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An Algorithm for Planning the Number and the Pose of the Iceballs in Cryoablation

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***Abstract*— We present an algorithm that computes the number and the pose (position and orientation) of iceballs in a cryoablation procedure, in order to completely cover the target region, i.e. the tumor. Constraints to needle insertion, such as regions that have to be avoided, are taken into account and satisfied.**

We developed a tool for cryosurgery planning in MATLAB and perform several simulations to extract information on the algorithm behavior and to verify that it always brings to a complete coverage.

I. INTRODUCTION

Cryoablation [1] is a technique for removing cancerous tissue by killing it with extreme cold temperature. Modern cryosurgery is frequently performed as a minimally-invasive procedure, with the application of hollow hypodermic needles (*cryoprobes*), strategically located in the area to be destroyed [2]. In this paper we focus on cryosurgery tasks related to the treatment of small ($\leq 4\ cm$) kidney tumors.

The cryoprobes layout is a key factor for the success of the cryoablation procedure. Currently, the process of selecting the correct placement of the cryoprobes is an art held by the surgeon, based on his/her experience and rules of thumb.

Few works have been done to develop computerized planning tools that automatically select the correct location for cryoprobes insertion. In [3] Lung et al. developed an optimization technique, called the *force-field analogy*, in which heat transfer simulations are executed to move the cryoprobes into an optimum layout. Then, in [4] Tanaka et al. implemented the force-field analogy together with a technique called *bubble packing* [5]. These works do not take into account the obstacles that have to be avoided while inserting the needle, e.g. ribs or organs, or specific constraints on the insertion procedure. Furthermore, the number of iceball to be used is chosen a priori by the surgeon.

The algorithm proposed in this paper automatically computes the number and the location of cryoprobes required to completely freeze the tumor, while minimizing the damage to the surrounding healthy tissue and satisfying all the possible constraints to needle insertion. The development of an automatic planning algorithm is critical to automate the whole cryoablation procedure, direction in which few preliminary work have already been done [6], [7].

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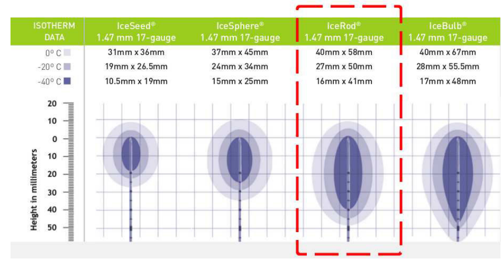


Fig. 1. Iceball shape and size related to different cryoprobes types [8]

II. PROBLEM STATEMENT

The cryoprobe generates an ellipsoidal iceball which is associated to a specific isotherm and the iceballs size depends on the kind of probe used (Fig. 1). Without loss of generality, in this paper we refer to the IceRod type. However, the algorithm can be easily applied to other kind of cryoprobes.

We considered the iceball as an ellipsoid of size 27x50 mm, corresponding to the isotherm of -20 °C (Fig. 1) for IceRod needles. However, this choice is for demonstration purposes only; the planning algorithm presented in this paper is independent of the value of the isotherm.

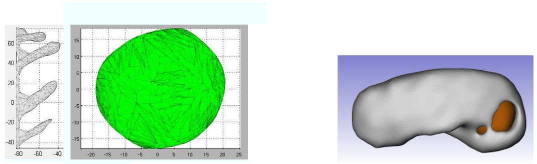
The essential task for a planning tool is to identify the number and the best locations for the cryoprobes to generate iceballs that completely freeze the target region, i.e. the tumor, while minimizing cryoinjury external to the target region. Furthermore, needle insertion is subjected to several constraints:

- *Forbidden regions.* Areas that the needle has to avoid (i.e. ribs and organs).
- *Tumor inserting area.* Surface of the tumor where needles can be inserted (healthy tissue of the kidney should not be damaged).
- *Maximum angle between needles.* Relative angle between needles should range from 0 to 20 degrees. However, the value for the maximum angle allowed can be chosen by the surgeon.
- *Insertion grid.* Needles can be inserted only through an adhesive grid applied on the skin.
- *Needle collision.* Needles must not collide each other.

III. PLANNING ALGORITHM FOR MULTIPROBE CRYOSURGERY

The planning algorithm computes the number and the location of needles necessary to entirely cover the tumor, while minimizing the damage to the healthy tissue and satisfying all the possible constraints to needle insertion.

The algorithm requires the points defining the surface of the tumor and the eventual constraints. These points are



(a) Points defining the ribs and the tumor surface

(b) CAD model of the phantom (kidney with tumor)

Fig. 2. Input data for the planning algorithm

extracted from the MRI image of the kidney with the tumor and its CAD model (that can be easily obtained from the MRI data). Figure 2(a) shows the ribs and the tumor points extracted from the CAD model (Fig. 2(b)) of a phantom of the kidney with a tumor. The system is completely configurable and every kind of obstacle can be taken into account, e.g. the Inferior Vena Cava or the suprarenal glands. Indeed, it is sufficient to provide to the algorithm the points defining the surface of the obstacle extracted from the MRI image, as for the kidney and the tumor.

The algorithm goes through the following steps (Fig. 3).

A. Computation of the Initial Number of Iceballs

At the beginning, the algorithm uses an iterative procedure based on the tumor volume and dimension and its relation with the iceballs volume and obtains an approximation of the minimum number of iceballs necessary to cover the tumor.

The initial positions of the centers of the iceballs are equally spaced along a circumference inscribed in the perimeter of the longitudinal section of the tumor.

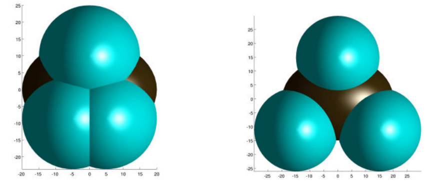
B. Bubble Packing

The initial configuration of the iceballs could present iceballs overlapping, as in Fig. 3(a), or an excessive distance among iceballs. In this situation the next steps of the algorithm would be too time consuming.

To avoid this problem, Bubble Packing [2], [5] has been applied (Fig. 3(b)). It is a physically–based approach that efficiently finds an even distribution of an arbitrary number of points inside a given geometric domain. The method first generates spherical elements, called *bubbles*, inside the domain, then defines van der Waals–like forces between bubbles. With this proximity-based force, two adjacent bubbles attract each other when they are too far apart, and repel each other when too close. Since in this phase only bubbles translation is performed, Bubble Packing can be extended to ellipsoidal bubbles, i.e. the iceballs generated by the cryoprobes, instead of spherical bubbles. Further details on Bubble Packing can be found in [2], [5].

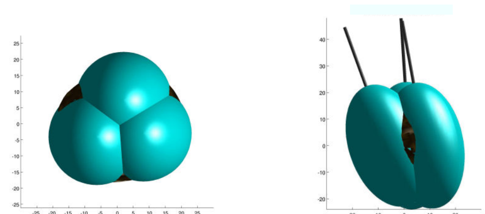
C. Force–Field Analogy

The third phase of the planning algorithm consists of a modified version of Force–Field Analogy suggested in [3]. This phase aims at finding the optimal position of the iceballs in order to completely cover the tumor, considering only iceballs translation. It is required not to damage healthy tissues over 10 mm out of the tumor contour.



(a) Initial configuration

(b) Bubble Packing



(c) Force-Field Analogy

(d) Orientation Optimization

Fig. 3. Steps of the planning algorithm. Iceballs (blue) and tumor (brown).

At the beginning, tumor, iceballs and the surrounding region are discretized into a set of points, named *defective points*. Each point applies an attractive or repulsive force on the iceballs to take them into an optimal configuration.

The points that apply a **repulsive force** are classified into the following types.

- *External defects* (T_E). Points located outside the tumor but inside the iceballs representing surrounding healthy tissues that would be wrongly cryoinjured.
- *Contour defects* (T_C). Points located into a shell 10 millimetres thick from the tumor contour and inside the iceballs representing the limit for healthy tissue damage.

Both the external and the contour defects apply a repulsive force on the center of the iceball in order to move the cryoprobes from the external region towards the center of the tumor.

- *Superposition defects* (I_I). Points located inside the intersection area between bubbles representing iceballs superposition. These defects apply a repulsive force in order to prevent gathering too many cryoprobes at the same locations.

The points that apply an **attractive force** are clustered into the following categories.

- *Internal defects* (T_I). Points located inside the tumor but outside the iceballs representing regions in the tumor that would not be cryoinjured.
- *Surface defects* (T_S). Points located on the surface of the tumor that are not covered by the iceballs.

Both the internal and the surface defects apply an attractive force on the iceball in order to attract the cryoprobes towards the areas that are not covered.

The defective points are used to directly drive the cryoprobes location. In fact, the iceball translation is performed proportionally to the total force applied to a cryoprobe, computed as

$$F_{TOT} = \sum_{i \in \mathcal{P}} W_i d_i^2 \quad (1)$$

where $\mathcal{P} = \{T_E, T_C, I_I, T_I, T_S\}$ is the set of defective points types, d_i is the distance between the center of mass of the defective points of type i related to a given iceball and the center of the iceball and W_i is an experimentally determined weight for defects of type i. For defects that apply an attractive force, the weight is positive, while for defects applying repulsive forces it is negative.

Since the total force is proportional to the distance d_i, the displacement of an iceball far away from the tumor is greater than the displacement of an iceball closer to the tumor. The iceball translation is performed only if the movement allows to reduce the value of the following objective function.

$$f = \left| \sum_{i \in \mathcal{P}} N_i W_i \right| \tag{2}$$

where N_i is the number of defects of type i.

The Force-Field phase stops when further iceballs movements would increase the value of the objective function (2). Because of the simple way the initial number of iceballs is computed, it may happen that at the end of this phase the tumor is not completely covered (i.e. $N_{T_I} > 0$ or $N_{T_S} > 0$). The resulting iceball configuration (Fig. 3(c)) represents the best solution considering only iceball translation.

At this point, the algorithm determines if it would be worth pursuing the Orientation Optimization by analysing the amount of uncovered surface. If not, the algorithm adds a further bubble and goes back to Phase I.

If the tumor is completely covered, the algorithm goes through the initial part of the Orientation Optimization, where the constraints satisfaction is verified. If all the constraints are satisfied, then the algorithm ends. Otherwise, the algorithm continues by changing the orientation of the iceballs for satisfying the constraints.

D. Orientation Optimization

The goal of this phase is to complete the tumor coverage, while satisfying the constraints to needle insertion described in Sec.II. The needle is computed as the straight line passing through the center of the iceball and the tip. The length and the diameter of the needle are given by the specifics of the cryoprobe.

The initial collisions between needles or between a needle and an obstacle are solved rotating the needle(s). Each step executed to solve a constraint is performed to reach the configuration with minimal differences compared with the one previously obtained. To this aim, the involved needle is rotated step-by-step towards sequence of points generated on the minimal distance line from the intersection point.

If the output of the Force-Field Analogy is to puncture a forbidden area on the kidney or on the tumor, the needle is rotated until a non-forbidden region is reached. In this phase, the defects are no longer considered as single points but as even regions.

If the iceballs configuration satisfies the constraints, the algorithm searches the defective regions which have not been covered in the previous phase.Then, the algorithm computes the center of mass for each defective region and its distance from each iceball's center. This distance is used to establish which iceball has to be rotated and the rotation direction. The rotation is performed towards the center of mass just computed, on the straight line connecting the iceball top and the center of mass. While the iceball is rotating, the algorithm constantly checks the constraints and introduces alternative solutions if one of them is wrong. Once the constraints have been satisfied, the tumor coverage is verified: if the covered part of the tumor is smaller than in the previous iteration, the last rotation is removed.

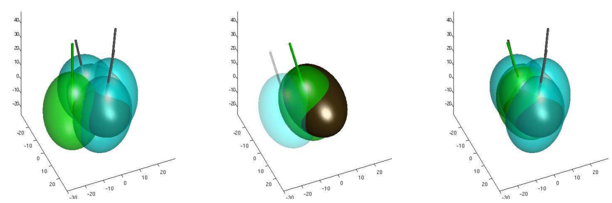
The Orientation Optimization stops when the tumor is completely covered or when there are no more convenient solutions (Fig. 3(d)).

E. Adding Iceball

The Orientation Optimization phase provides a possible solution considering the given iceball number and the imposed constraints. If the constraints are too restrictive or the tumor has a particular conformation hard to deal with, it is possible that at the end of the previous phase some parts of the tumor are not covered, as in Fig. 3(d).

Since the total tumor coverage is mandatory, an additional iceball is required. The location of the further iceball depends on the number and position of the uncovered regions.

If there is only one uncovered tumor region, the new iceball is inserted with the center coincident with the center of mass of the defective area. The iceball is then rotated and translated towards the center of the tumor, in order to minimize the damage to the outer healthy tissues (Fig. 4). The translation continues until a part of tumor becomes uncovered again or any constraint is broken.



(a) The iceball is inserted into the center of mass

(b) The iceball is rotated and translated

(c) Iceball final position

Fig. 4. Optimization of the position of the new iceball

If the defective regions at the end of Orientation Optimization are more than one, it is hard to find a position for the added iceball which would not violate the imposed constraints. However, the algorithm tries to find a solution to achieve the final goal. The new iceball is inserted in correspondence of the center of mass of all the defective regions and rotated towards the nearest defective area, always checking the constraints satisfaction.

If the additional iceball cannot complete the tumor coverage with the technique here reported, or if some constraint is not satisfied, the algorithm goes back to Phase I, and run again including the further iceball.

The final result of the planning algorithm is an output file containing, for each needle, the inserting pose (position and orientation) on the skin and the target pose on the tumor.

A video clip showing a complete running of the algorithm can be found at http://www.arscontrol.unimore.it/embc2013.

IV. SIMULATION RESULTS

A tool for cryosurgery planning has been developed in MATLAB, based on the planning algorithm described in this paper. We performed 182 simulations of the algorithm, considering different sizes of the tumor, on a 1.66 GHz Intel Core-Duo processor running Ubuntu 10.04.

The tumor is approximated as an ellipsoid with maximum semi-axes dimensions of [20 15 15] mm. Then, the tumor dimensions are chosen by the algorithm randomly varying the length of the x and y semi-axes satisfying this constraint. In order to validate the robustness of the algorithm in every condition, even the initial positions of the iceballs are set to be randomly chosen into the tumor domain.

The weights in (1) are chosen as follows.

Defect Type	Weight W_i
External defects	-200
Contour defects	-15
Superposition defects	-10
Internal defects	+30
Surface defects	+20

As requested by the task, all the simulations ended with the freezing region that completely covers the tumor.

The mean time for running a simulation was 104.4 seconds. However, if we do not consider the simulations where it is requested to add a further iceball besides the initial number, i.e. the last step of the algorithm, the mean simulation time decreased to 66.6 seconds. An additional iceball was required in 39 of the 182 simulations.

The simulations highlight that the number of iceballs necessary to completely cover the tumor depends both on the tumor volume and on the ratio between the semi-axes. Tumors with similar volume could require a different number of iceballs, e.g. in case of narrow and elongated tumors.

To evaluate the results obtained in the simulations, we considered two indices:

- *volumes ratio*, defined as:

$$V = \frac{V_T}{V_F} \leq 1 \tag{3}$$

  where V_T is the volume of the tumor, while V_F is the total volume of the whole freezing region.

The volumes ratio compares the volume of the tumor with the volume of the freezing region, computed as the union of the iceballs at the end of each simulation. Values of this index near to 1 mean that the whole freezing region is used to cover the tumor.

- *iceballs overlapping ratio*, defined as:

$$I = \frac{V_F}{nV_I} \leq 1 \tag{4}$$

  n is the number of iceballs and V_I is the volume of a single iceball.

The iceballs overlapping ratio compares the real freezing region with the freezing region that would occur if iceballs do not cross each other. An iceball overlapping ratio $I = 1$ mean that the iceballs never cross each other, while values near to 0 mean that the iceballs are overlapping too much.

These indices give information about the iceballs exploitation. The mean value for the volumes ratios is 0.305, while the variance is 0.0036, meaning that the volumes ratios do not move away from the mean value. The resulting volumes ratio is not very high, revealing that a lot of the freezing volume goes out of the tumor contour. However, this result allows to guarantee the uniform destruction of all viable tumor cells. In fact, clinical results [1] show that to ensure adequate treatment in clinical use, the freezing region should extend 1 cm beyond the tumor margin. The mean value for the iceball overlapping ratios is 0.844, and the variance is 0.13. This result shows that the superimposition of the iceballs is not very high.

V. CONCLUSIONS

In this paper we presented an algorithm that automatically computes the number and the position of iceballs in a cryoablation procedure to create a freezing region that completely cover the tumor, while satisfying all the constraints to needle insertion. Even if the algorithm does not find the global optimum, it always heuristically provides a possible configuration that reaches the goal and satisfy all the constraints.

Future work aims at improve the way the number of iceballs are initially chosen, in order to avoid the need for a further iceball. As shown in the simulation results, in this way we could decrease the simulation time. Furthermore we are studying an extension of the algorithm that could bring to the optimal solution.

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