of secure trajectories for the probe, the destruction of a maximum number of cancerous cells, and a minimum amount of affected healthy tissues. Unfortunately, planning such a treatment according to these factors is quite difficult for a radiologist who can only rely on 2D scanner slices.

Scanner image reconstruction allows a more intuitive 3D visualization of the patient's anatomy [3], that makes the simulation of needle placement easier. The expected follows up of this functionality are both the visualization of the necrosis of treated zones, and the automatic planning of needle trajectories that would optimize the three criteria.

In this paper, after a summary of recent studies on lesion size and shape, and on treatment planning, we explain how we simulate the necrosis of the treated area. Then, we show how we plan to automatically compute optimal needle positions, and which future improvements this work will bring in RFA treatment.

2 State of the Art

2.1 Lesion Size and Shape

3D simulation of radiofrequency necrosis depends directly on recent studies on lesion size and shape. Indeed, to accurately simulate lesions, it is necessary to know all the factors that have an influence on them. Literature shows that several kinds of factors are important to predict how lesions will look like [4].

- *Device-dependent factors*:
  The shape of the necrosis zone depends on the type of probe used for the treatment. Different kinds of probes are used in radiofrequency ablation. Expandable multi-array needles, which are insulated needles containing hook-shaped inner electrodes that can be deployed once the target is reached, produce a more or less spherical lesion. Other types, single or clustered cooled needles, produce an ellipsoidal lesion shape. A comparative study of these systems can be found in [5].
  Technological advancements in needle design tend to increase lesion size. Needle design (electrode's diameter and tip length) also modifies lesion size and shape. Moreover, the different kinds of provided generators use various ablation algorithms [1]. According to the power they can supply, the lesion size may be greater. It is possible to control lesion size and shape by changing intensity and duration of the supplied current.
- *strategy-dependent factors:*
  Since larger lesions may avoid multiple needle insertions, different strategies have been studied to increase lesion size. Radiofrequency lesions can be enlarged by a temporary occlusion of the tumor blood supply, because blood flow in large vessels has a "heat-sink" effect that cools the thermal process [6]. Infusion of a saline solution into the target tissue via a cannulated radiofrequency probe also amplifies the ablative volume [7].
- *anatomic factors:*
  As we said previously, blood flow in large vessels causes thermal process cooling. If the needle tip is placed close to large vessels, they will not be affected by the treatment, and the lesion shape will be deformed, and model itself to the shape of the vessels. As for smaller vessels ($\varnothing < 2$ to 3 mm), they seem to be obstructed by clots after radiofrequency treatment, and have no consequence on lesion shape or size [5].
- *pathologic factors:*
  Some studies showed that in the case of cirrhotic livers, the shape of the

thermal lesion was more extended and almost modelled to the tumor shape, whereas less surrounding cirrhotic tissue was burnt. Livraghi et al. attribute this difference to a phenomenon called "oven effect" [8].

All these factors, directly influencing size and shape of the necrosis zone, obviously have to be taken into account for an accurate RFA simulation. Indeed, a computer-aided treatment planning has to offer a maximal guarantee of success and safety for the patient, for a better survival rate.

2.2 Treatment Simulation and Planning

Previous studies on treatment simulation and planning have already been carried out, but they were mainly focused on other minimally invasive treatments such as cryotherapy [9, 10], or they were centered on finite element modelling [11], but very few works have been done on radiofrequency real-time 3D simulation and treatment planning.

Cryotherapy is with RF, one of the most often used systems to treat liver tumors. So far, it has been more widely studied in computer science than radiofrequency, and some teams carried out softwares able to simulate iceball growth. Most are based on finite element methods and compute the propagation of freezing inside tissues [9], others approximate lesions by ellipsoids [10].

Both also tried to initiate a treatment planning for cryotherapy [10, 12], but with some limitations. For instance, T. Butz proposed a very interesting cryotherapy simulator and planner, included in *3D-Slicer*, that can also be extended to one type of radiofrequency probe. However, it can only compute the best positioning of cryoprobes within a predefined window of the body, and doesn't take into account the presence of surrounding organs. In [11], a finite element model for radiofrequency is presented, based on the resolution of bioheat equation, but it doesn't seem to be real-time.

3 Radiofrequency Ablation Simulation

The researches we carried out, and that we will detail here, were justified by the fact that many radiologists expressed a need of information about their patients that would be easier to visualize, and of having the ability to simulate accurately and realistically the radiofrequency treatment before operating.

We present here a tool, called *RF-Sim*, that links 3D reconstruction and visualization of slices, and a virtual RF probe placement simulator. The whole project allows to easily visualize the patient's anatomy in 3D and to localize his tumors, and has several useful functionalities such as security margin display, volume calculation, and inner navigation. *RF-Sim* adds the ability to append RF probes in the scene, and to place them by taking into account security margins, and surrounding organs and factors.

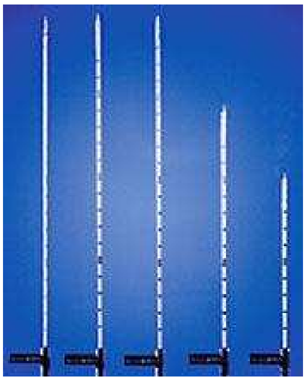

Fig. 1. Berchtold® electrodes

Fig. 2. Expandable needle

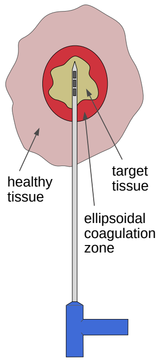

Fig. 3. Ellipsoidal lesion zone

3.1 Chosen Framework

First of all, we perform the 3D reconstruction of a patient's liver and tumors from an enhanced spiral CT scan using an automated algorithm described in [3]. All the experiments that were made with this simulator were based on real patients' data that came from Strasbourg's Civil Hospital, and that were performed within a preoperative framework.

For this simulator, aimed at being first tested in this hospital, we chose to represent the electrode model that is mainly used by our radiologists, that is the Berchtold® HITT system (see Fig.1). This kind of needle produces a quite ellipsoidal lesion zone around the tip, as shown on Fig.3. Therefore, we first chose to represent the necrosis zone by a meshed ellipsoid (see Fig.4). However, we could easily extend our simulator to other types of needles, like expandable (see Fig.2) or clustered systems, by simply changing the appearance of the needle and the general shape of the lesion.

Fig. 4. Virtual needle electrode and its associated ellipsoidal lesion around tip

3.2 Enhancement of Realism

Once the basic shape of the lesion zone had been chosen, we tried to make it even more realistic by taking into account surrounding factors. One of the most important of them is the proximity of large vessels, that cools the surrounding tissue zone, and avoids a complete burning of the ellipsoidal zone if the blood flow is not occluded. When done close to a large vessel, a RF treatment causes a deformed necrosis zone. However, we also have to consider that, on the contrary, small vessels don't affect the treatment and are completely burnt.

Deformation of the Ellipsoid: We consider that the heat produced by the electrode and propagating within the tissue is coming from the tip and is directed towards the boundary of the ellipsoid, following the heat flow. We approximate the "heat-sink" phenomenon by saying that if the heat flow comes near a vessel, it is stopped. That way, we can represent the necrosis zone by a quite simple deformation of the ellipsoid, following the shape of the vessel.

Technically talking, for each vertex of the theoric ellipsoid, we test if it is inside the deformation zone. If so, we replace it by the vertex placed on the same vector and that is as far as possible from the center of the ellipsoid, while being outside the deformation zone. Intuitively, we "repulse" the vertex away from the vessel, but keep it on the same radius of the ellipsoid (see Fig.5).

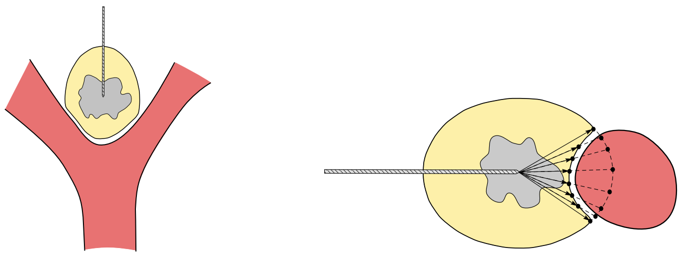

Fig. 5. Deformed shape of the necrosis zone close to large vessels

Computing Deformation Zone from Vessels: As we said earlier, large vessels cool their surrounding area and remain unchanged after the treatment, whereas small vessels are considered as being burnt. To reproduce this effect, we have to compute a deformation zone that includes large vessels but excludes the smallest ones. We chose to use the voxel version of the whole vessel network in order to perform an opening on it. An opening is a composition of one or more erosions and of the same number of dilations [13].

We have to perform a sufficient number of erosions on voxel shape to make small vessels disappear, only thinning large ones. The number of erosions is determined by the size of small vessels to eliminate ($\varnothing$ < 2 to 3 mm) and the resolution of the voxel mask. The average resolution of the masks we currently use is $0.6 \times 0.6 \times 0.6$ mm, so we perform 2 erosions in order to eliminate vessels having a radius < 1.2 mm, *i.e.* a diameter < 2.4 mm. Performing 3 erosions would eliminate too many vessels ($\varnothing < 3.6$) and performing only 1 erosion would miss out on some vessels ($1.2 < \varnothing < 2.4$). Then, the same number of dilations bring large vessels to their initial thickness.

In a second step, we perform some more dilations, in order to increase thickness of large vessels. Indeed, the "heat-sink" effect also cools the area surrounding the vessel, so the zone has to be extended to include this area. We obtain a deformation zone that incorporates large vessels and their neighborhood, and that excludes small vessels. An example for a portal vein is shown on Fig.6, where the voxels are represented by their center point.

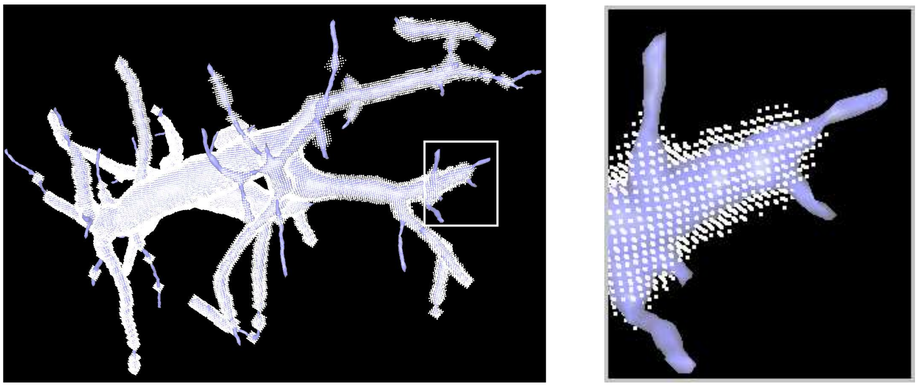

Fig. 6. Voxel deformation zone of a portal vein

4 Results and Perspectives

We present on Fig.7 the results of 2 deformations of a virtual necrosis zone based on the voxel deformation shape. In these snapshots, we can easily see the deformations induced by large vessels. For each one of them, we present 2 views: in the second one, veins are not drawn in order to see the deformation more easily. The manipulation of the needles and of their associated scalable lesion zone is a real-time operation.

Finally, we present on Fig.8 a snapshot of a typical *RF-Sim* scene, showing the simulation of a RF treatment. Several electrodes are placed on tumors, some of them produce overlapping lesions to treat a large tumor. To have a better visualization, skin and liver are drawn in a transparent mode, and lesion zones in a semi-transparent mode.

This example is taken from a set of 18 real study cases on which we made our experiments so far. These patient data were taken from the Strasbourg Civil Hospital radiology service's database, among patients that were candidate for a RF treatment. All these experiments will soon be subjected to post-treatment medical validation by experts.

These experiments consisted, for each case, in opening the set of reconstructed organs and tumors of a patient, and then trying to place manually as many needles as necessary to cover all tumors plus margin volumes, while also trying to minimize healthy tissue burning, and to avoid inserting needles through vital organs. In other words, it consisted in thinking about a placement plan for each case, trying to apply it by placing virtual needles, checking if the predicted locations were appropriate by comparing margin and lesion shapes and volumes, and if necessary correcting the plan until a satisfactory treatment was found.

The experiments clearly showed that when a tumor is located too close to vessels, it is often impossible to find a needle configuration that would totally burn the additional margin volume, because the cooling process interferes. The direct manipulation of the needles and the real-time deformation of the lesion shape significantly improved the visualization of this phenomenon, and seem to be helpful in the prediction of treatment efficiency.

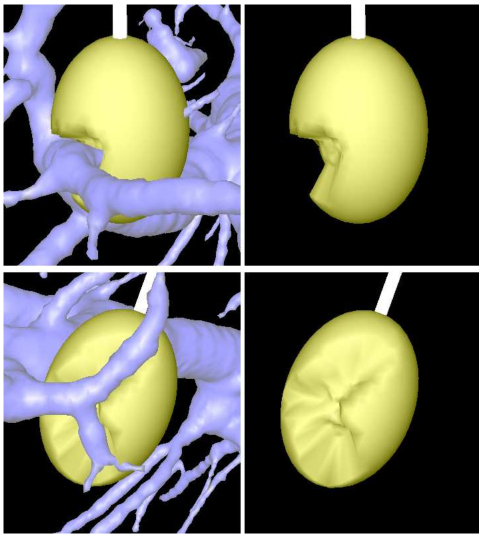

Fig. 7. Deformed virtual necrosis zones

The direct extension of this work is obviously RF treatment planning. Let us explain here what will be the main points of this study, and how they will be carried out.

First, we have to define what is an optimal treatment plan. It has to fulfill the 3 criteria of an efficient treatment: burn all the cancerous cells, burn a minimum of healthy tissue, and be safe. But it also has to take into account accessibility (bones), and treatment simplicity (minimum number of needle insertions) in order to be more comfortable for the patient and easier for the radiologist.

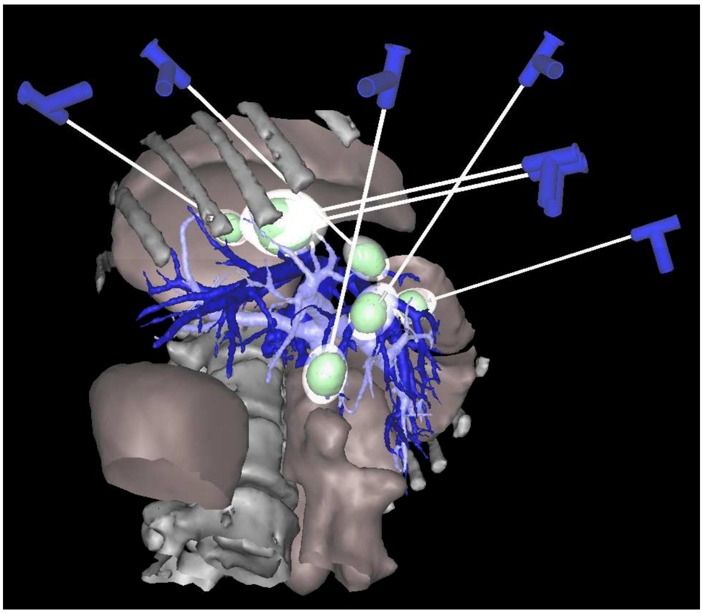

Fig. 8. Snapshot of *RF-Sim*

We plan to compute electrode placements in 3 phases:

- definition of a range of possible paths for needle placements, in order to eliminate unaccessible or unsafe directions,
- computation of a set of accurate overlapping ellipsoid configurations, that produce compound lesions allowing to burn cancerous tissues efficiently,
- choice of the best configuration among those previously computed, minimizing the burning of healthy tissue, and maximizing the simplicity criteria.

The first phase is mainly a collision detection operation, defining a set of 3D shapes inside of which needles can manoeuvre to reach their goals. The second phase is probably an extension of the work of T. Butz [10], that allowed to compute the best overlapping ellipsoid configuration to cover the tumor plus margin shape, the needle being inserted within a predefined window. For us, the window will be extended to the previously computed 3D shapes of possible directions. Then, the third step is a heuristics-based selection of the best solution among many according to several fixed constraints.

5 Conclusion

The simulator *RF-Sim* we presented here represents a first step to a complete treatment planning and simulation tool that will assist radiologists in their work. It allows to see easily the patient's anatomy in 3D, to append virtual RF probes and their associated lesion zone, that are realistically rendered according to surrounding parameters. With the adjunction of the planning tool, radiologists will be able not only to simulate the treatment they plan to perform, but also to ask the computer for advice. This study on RF ablation simulation may lead in the future to considerable improvements in the treatment of cancers.

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