

2013 2nd AASRI Conference on Computational Intelligence and Bioinformatics

Planning and Simulation of Percutaneous Cryoablation

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Abstract

New technological methods to assist percutaneous cryoablation procedures are here presented, namely a planning software and a simulation algorithm. The first has the role to calculate a feasible displacement of the tools to ensure an effective ablation of the lesion, satisfying well-specified procedural constraints. Starting from intra-operative CT scans of the patient, a virtual model of the anatomical site is obtained and uploaded. The displacement of the cryoprobes is computed in order to cover the whole volume of the tumour with the developed iceball, but minimizing the damage to surrounding healthy renal tissue. On the other hand, the simulation algorithm is a graphical tool useful to assess the temperature distribution throughout the evolution of the procedure. A discrete iterative function calculates the heat transfer from the probes to the surrounding tissue within a specified three-dimensional grid: the isolation of significant isotherms can help to assess whether the whole tumour will be frozen or not. By using a real intra-operative dataset of a successful percutaneous cryoablation, the volume of the real iceball has been matched with that generated from the simulator, showing a good accuracy in terms of dimension and shape. Even though been designed to be integrated within a robotic system, this method is usable and extensible for different purposes and adapted to simulate other scenarios or procedures.

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Peer-review under responsibility of Scientific Committee of American Applied Science Research Institute

Keywords: cryoablation; planning; simulation; iceball.

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1. Introduction

This work has been developed within I-SUR, a FP7 EU-funded research project which aims at developing new technologies and methods to assess the feasibility of the introduction of automation principles in surgical robotics; one of the chosen case studies is the percutaneous cryoablation of kidney tumours, which requires imaging devices (CT, MR or US) to precisely place one or more cryoprobes directly through the skin into the lesion. The cryoablation involves cycles of freezing and thaw in order to kill the tumoral cells while preserving the healthy tissue and the surrounding anatomical structures (liver, bowel, spleen, ureters) according to Clarke et al, 2007 [1]. This technique represents a valuable alternative to the open surgery or laparoscopy, ensuring safety with a low morbidity and high efficacy on oncological results, as reported by Mues and Landman, 2009 [2]. The main requirement for the correct execution of this procedure is the accuracy in the needle displacement: during the planning phase, the optimal target points for the cryoprobes must take into account both dimension/location of the lesion and the temperature distribution of the generated iceball (irreversible tissue destruction occurs from -20 °C to -40°C).

The presented methods aim at assisting the operator – i.e. surgeon or interventional radiologist – in the decision making relative to the surgical process. Being the insertion automatic (by the robot, as addressed by this project) or manual, the planning of needle insertion is a crucial key point of this procedure, directly conditioning the final outcome. The planning software proposed in this work represents a useful tool for the purpose, especially when the lesion is hard to reach (e.g. under the ribs) or close to other anatomical structures. Moreover, a further advantage here presented is the availability of a 3D simulator to assess the evolution of iceball formation and the coverage of the lesion at the end of the process, therefore to validate the planned displacement of the cryoprobes even before the insertion and beginning of the ablation cycle.

In Chapter 2 a brief description of the method used to build the 3D model of patient's anatomy and iceball is reported. In Chapters 3 and 4, respectively, the operative principles of both planning software and the simulator are shown.

Nomenclature

CT	Computer Tomography
MR	Magnetic Resonance
US	Ultrasound
CAD	Computer Aided Design
PDE	Partial Differential Equation

2. Building Patient's Model

Anonymized series of CT scans from a patient going through kidney tumor cryoablation were retrieved from the San Raffaele Turro (Milan) database to reconstruct part of the patient's abdomen for evaluating the iceball growth algorithm. The segmentation of the abdomen covered the right kidney and the surrounding structures and organs (i.e. part of liver, ribs, intestine and back-bone). Fat, muscles and skin were segmented as homogeneous layer. The models of the organs were segmented from the first series where one of the cryoablation needles was already inserted into the kidney tumor. This scan was chosen for good visibility of the tumor and for matching the CT scan series with the later phase CT scan series by the using the first needle position as a reference. The reconstruction of the organs was done by using open source software 3D Slicer [3]. The CT scan with the visible first needle was first cropped down (see Fig. 1) for faster segmentation process. The segmentation of the organs was done semi-automatically by using simple region growing segmentation algorithm and later repairing the results manually. The segmented layers were then assembled into 3D models by using Model Maker module in 3D Slicer.

The segmentation of the iceball was done from a CT scan series with 4 visible needles with similar technique described before. Because of the movements of the patient throughout the procedure, the CT scans were misaligned. The scans were manually aligned (by changing the image origin of the 4-needle scan) according to the first inserted needle's tip and to the edges of the kidney. The model of the iceball aligned to other models can be seen (with blue color) in Fig. 2. Finally, two point coordinates of each needle were collected from the CT scan to reconstruct the same situation in the iceball growth simulation (see image above right lower corner for the visible needle points), as reported in Chapter 4.

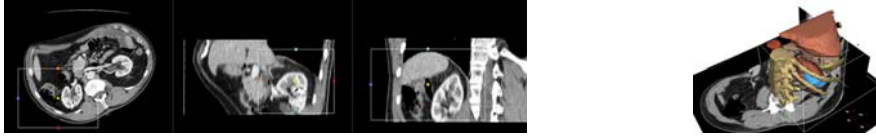


Fig. 1. Cropped volume of the CT scan

Fig. 2. Models of liver, intestine, aorta, backbone and kidney with iceball from the CT data

3. Planning of Cryoprobes Displacement

The planning algorithm, based on the approach described in Torricelli et al., 2013 [4], computes the number and the best locations for the cryoprobes to generate an iceball that completely freezes the target region, i.e. the tumour, while minimizing injury to the healthy tissue external to the target region. Several constraints have to be satisfied while performing the insertion of each needle: forbidden regions have to be avoided (i.e. ribs and organs), the specific inserting areas, the maximum relative angle between needles, collisions avoidance between needles. The operation principles are reported in the Fig. 3.

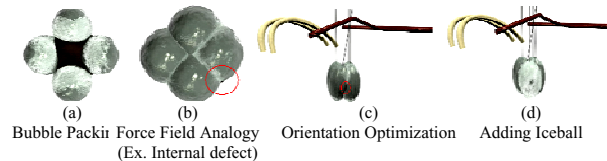


Fig. 3. Operational steps of the Planning Software

First of all, according to tumor and iceball volumes, an approximated minimum number of iceballs is calculated and displaced on a circumference inscribed within the longitudinal section of the target. Then Bubble Packing method (Rossi et al., 2008 [5]) is applied to solve problems such as overlapping or excessive distance among iceballs: spherical elements ("bubbles") are generated inside the domain and van der Waals-like forces (proximity-based, inter-bubble) between them are defined. In this way, two adjacent bubbles attract each other when too far apart and repel each other when too close. The objective of the Bubble Packing phase is to evenly distribute the cryoprobes, in order to shorten the optimization process in the following phases of planning.

A modified version of the Force-Field algorithm proposed by Lung et al., 2004 [6] is then implemented. The goal of this phase is to cover the tumour just by translating the iceballs. For safety reasons, the iceball must not extend over 10 mm out of the tumor contour to minimize the healthy tissue damaged. At the beginning, the anatomical site is discretized into a set of points – named "defective points" – close together: each of them applies on the iceballs an attractive or repulsive force in order to lead them into an optimal configuration. These points are used to directly drive the cryoprobes location and can be of different types:

- External defects – Points outside the tumor but inside the iceballs belonging to healthy tissues included in the ablation..
- Contour defects – Points located within a 10 millimeters thick shell from the tumor contour and inside the iceballs representing the limit for healthy tissue damage.
- Superposition defects –Points located in the intersection area between two or more bubbles representing iceballs superposition.

- Internal defects – Points located into the tumor but outside the iceballs, representing areas in the target excluded by the ablation but to be necessarily included.
- Surface defects – Points belonging to the surface of the tumor but not yet covered by the iceballs..

External, contour and superposition defects apply a repulsive force on the center of the iceball in order to translate the cryoprobes towards the center of the tumour, while internal and surface defects apply an attractive force in order to attract the cryoprobes to the internal defective region. Since the initial iceball number is a minimum, probably the tumor at the end of Force-Field is not completely covered. Anyway, the Force-Field simulation stops when all the iceballs movements would increase the value of an objective function defined assigning a weight to each defective typology. In this sense, the resulting iceballs configuration represents the optimal solution considering only iceballs translation, but the planning objective has not been reached, since defective areas can still be present. At this point, the algorithm determines if it would be worth pursuing the orientation optimization by analyzing the amount of uncovered surface. If not, the algorithm adds another bubble and goes back to Phase 1.

Next step is Orientation Optimization, targeted to complete the tumor coverage rotating the iceballs coming from the Force- Field Analogy and satisfy the constraints to needle insertion by moving the iceballs to solve the collisions while maintaining an optimal configuration. The needle shape is considered as a straight line passing through the iceball center and the tip. The probe parameters (length and diameter) are taken from manufacturer's datasheet. Depending on the nearest defective region, one iceball is rotated towards the center of mass of that area. During iceball rotation, constraints are constantly checked and alternative solutions are introduced just in case some of them are not respected. This step ends as soon as the whole volume of the target is covered or any other effective options can be implemented.

If constraints are high demanding or target characteristics prevent an efficient coverage with the current configuration, some parts of the tumour may be not covered. In such case, an additional iceball is strategically added according to number and position of the areas still to be included in the ablation volume. The new bubble is placed in correspondence of the center of mass of all the defective regions and rotated towards the nearest one. The previously defined constraints are checked again. Even with the additional iceball, if the tumor coverage is not completed or some constraints not satisfied, the planning algorithm starts again from the first phase, but adding the further iceball.

4. Simulation of Iceball Growth

The model has been made starting from the thermal energy balance for perfused tissue, expressed in the following form

$$\rho C \frac{\partial T}{\partial t} = k \nabla^2 T + h_m + h_b \quad (1)$$

where ρ , C and k are thermal parameters of tissue, h_b is the rate of heat transfer per unit volume of tissue and h_m is the rate of metabolic heat production per unit volume of tissue. The equation has been simplified through simple assumptions coherent to cryoablation procedure: during the freezing phase, capillary blood perfusion rate and metabolic heat generation quickly drop to zero, as reported by Shitzer, 2011 [3], thus terms III and IV in Equation (1) have been ignored.

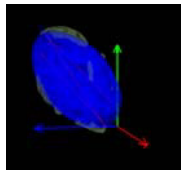


Fig. 4. Superimposition of simulated iceball (blue) on real CT data (green). Cryoprobes are visible inside (red)

In order to easily solve the heat transfer PDE, a finite-difference method has been chosen for approximating the spatial derivatives, i.e. a first order forward difference for the first term and a second order central difference for the second one. The continuous function then turned into discrete within a 3D grid with a sub millimeter resolution. Body temperature has been chosen as initial condition, while the temperature profile of the external surface of each probe has been set as boundary condition. To validate this approach, it has been chosen to match the 3D model reconstructed from intra-operative imaging (as reported in Chapter 2) with the simulation of iceball growth taking as initial positions the cryoprobes displacement obtained from the same CT dataset, discretized and adapted in the computation grid. Even though the -40° isotherm is the one interesting for planning purposes, the validation protocol has taken into account just the 0° line because its compatibility with CT data. The models are comparable in terms of dimension and shape, as can be seen in Fig. 4.

5. Future Work

A new methodology to assist and simulate cryosurgical therapies have been presented in this paper. Even if designed to be integrated within an autonomous robotic system, the methods are portable and extensible for different purposes. For instance, a surgeon can take advantage of the planning software to extrapolate a feasible disposition of the tools even for a standard manual insertion; furthermore, for a given configuration of the cryoprobes, the mathematic algorithm can calculate the temperature distribution in the surgical site with a good accuracy, giving a preliminary preview of the surgical outcome. Being modular and parameterized, such model can be adapted to simulate other scenarios (liver, lung, heart, prostate) or procedures (laser or radio frequency ablations).

More activities to improve these methods will be done in next period. For instance, the simulation algorithm can be improved adding further parameters, taking into account thermal dynamics and interactions simplified so far. Of course, planning software and simulator will be integrated in the same tool in order to allow the operator to calculate the probes displacement and assess the therapy outcome without the need of intermediate passages.

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