Precise Determination of Regions of Interest for Hepatic RFA Planning

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ABSTRACT

Percutaneous radiofrequency ablation is one of the most promising alternatives to open surgery for the treatment of liver cancer. This operation is a minimally invasive procedure that consists in inserting a needle in targeted tissues that are destroyed by heat. The success of such an operation mainly depends on the accuracy of the needle insertion, making it possible to destroy the whole tumor, while avoiding damages on other organs and minimizing risks of a local recurrence. We are developing a software that applies planning rules on patient-specific 3D reconstructions, in order to suggest relevant options for the choice of a path to the tumor, and that displays various information allowing to adjust the final choice. In this context we propose a method to compute automatically, quickly, and accurately, the possible insertion areas on the skin. Within these areas, an insertion of the probe targeting the tumor respects the numerous strong (boolean) constraints required for a radiofrequency ablation. Besides, these insertion zones define the research domain of the optimization process, taking into account soft constraints to refine the solutions. They are also displayed on the skin of the virtual patient to inform the physician about the different possibilities specific to each case, allowing him at the end of the automatic process, to modify interactively the proposed strategy, with a real-time update of the related information. We discuss in this paper about the importance of a precise delineation of these areas.

Keywords: minimally invasive surgery, preoperative planning

1. INTRODUCTION

Even if open surgery remains the main curative treatment for liver cancer, liver resection is a painful operation that is not always possible due to the patient's condition, multiple tumor location or insufficient hepatic reserve. During the last years, several minimal invasive procedures have been developed in order to treat patients that are not good candidates for surgery. Among them, we can mention radiofrequency ablation, cryoablation, ethanol injection or focused ultrasound. We are specifically interested in percutaneous radiofrequency ablation (RFA) that is increasingly used since it demonstrates good results, minimizing local recurrence and complications[6] .

Percutaneous RF ablation consists in inserting through the patient's skin a RF-needle that heats tissues until destruction. The radiologist places his needle in the tumor in order to kill cancerous cells and a surrounding 1cm safe margin. Because of the limited visibility during this kind of operation[3] (needle placement is generally guided by CT or US imaging), preoperative planning takes an important place in the success of the therapy. The physician has to choose a needle path that allows a safe access to the tumor and a secure ablation relying on 2D-slices of the patient obtained by CT-scan. Planning from 2D slices is not really intuitive and requires a long learning process[9] . As advances in medical image processing allow to rapidly reconstruct a virtual 3D model of the patient from CT-scan slices[12] , we are developing a planning software based on the visualization of such 3D-reconstructed patients that would assist the physician's decision. Our work is organized in 3 axis:

- Integration of constraints and rules governing RFA planning: strategies may vary from a specialist to another however we have extracted recurrent information from them and from medical literature[8, 10] to define constraints included in the software.
- Resolution of the geometric problem corresponding to the previously specified constraints.
- Display facilities to browse the solution space: the physician may need to have access to various information concerning the different possible strategies.

We focus here on the second axis that is divided in two parts: firstly the determination of all solutions and secondly the choice of the optimal solution. In this paper, we detail the method we developped for a fast computation of all needle trajectories that are technically feasible for each operation. The determination of an optimal trajectory among them is presented in[13] . Firstly, we briefly expose the approach that has been chosen to eliminate bad solutions in other studies concerning planning of minimal invasive interventions. Then, we explain on which criteria we define a needle trajectory as being valid and we detail our method that computes with precision possible insertion zone on the skin, guaranteeing a safe access to the tumor. Finally we present and comment our results on several virtual patients.

2. PREVIOUS WORKS

Various works have been recently published on computer assisted planning of different minimally invasive techniques, aiming at guiding the physician's decision. The problem of optimizing surgical tool placement has being addressed in a few studies. Optimizations have been performed regarding different criteria according to the therapy. In the case of thermal ablation (radiofrequency ablation[2, 5] or cryoablation[4, 7]), the different studies focus on minimizing damages to healthy tissues while killing the whole tumor. Concerning robotically assisted heart intervention, the important criteria mainly concern distance between tools and angle between tools and patient[1, 11] . In both cases, some trajectories could be dismissed out of hand for different reasons independent of the optimization criteria. For example the tools cannot cross bones in any case, the tools must be long enough to reach the surgical site or in case of the insertion of an endoscope, the surgical site must belong to the field of vision. These cases have to be taken into account otherwise there is no guarantee that the proposed optimized solution will be valid. In most of the studies this problem is avoided by the physician's intervention. The optimization is restricted within a limited number of solutions or an authorized access window that are provided by the surgeon and considered as valid. In one study[1] , the set of insertion points proposed by the physician is controlled and insertion points that correspond to an intersection with an organ are eliminated.

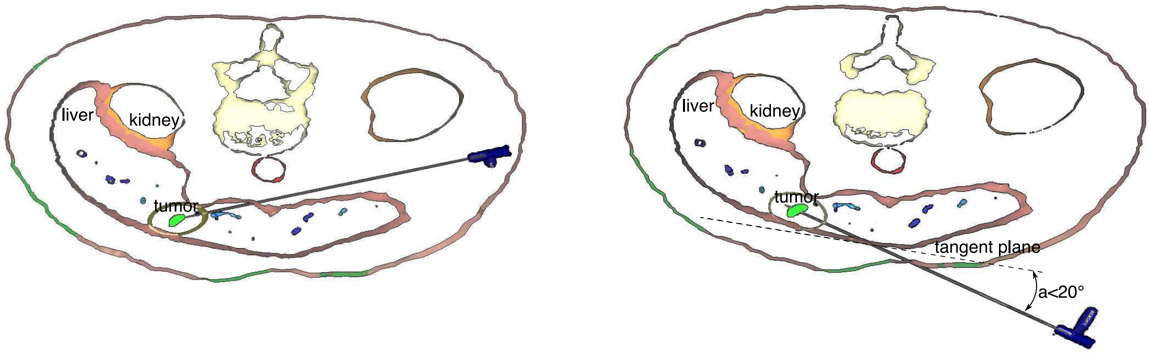
While most of studies propose an exhaustive examination of a limited number of possibilities selected by the physician, our approach consists in taking into account any possibility and proposing solutions without intervention of the physician. In a previous article[14] we presented a first approach that consisted in integrating the elimination of trajectories crossing vital organs in the optimization process. The optimization function was artificially modified by adding a huge penalty to these trajectories that were naturally avoided by the optimization process. However this method introduced artificial local minima in the optimization function, therefore we developed an other approach consisting in computing an authorized insertion zone before the optimization step.

3. OBJECTIVE

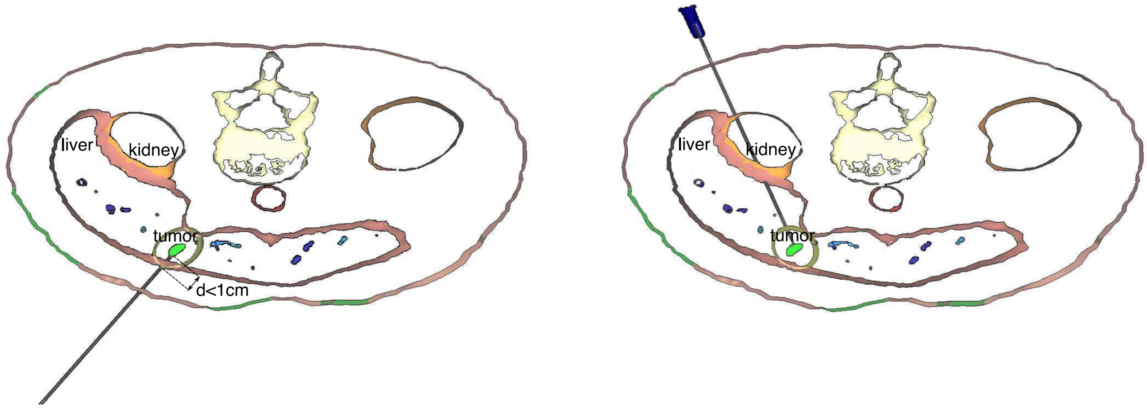
This study aims at designing and implementing a method that automatically computes possible trajectories for each operation. We must then define what we consider as a possible trajectory. A trajectory can be regarded as a possible choice if it satisfies all the required conditions for an operation. At this time, several constraints governing RFA planning have been identified thanks to bibliography and interviews with specialists. Among these constraints, some are strict constraints that define the validity of a trajectory, others are soft constraints that have to be optimized and combined with an appropriate weighting. In this paper, we focus on the processing of stricts constraints, that are directly involved in the determination of the feasible trajectories, as soft constraints only provide information on their quality.

Among these strict constraints, we selected four of them, either because they were the most obvious ones, or because they were the most often cited by the radiologists.

1. the insertion depth has to be below the needle size
2. tangency (less than $20°$) between the needle and the liver's capsule has to be avoided, in order to be sure not to slip on the surface
3. a portion (at least 1 cm) of healthy liver has to be included in the trajectory, for cauterization
4. a valid trajectory cannot cross neither bones, large vessels nor surrounding vital organs



(a) needle length constraint (b) tangency constraint



(c) safe portion of liver constraint (d) occlusion constraint

Figure 1. Slices in transverse plane representing, for each constraint, a case where the considered trajectory is not satisfying

Fig. 1 illustrates the four constraints by showing for each one of them a counter-example that does not fulfill the constraint.

Of course, our method could easily be adapted to additional strict constraints. For example, the physician could consider that a trajectory approaching a vital organ with less than 1 cm is not a possibility.

In order to precisely define the *possible trajectories*, we chose to determine what are the *possible insertion points* on the skin. The possible insertion points are materialized by a simple zone on the skin's mesh that can be easily visualized (see example on Fig.2). To each possible trajectory corresponds one single insertion point: if this point belongs to the *possible insertion zone* then the trajectory is valid. Conversely, to each insertion point corresponds a whole set of trajectories, and among them a few are *pertinent*: a trajectory is considered as pertinent if the target point belongs the tumor. Then an insertion point is accepted in the possible insertion zone if all the corresponding pertinent trajectories verify the constraints. On Fig.2, trajectory 1 corresponds to a valid insertion point but is not pertinent, trajectory 2 corresponds to a non valid insertion point, and trajectory 3 corresponds to a valid insertion point and a pertinent trajectory so it is the only possible trajectory among the 3. Our objective is to compute accurately the *possible insertion zone*, i.e. the set of all possible insertion points on the skin.

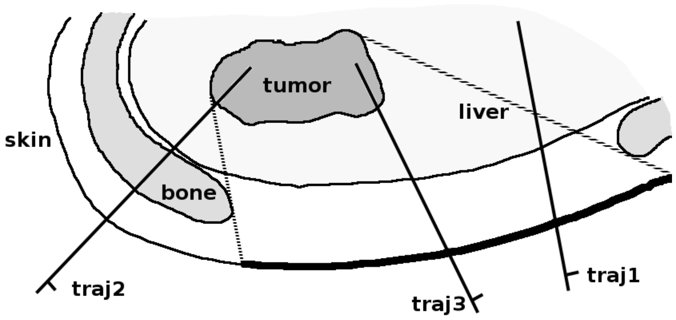


Figure 2. Example of considered trajectories, #1 is not pertinent, #2 is not valid, and #3 is pertinent and valid. Possible insertion zone is in bold

4. METHOD

We want then to determine precisely all the points of the skin that correspond to valid trajectories. A needle trajectory is considered as a valid solution if it verifies all of the 4 above mentioned constraints. The initial possible trajectories are materialized by the surface mesh of the patient's skin. Triangles are progressively eliminated as the corresponding trajectories are declared not satisfactory regarding the previously specified conditions. The 4 algorithms corresponding to the 4 constraints can be summarized in:

```
Input :
$S\ =\ list\,of\ skin's\,triangles,$
$L\ =\ list\,of\ livers'\!s\,triangles,$
$C\ =\ center\ of\ the\ tumor's\ bounding\ box,$
$O\ =\ set\ of\ organs\ to\ avoid$

$//\ Constraint\ 1 : elimination\ of\ insertion\ points\ that\ are\ too\ far\ from\ the\ tumor$
For $each\ triangle\ s\ in\ S$
    If $distAboveNeedleLength(C,\ s)$
        $eraseFrom(S,\ s)$
    Else if $distPartlyAboveNeedleLength(C,\ s)$
        $eraseFrom(S,\ s)\ and\ subdivideAndAddTail(S,\ s)$

$//\ Constraint\ 2 : construction\ of\ a\ new\ obstacle\ with\ liver's\ triangles\ that\ would\ cause\ tangency$
For $each\ voxel\ v\ in\ tumor's\ border$
    For $each\ triangle\ l\ in\ L$
        If $angleIsNotAcceptable(v,\ l)$
            $addInObstacles(l, O)$
        Else if $angleIsPartlyNotAcceptable(v,\ l)$
            $eraseFrom(L,\ l)\ and\ subdivideAndAddTail(L,\ l)$

$//\ Constraint\ 3 : construction\ of\ a\ new\ obstacle\ with\ liver's\ triangles\ that\ are\ too\ close\ to\ the\ tumor$
For $each\ voxel\ v\ in\ tumor's\ border$
    For $each\ triangle\ l\ in\ L$
        If $isTooCloseToTumor(l,\ v)$
            $addInObstacles(l, O)$
        Else if $isPartlyTooCloseToTumor(l,\ v)$
            $eraseFrom(L,\ l)\ and\ subdivideAndAddTail(L,\ l)$
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$// \, Constraint\ 4 : elimination\ of\ insertion\ points\ that\ don't\ provide\ an\ access\ to\ the\ tumor$
For $each\ voxel\ v\ in\ tumor's\ border$
    $r = renderScene(v, O)$
    For $each\ triangle\ s\ in\ S$
        If $hiddenFrom(r, s)$
            $eraseFrom(S,\ s)$
        Else if $partlyHiddenFrom(r, s)$
            $eraseFrom(S,\ s)\ and\ subdivideAndAddTail(S,\ s)$

Output : $S\ =\ list\ of\ eligible\ triangles\ of\ the\ skin$
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All the algorithms follows this principle: a triangle that does not respect the constraint is definitely eliminated (function $eraseFrom$). A triangle that partly fulfills a constraint is subdivided in four subtriangles that replace it in the list (function $subdivideAndAddTail$), and will be evaluated separately. Other triangles are kept in the temporary list of triangles of the possible insertion zone.

For constraints #2 and 3 that are directly linked to the liver's surface, there is a preliminary step. It consists in constructing an artificial obstacle composed of the portions of the liver to avoid. These portions are computed and added to the list of obstacles to avoid for constraint #4, and then the whole set of obstacles is processed by Algorithm #4. Function $angleIsNotAcceptable$ returns true if the angle between the considered needle trajectory (from current liver triangle to current voxel in the loops) and the normal at the current liver's triangle is higher than 70° (or if the angle with the tangent is lower than 20°). Function $isTooCloseToTumor$ returns true if the distance between the current insertion point on the liver and the current voxel is lower than 1 cm.

Finally the definitive zone of candidate insertion positions only contains triangles that satisfy all the constraints. Other constraints could be added easily to this algorithm, assuming that it is possible to determine quickly if a needle insertion in a triangle fulfills the constraint in all cases, in some cases or in no case.

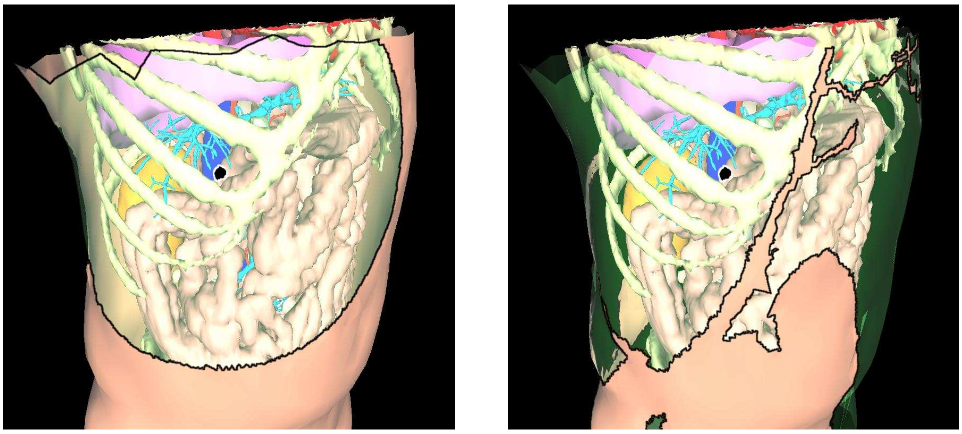
Concerning our first constraint, the validity of an insertion triangle is determined by computing the distance between the center of the tumor's bounding box and the three corners of the triangle. The determination of the validity according to the other constraints requires a more complete verification. We chose to check the constraint not only for trajectories targeting the tumor's center but for an access to the whole tumor. It is important for these constraints that a light displacement from the trajectory does not compromise the validity of the trajectory. The tests are then executed while targeting each voxel of the tumor's border. Our accessibility problem can be considered as a visibility problem. If a triangle is completely visible from the target point that means that no obstacle is on the way between any point of the triangle and the target. From a position, the visibility (partial visibility, total visibility or invisibility) of all candidate triangles can be determined by observing six renderings of the scene, each corresponding to a face of a virtual cube placed around the target position. More details can be found in[13] where we presented a first version of our computation of insertion zones.

On Fig.3, we show the resulting candidate zone if each constraint is used independently (3(a) to 3(d)). The result of the whole process taking into account all the 4 constraints is shown on Fig.(3(e)). It corresponds to the intersection of the 4 previous zones.

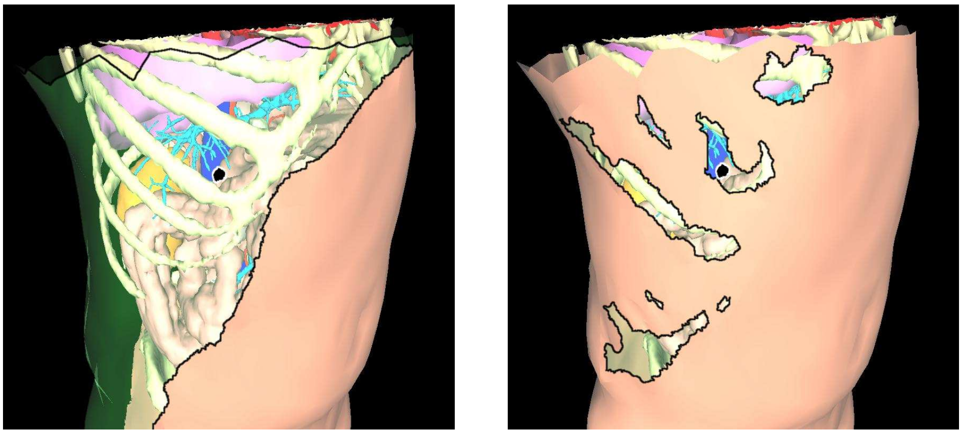
The subdivision of border triangles results in the loss of neighbourhood information. However, in our context this kind of information is not necessary as we use the mesh of the insertion zone only to test if trajectories cross it. The subdivision of the triangles allows to compute precisely the insertion zone independently of the precision of the initial mesh of the skin. The maximum authorized subdivision level determines the precision of the borders of the insertion zone. Above this maximum subdivision level or below a significant size limit, triangles that do not completely fulfill a constraint are dismissed without subdivision. A reduced number of subdivisions enables to compute the insertion zone with a satisfying precision. We will detail our results in the next section.

5. RESULTS

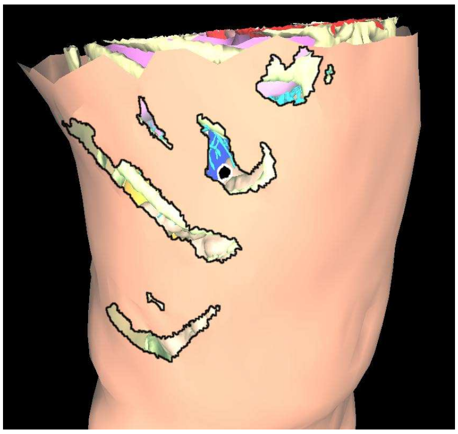
Insertion zones have been computed for 18 tumors in 7 virtually reconstructed patients (represented in tab.1). The surfaces of zones are variable (10-250 cm^2) since tumors are more or less accessible. Although computing zones without triangles



(a) needle length constraint (b) tangency constraint



(c) safe portion of liver constraint (d) occlusion constraint



(e) merged constraints

Figure 3. Examples of resulting zones for each separate constraint, and for merged constraints. Tumor is in black encircled by white, and liver is transparent for readability reasons

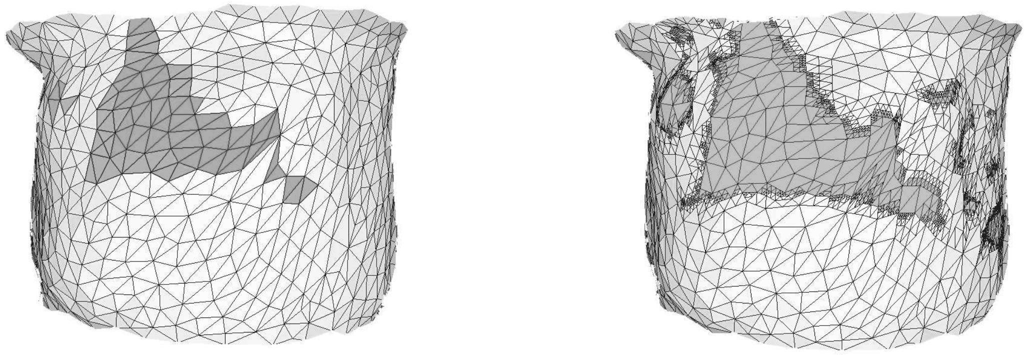


Figure 4. Insertion zones with 0 and 3 subdivision levels

subdivisions provides a good idea of possible strategies, it discards many possible insertion points. The average surface loss between computations with 3 and no subdivision is 56% and often more important when the insertion zone is small. By observing fig. 4 we notice that the biggest zone is well represented in both cases while thin zones are occulted in the case of a computation without subdivisions. Computation with 3 subdivision levels provides insertion zones with a good precision in 4 seconds to 2 minutes (average: 32s) that represents 250% of the computation time without sudivision.With more subdivision levels, the resulting surface does not differ significantly from the zone computed with only 3 levels while taking much more time (140% of the time with 3 subdivisions). At a same subdivision level, the computation time can vary between tumors, that mainly depends on the number of tumor's voxels (150-13000) since it determines the number of time the visibility tests have to be done.

Table 1. Comparison of surface of insertion zones and computation time with 0 or 3 subdivision levels

case	surf. of insert. zones (cm^2)		computation time (s)	
	no subd.	3 subd.	no subd.	3 subd.
1	3	23	47	130
2	5	44	9	41
3	86	123	10	28
4	45	86	8	19
5	60	140	8	32
6	35	123	5	26
7	171	256	29	71
8	35	78	25	56
9	17	72	11	29
10	163	242	11	24
11	203	238	7	12
12	92	171	20	31
13	68	158	3	10
14	45	128	3	8
15	62	158	3	6
16	0	10	2	4
17	5	41	23	28
18	0	54	10	16

6. CONCLUSION

In this paper, we presented a method for computing automatically possible insertion zones on the skin for the planning of a radiofrequency ablation. Any needle insertion in this zone respects two constraints : it does not cross any vital organs, bone or large vessel and the needle can reach the tumor from the corresponding insertion point on the skin.

Our method based on elimination and subdivision of triangles of the skin that do not respect the constraints quickly produces possible insertion zones on the skin with high precision. These zones are used in our patient-specific preoperative planning software to reduce the research domain for the optimization stage and provide valuable information to the physician who can easily see all possibilities for each operation.

Acknowledgments

We would like to thank Region Alsace, "Medical and Surgical Imaging and Robotics" Multi-Laboratory Research Program, and IRCAD for their financial support.

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