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Coverage planning in computer-assisted ablation based on Genetic Algorithm

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ABSTRACT

An ablation planning system plays a pivotal role in tumor ablation procedures, as it provides a dry run to guide the surgeons in a complicated anatomical environment. Over-ablation, over-perforation or under-ablation may result in complications during the treatments. An optimal solution is desired to have complete tumor coverage with minimal invasiveness, including minimal number of ablations and minimal number of perforation trajectories. As the planning of tumor ablation is a multi-objective problem, it is challenging to obtain optimal covering solutions based on clinician's experiences. Meanwhile, it is effective for computer-assisted systems to decide a set of optimal plans. This paper proposes a novel approach of integrating a computational optimization algorithm into the ablation planning system. The proposed ablation planning system is designed based on the following objectives: to achieve complete tumor coverage and to minimize the number of ablations, number of needle trajectories and over-ablation to the healthy tissue. These objectives are taken into account using a Genetic Algorithm, which is capable of generating feasible solutions within a constrained search space. The candidate ablation plans can be encoded in generations of chromosomes, which subsequently evolve based on a fitness function. In this paper, an exponential weight-criterion fitness function has been designed by incorporating constraint parameters that were reflective of the different objectives. According to the test results, the proposed planner is able to generate the set of optimal solutions for tumor ablation problem, thereby fulfilling the aforementioned multiple objectives.

1. Introduction

Nowadays the trend of surgeries and interventions is shifting towards being minimally invasive and further being non-invasive. Such surgeries lessen the complications because more precise and sophisticated instruments are now employed to perform the surgeries [1–4]. The increase in performance accuracy and lesser invasiveness of these surgeries therefore extend its potential benefits to a wider population of patients, especially for the groups who are unable to undergo open surgeries [5–13]. Minimally invasive surgeries also result in a shorter surgical duration, which translate into lesser physical trauma and lower financial costs for the patients [14,15].

As one type of minimally invasive interventional procedures, tumor ablation is the removal of tumor tissue using techniques like cryoablation [16,17], high-intensity focused ultrasound (HIFU) [5,18], or radio-frequency (RFA) [5,6,8,10,19]. These techniques rely on minimally invasive principles to ablate tumor tissues, without having to directly expose the affected regions to the environment. Therefore, it has been widely noted that the success of a tumor ablation procedure hinges greatly on its pre-operative planning [5,6,14,18,20]. The proposed ablation planning system in this paper focuses mainly on the radio-frequency ablation (RFA) of hepatic tumors.

Based on pre-operative medical scans, computer-assisted ablation planning systems are used to generate optimal surgical plans. Software modules like IGSTK [15], 3D Slicer [21] are currently used by surgeons and biomedical engineers to assist in the visualization of anatomical structures, registration and navigation of real-time images. By developing optimal treatment plans in these toolkits, it enables surgeons to visualize the 3-D tumor regions as well as the envisioned ablations. It makes feasible for surgeons to exploit and assess the treatments along operations. Heuristical Optimization is an effective approach to obtain acceptable solutions in multi-objective problems. In this paper, the tumor coverage, the number of ablations, the number of trajectories of needles are considered as objectives to optimize [22]. Genetic Algorithm, as a classic heuristic algorithm, is then employed in the optimization.

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The rest of this paper is organized as follows. In Section 2, the paper reviews prior studies of ablation planning systems. In Sections 3 and 4, the paper proposes and highlights the relevance of using a Genetic Algorithm (GA) in an ablation planning system, respectively. Section 5 describes how the tumor ablation is planned in GA. Section 6 describes the experiments performed on tumors. Section 7 concludes the paper.

2. Related work

2.1. Radiofrequency ablation (RFA)

There exist several minimally invasive techniques to perform tumor ablation procedures. Unlike cyroablation that freezes the tumor tissues to extremely low temperatures, radiofrequency ablation (RFA) heats up, denatures and coagulates the tumor cells, therefore destroying its cancerous function [17]. RFA is a thermal ablation procedure that inserts a needle-like electrode into the skin towards the tumor, which passes alternating high-frequency current to its tip [5,6,19,14,23]. The high-frequency current then heats up and ablates the tumor tissues. RFA technique has been favored because of its safety, effectiveness and predictability of results [5,6,8,14,23].

Depending on the tumor location and the tumor size, RFA electrodes of different tips can be employed, either having tines that expand out in an umbrella shape, or using a simple needle tip (as shown in Fig. 1). However, the choice of electrodes and effectiveness of tumor ablation surgeries are also limited by the aforementioned tumor characteristics. Research has shown that a single ablation application is sufficient in the complete destruction of tumors smaller than 2 cm in diameter, and for tumors that reside near the peripheral of the organ [14,23,17,19]. Large and deeply localized tumors require multiple ablation applications, which incur more healthy tissue damage and increase the risks of incomplete tumor destruction [8]. Multiple ablation applications of the tumor tissues may also result in decreased opacity of the tumor due to necrosis, therefore compromising the accuracy of a RFA therapy [19].

To overcome the unnecessary risks that the tumor characteristics may pose during the ablation, treatment planning is crucial to get optimal pathways of how the RFA electrode is inserted and to achieve complete tumor coverage. As such, computer-assisted interventions are significant in pre-operative phase of tumor ablations. In this planning phase, optimization algorithms can be used to generate optimized needle trajectories and ablation center-points. It should be noted that every surgical plan should be customized to the patient. Hence, while the ablation planning system can provide optimized candidate solutions based on pre-operative data sets, the surgeon ultimately makes the final decision to adopt the solution for his patients.

2.2. Intraoperative tracking and targeting

RFA typically relies on image guidance to manually place the radiofrequency needle within the tumor, such as ultrasound for guiding liver tumor ablation [24], and CT for guiding lung tumor ablation. However, ultrasound imaging can be problematic for monitoring the ablation region due to hyperechogenicity [17] and imaging artifacts [25], especially in the presence of a metallic RFA probe. In comparison, CT offers better imaging quality but increases the radiation exposure to the patient and potentially the operator. To avoid radiation, one solution is to employ a tracking system to obtain the relative position between ablation probe and target, by landmark registration to a pre-operative CT image [15]. This approach assumes that the target organ deformation is acceptable for treatment purposes by using preoperative images for intra-operative treatment.

The deformation of tissue and tumor is an important topic for improving the accuracy of image-guided procedures and there is a large body of research studies on tissue motion estimation. This paper is focusing on the ablation planning approach and the motion estimation is beyond the scope of this paper. The proposed techniques could be used clinically if care is taken with patient positioning.

2.3. Ablation planning

This section reviews the ablation planning systems and approaches that have been investigated in the past decade. From these studies, common goals of an ablation planning system have been identified to form the objectives of the proposed ablation planning system.

In [5,6,14,23], the authors have developed a comprehensive planning tool called RF-Sim, which can automatically reconstruct 3D livers based on spiral CT scans. The tumor region was represented by a set of voxels (i.e cubes), where voxels with a direct connection from the skin to the tumor were considered as candidate entry points for needle insertion. The algorithm of RF-Sim was largely based on a volume criterion. It first assumed a spherical shape of the lesion produced by the electrode, and a fixed needle trajectory [6,23]. It then used the Downhill Simplex to return a few optimized trajectories that minimize healthy tissue damage. The method was found to be useful for small tumors; but for larger tumors, an initialization phase had to be incorporated to overcome the drawback of Downhill Simplex, thereby minimizing the healthy tissue damage. In [19], the author have proposed a software application for RFA therapy. The software was able to reconstruct

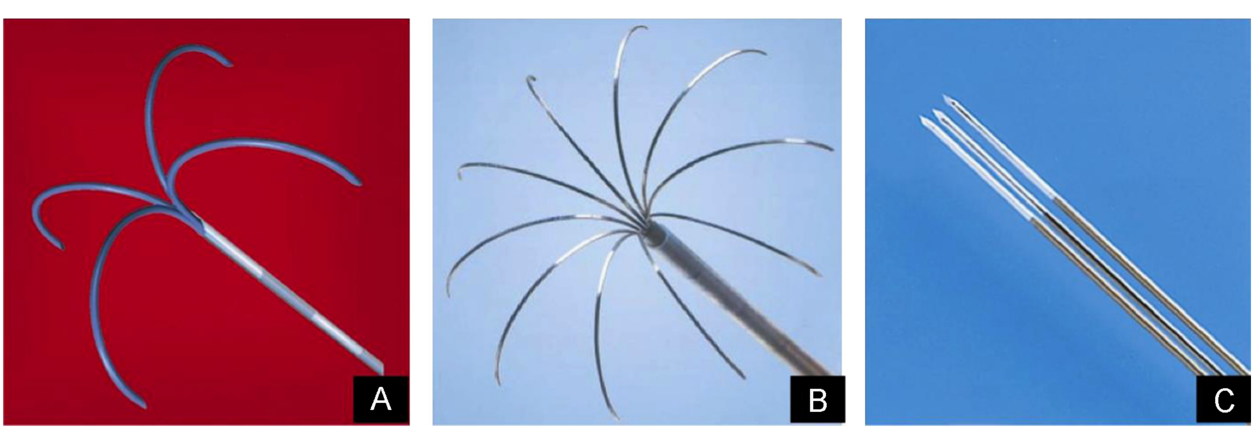

Fig. 1. 15-gauge needle electrode with four retractable prongs (Rita Medical Systems) (A); 14-gauge needle electrode with ten retractable prongs (Radiotherapeutics) (B); 17-gauge needle electrode in a three-needle cluster (Radionics) (C).