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Cryotrack: Planning and Navigation for Computer Assisted Cryoablation

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Abstract. Needle guidance in percutaneous ablation procedures is challenging due to the absence of a free line-of-sight. To date, the needle trajectory is manually planned on a pre-operative CT slice, and then the entry point and depth are transferred to patient and needle with a ruler. Usually, the needle is inserted in multiple strokes with interleaved control CTs, increasing the number of exchanges between OR and control room and exposure of the patient to radiation. This procedure is not only tedious, but also introduces a navigation error of several centimeters if the entry point was not chosen precisely. In this paper, we present **Cryotrack**, a pre- and intra-operative planning assistant for needle guidance in cryoablation. Cryotrack computes possible insertion areas, considering obstacles (bones) and risk structures. During the intervention, cryotrack supplies intra-operative guidance with a user-friendly 3D interface. Our system is evaluated in a phantom study with an experienced surgeon and two novice operators, showing that Cryotrack reduces the time of the intervention to a fourth while being on par with traditional planning in terms of safety and accuracy, and being usable by novices.

Keywords: Navigation and Planning · Cryoablation · Percutaneous Needle Guidance · Computer Assisted Surgery

1 Introduction

Percutaneous procedures such as thermal ablations (cryoablation, radiofrequency ablation) of tumors, are meticulous interventions that require a high accuracy while the target is out of sight, thus demanding a high level of expertise from the operator. More particularly, most cryoablation interventions require the insertion of several needles to completely cover a tumor with an iceball. Precise needle positioning is critical to avoid local tumor recurrence and damage to surrounding vital structures. Planning is typically carried out manually, using pre- and intra-operative CT imaging as a gold standard. Traditionally, the needle entry point and insertion depth are determined under the use of a CT image, which are then translated to the patient using the O-arm's laser beam and felt

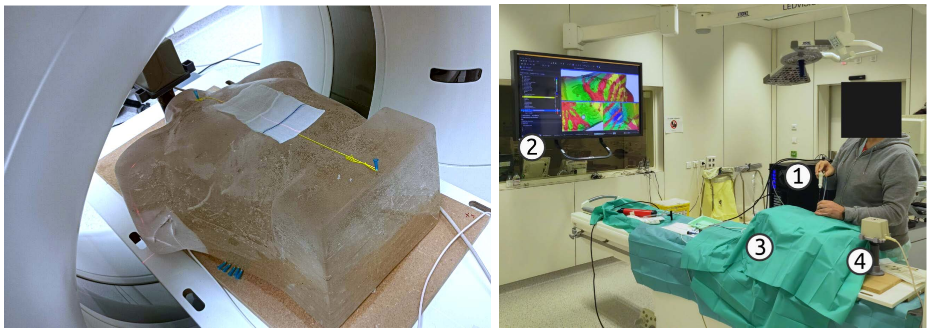

Fig. 1. Interventional setup. Left: Traditional setup. Intersection of blue sharpie line and yellow string on the phantom marks the desired entry point. Right: Cryotrack setup. The operator maneuvers an EM-tracked needle (1) while observing the Cryotrack UI displayed on a monitor (2). The phantom (3) is disguised by surgical drapes and stands next to a mid-range EMT field generator (4).

pens to mark the desired entry point on the patient's skin (Figure 1 left). Then a multi-stroke insertion requiring multiple image acquisitions at regular intervals is necessary, overexposing the patient to radiation. This procedure is rather tedious and requires multiple exchanges between OR and control room, requiring the interventionist to scrub up before entering the OR again. Adding to the tediousness, out-of-plane insertions are difficult to plan in this setting, leading the surgeons to prefer almost exclusively in-plane insertions, thus constraining the possible set of operative plans.

While planning solutions for percutaneous ablations have already been proposed [3,10,11], most of these assist the surgeon in the pre-operative planning process, and a translation of the pre-operative plan to the patient is still required. A few intra-operative tracking solutions have also been proposed, either based on electromagnetic optical [9], [13], or even markerless tracking [12], and highlighted the interest of tracking the needle in real time to improve targeting accuracy. However they mostly focus on intra-operative navigation and visualization while lacking intra-operative risk structure avoidance [1,7]. Some authors proposed to use augmented reality (see for instance [5,9]) to enhance the visual perception of the positions and navigation in 3D space, but giving little or no guidance on risks or optimal positions.

In this paper, we present **Cryotrack**, a holistic intra-operative planning and navigation tool for computer assisted cryoablation. Cryotrack allows the interventionist to select a previously annotated target, for which optimal insertion points and angles are calculated and conveniently displayed in real time. During the insertion, Cryotrack assists the clinician to maintain a good needle trajectory until the target is reached. In contrast to mere pre-operative solutions, Cryotrack assists the clinician throughout the intervention, increasing the confidence in the procedure while eliminating the requirement for intermediate control CTs and exchanges between OR and control room. Our contributions include:

1. We present Cryotrack, the first intra-operative-planning pipeline for computer-assisted Cryoablation. Our system considers distances to risk structures while guiding the user to an optimal trajectory and depth during the entire procedure.
2. The Cryotrack User Interface (UI) is integrated into 3D Slicer [4], and is updated in real time. The 3D Slicer extension will be made available to the public upon acceptance.

The proposed system is compared against traditional pre-operative planning and insertion, showing that Cryotrack has similar accuracy and safety while significantly improving the efficiency of the procedure.

2 Methods

Cryotrack provides a set of three pipeline stages (Figure 2) to help clinicians plan and insert needles more easily. They are detailed in the following sections.

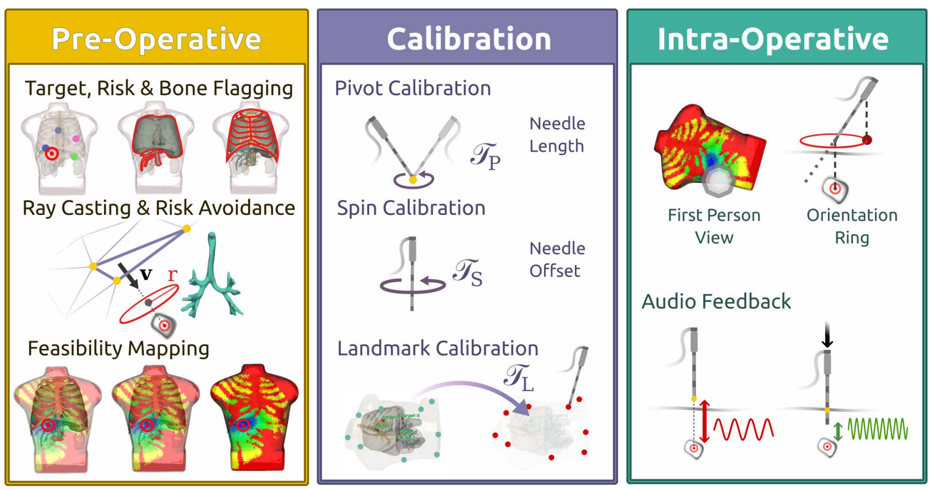

Fig. 2. Three-stage planning and calibration pipeline of Cryotrack.

Pre-operative Pipeline: The first step of the pre-operative pipeline is the automatic flagging of risk structures and obstacles such as vessels or bones, the obstacles (such as bones), which are then highlighted in the 3D view. The target is then selected by the user and is also highlighted. Once these structures are defined, a ray casting algorithm is used to create an insertion feasibility map on the 3D surface mesh representing the skin (Figure 3 left).

A ray is cast towards the target from the centroid of each triangle face of the skin model. The distance of each entry point to the target is evaluated, along with the collisions of the ray with the flagged structures that need to be

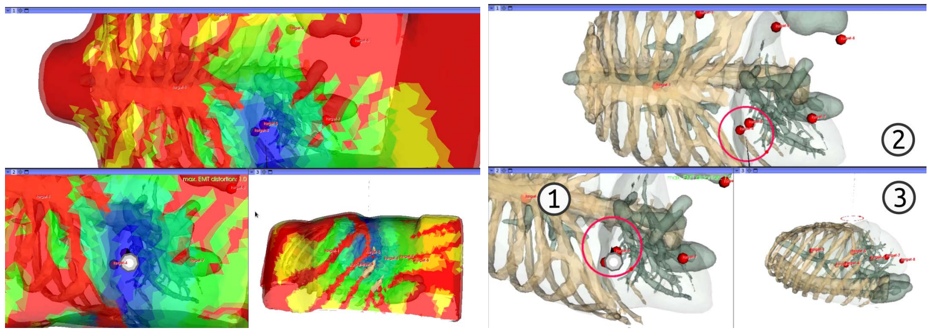

Fig. 3. Cryotrack UI. Left: UI before insertion. Optimal entry area is shown as a heatmap overlay. Right: UI during insertion. First-person view of the needle (1), AP (2) and LR (3) projections of the thorax. Targets are highlighted in red, risk structures appear in green. The red circle around the needle is the navigation ring.

avoided, plus a configurable safety radius r. The skin model is colorized with a jet gradient ranging from blue for the optimal entry points to red for the unfeasible entry points. In our system, an optimal entry point is defined as providing the shortest path from the skin to a target from which a ray does not intersect with a flagged structure. An infeasible entry point refers to points on the skin where the distance to the target is greater than the needle length or from which the ray intersects with a flagged structure.

Calibration: Two calibration steps are necessary to prepare the intervention. The first step is to calibrate the EM-tracked needle in order to obtain a linear transform that maps the Electromagnetic Tracking (EMT) position and angle to the needle tip. It is common to use a combination of pivot and spin calibration for this purpose [6]. Since this functionality is already provided in the OpenIGTLink Slicer extension [4,14], Cryotrack guides the user to this UI widget in the beginning. The final root mean square errors of the calibration obtained for the user study were 1.0 mm for pivot and 0.009 mm for spin calibration.

Once the needle is calibrated, the virtual scene of the phantom (including risk structures and targets) is registered to the coordinate frame of the EM-tracked needle tip by landmark calibration. Among the landmark registration approaches provided by the OpenIGTLink extension, a similarity transform $\mathscr{T}_L$ with nine point correspondences produced the most reliable results for our study. The whole calibration pipeline takes around five minutes to execute.

Intra-operative Pipeline: In the first step of the intra-operative pipeline, the operator uses the insertion feasibility map to position the needle tip at an optimal entry point on the skin of the phantom, thanks to a general view of the scene and a first-person view in the needle direction.

Once the needle tip is positioned, the operator switches the software to *insertion mode*. In this setup, the map is hidden, and the 3D view shows the most essential elements for the insertion: the risk structures to avoid, the targeted tumor centroid and the needle with a red navigation ring (Figure 3 right). The navigation ring provides a visual cue to align the needle with the target. The radius of the ring reflects the projection error between the needle and the line from the entry point to the target centroid. Once the orientations match, the ring is very small and it turns green to indicate that the insertion can start. We provide a video of this visualization in our public supplemental material.

During the needle insertion, the operator continuously receives visual feedback from the ring that is updated in real time. Additionally, an audio feedback consisting of rhythmic sounds informs the operator about the remaining distance between the needle tip and the target, similar to the concept of a parking assistant. The frequency and pitch of sounds increases as the remaining distance decreases, until it becomes a constant sound when the target is reached.

3D Slicer Extension: The whole pre- and intra-operative process comprising the three pipeline stages described above (see Figure 2) are wrapped in a *3D Slicer* [4] extension. It provides a visualization of the scene and tool, and an interface with a focus on a straightforward and intuitive user experience. A major design goal was to keep the user within our extension, so that common sequences of user actions are automated with one push of a button. Notable time-savers include automatic form filling, filtering and classification of scene components, as well as the quick calibration helper that automatically switches to the calibration module of 3D Slicer, initialized with custom parameters. The EMT system is connected to 3D Slicer via the IGTLink protocol using custom server software. We publish the code [4].

3 Experimental Setup

The experimental setup comprised a phantom torso made of radiolucent ballistic gel (10% Gel Joe Fit dummy by Clear Ballistics LLC), with five metallic spheres inserted at random locations. A pre-operative CT acquisition allowed to locate the spheres that are used as virtual tumor centroids, and segment other structures such as the skin as 3D models. The risk structures and tumor models were derived from manual segmentations of patients images, added to the virtual scene and overlaid on the phantom. In particular, we considered models of the trachea, hepatic vein and portal vein as risk structures.

The complete setup is illustrated in Figure 1. The phantom was placed on the table of the CT scanner. The needle was tracked by a trakSTAR ™ 3D Guidance® system from NDI, using the 800-type sensor, which is the most robust against electromagnetic interference. A mid-range field generator was positioned so that the torso was inside in the optimal tracking volume. After installation, the torso was entirely covered with surgical drapes to hide the metallic spheres from the operator and avoid any bias.

[4] GitHub organization: `https://github.com/Cryotrack`

All pre- and intra-operative planning and guidance with Cryotrack was carried out on a Lenovo Thinkpad P51 workstation laptop with 16 GB RAM, NVidia Quadro M1200 GPU and a 6th Gen intel i7 CPU, running Linux Mint 20.2. During the intervention, the visualization ran smoothly at a speed of 30 FPS.

Phantom Study Protocol: Four insertion studies were conducted to compare the accuracy, safety and speed of the whole process using Cryotrack to conventional CT-based planning:

1. **Novice with Cryotrack:** Novice operators N1 and N2 performed 1 in-plane and 1 out-of-plane insertion for 5 different targets, total 20 insertions.
2. **Surgeon with Cryotrack:** Surgeon S performed 2 in-plane and 2 out-of-plane insertions per target for 5 targets, total 20 insertions.
3. **Surgeon, traditional CT, single insertion:** Surgeon S inserted the needle based on a pre-operative CT plan in a single stroke, 1 in-plane and 1 out-of-plane insertions for 5 different targets, total 10 insertions.
4. **Surgeon, traditional CT, stepwise insertion:** The surgeon S inserted the needle in three strokes with a control CT after each stroke, 1 in-plane and 1 out-of-plane insertions for 5 different targets, total 10 insertions.

The two last configurations serve as baseline setups for reference. A control CT was acquired after each insertion to validate the final insertion *accuracy*. The needle coordinates were manually annotated in the control CT with 3D Slicer, and were used to calculate the Euclidean distance between needle tip and target mesh. Similarly, the Euclidean distance between the needle tip and the closest point in a risk structure mesh were calculated as a measure for *safety*.

Time was measured between the start and the end of the process. In the Cryotrack setting, the start is defined as the point in time when the operator generates the feasibility map in the UI. Typically, the intervention is started shortly after this action. In the CT setting, the start is defined when the surgeon picked the ruler or marker to draw the chosen entry point. This baseline setting requires all the trajectories, for each target, to be planned beforehand based on the images, which is not included in the reported process times. Any intervention is considered finished when the operator releases the needle.

4 Results

In most percutaneous procedures, a targeting accuracy of less than 5 mm is recommended [2]. As can be seen on Table 1 that reports the average results for each operator in each of the four configurations, using Cryotrack the expert surgeon reached an accuracy comparable to the baseline setups, even performing better than the stepwise insertions. This result was achieved in three to four times less time than the baseline configurations.

A disparity between novice and skilled operators can be observed in both Table 1 and Figure 4. Although novices could not achieve the desired accuracy, they were able to conduct safe insertions with the help of real-time intraoperative planning even if it was their first time achieving this task. One operator could even achieve an accuracy very close to the 5 mm threshold (6.53 mm), in-plane. In one case (#5), all operators including the novices even performed better using Cryotrack than without.

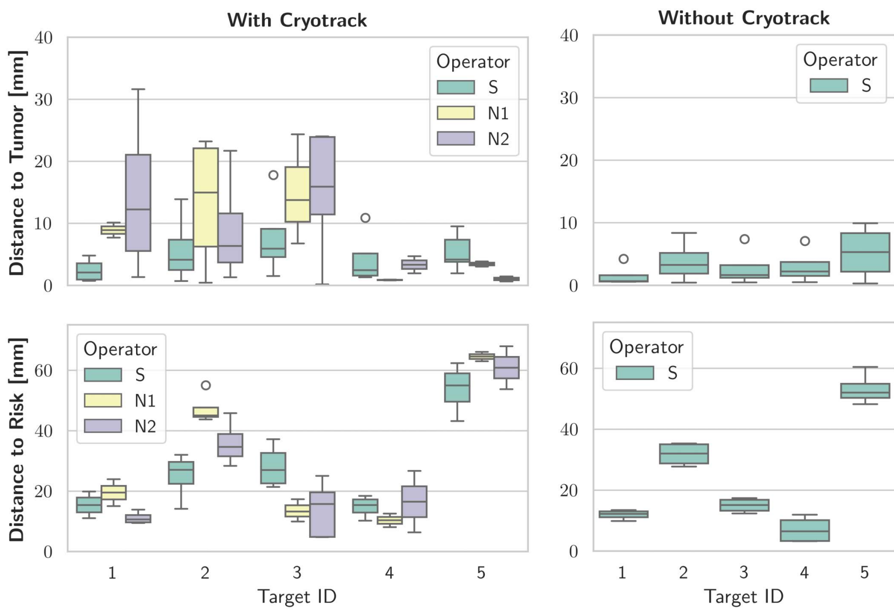

Fig. 4. Top: tip to tumor distance (lower is better). Bottom: distance from tip to closest risk volume (higher is better). S: Surgeon, N1, N2: Novice operators.

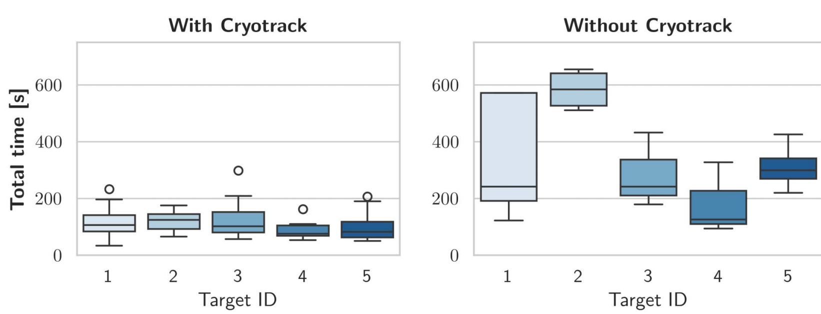

Fig. 5. Total intervention time, including pre-operative planning. With support by Cryotrack (left) compared to CT baseline (right).

This suggests that the proposed system is sufficiently easy to use, enabling even an inexperienced operator to perform a task that they would otherwise not be able to do. In fact, Cryotrack increases confidence and makes the procedure resilient against operator error. The lack of accuracy of novices can be attributed to a lack of skill and experience as the surgeon's insertions are similarly accurate in both scenarios. The distance to risk structures was relatively comparable and even slightly higher on average using Cryotrack, highlighting that the system assists the insertion in a *safe* manner.

	Op.	Plane	Strokes	Tumor distance [mm] ↓	Risk distance [mm] ↑	Time [s] ↓
Cryotrack	N1	IP	1	10.95±9.99	31.83±22.16	106.57±35.43
	N1	OOP	1	8.03±7.30	32.48±22.55	86.64±31.37
	N2	IP	1	6.52±7.12	28.33±15.86	166.43±52.41
	N2	OOP	1	13.89±11.42	20.59±20.48	150.04±78.85
	S	IP	1	3.27±2.21	29.23±17.11	100.92±32.07
	S	OOP	1	7.14±5.67	28.07±16.37	80.19±48.11
		Avg.		8.30±3.25	28.42±3.00	115.13±17.42
Baseline	S	IP	1	1.96±3.27	20.82±17.67	453.19±468.30
	S	OOP	1	2.38±2.74	27.45±20.60	456.56±111.61
	S	IP	3	4.34±3.36	21.70±18.78	309.54±201.64
	S	OOP	3	4.38±3.31	25.02±18.86	330.79±151.83
		Avg.		3.26±0.29	23.75±1.21	387.52±78.27

Table 1. Average accuracy (tumor distance), safety (distance to closest risk) and efficiency (time), grouped by operator, in/out-of-plane and number of strokes.

Interventions using Cryotrack were significantly faster to plan and conduct (Figure 5). On average, procedure times with Cryotrack were 3.37 times shorter than with the CT-based reference setting, which is a significant benefit in multi-needle procedures such as cryoablation. This does not even include the upfront preoperative trajectory planning required for CT-based insertions, that took just above one hour for the five targets, which has to be added to the overall time.

5 Conclusion

We have presented Cryotrack, the first integrated intra-operative planning and navigation tool for computer-assisted cryoablation. While Cryotrack competes with traditional CT-based planning in terms of accuracy and safety, it is significantly faster and intuitive to conduct an intervention with continuous intra-operative support. In the future, we plan to integrate additional modalities, such as stereotactic vision [3,8], to compensate for respiratory motion. Although the system was originally designed for cryoablation, Cryotrack can be adapted to similar procedures like radiofrequency ablation by addressing domain-specific requirements. With this work and future developments around Cryotrack, we expect the under-researched field of intra-operative insertion planning to gain momentum.

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